Large-screen projection of television pictures with an optical-relay tube based on the Pockels effect

G. Marie

The only solutions at present offered for the problem of reproducing television pictures in dimensions comparable with those of the cinema screen — all of them involving projection — are complicated and often very costly.

In the first part of this article, we shall examine a number of solutions proposed or already in use. In the second part, a real-time system will be described which is based on a new type of optical relay using an electro-optic effect. Its chief advantages are ease of operation and absence of flicker in the reproduced images.

Comparison between some existing projection systems

In this section we shall examine the following television picture projection systems, stating their performances and comparing their efficiencies:

1) The optical relay, which does not operate in real time, the images being recorded on film and then projected.
2) Projection from cathode-ray tubes.
3) Optical relays operating in real time and in which scanning is achieved either by a moving light beam (laser system) or by an electron beam (Eidophor).

Cinema-type projection

Projection of a television picture via a recording on film offers the advantage of a high efficiency which makes it possible to use very large screens (e.g. 150 m²). This, however, is a costly solution because it employs special film material which cannot be erased and because the exposed film, generally speaking, will never be used again; moreover, it inevitably involves a time delay between the moment of transmission of the picture and the moment at which that picture is projected.

This second disadvantage can be overcome and the time delay reduced to less than a minute by using films, either of the conventional type (e.g. Kelvin-Hughes [11]) or of the vesicular type (e.g. Kalvar [12]), which can be developed rapidly. The cost of these films does not normally allow them to be used except in the case of short sequences. However, they are often used for the reproduction of slow-scan pictures, such as those obtained with radar.

In order to compare the performance of the various projection systems, we shall calculate the electrical power per unit of screen surface area necessary to obtain a maximum luminance of 28 cd/m², the average maximum value found in cinemas. If we assume that the screen reflects light in accordance with Lambert's law and with an efficiency of 80%, the necessary illumination is then 110 lux. The light source generally used is a high-pressure xenon lamp whose luminous efficiency can be as much as 33 lumens per watt. Since the individual efficiencies can be evaluated as 50% for the light-collection system, 66% for the maximum transparency of the film and the objective and 50% for the relative projection time, we obtain a consumption of 20 W/m² (Table I).

Projection by cathode-ray tube

Cathode-ray-tube projection was the first high-resolution system for the projection of television pictures [3]. The performance of this system, however, is limited by the maximum permissible dissipation on the tube screen. In one of the most highly developed solutions [4], a tube is used which can dissipate a mean electrical power of 25 W. The fluorescent screen of the tube radiates in accordance with Lambert's law, with an efficiency close to 8 lm/W. The projection system, which uses large-aperture optics (Schmidt system), has an overall efficiency of the order of 25%. Taking into account the fact that the power consumption is proportional only to the mean luminance of the picture, which is generally about a third of the maximum luminance, we can assign a value of 3 to the "modulation efficiency" (Table I). From this, we deduce a consumption of 18 W/m² for a screen luminance of 28 cd/m². As the power which the tube can dissipate is limited (25 W in the example quoted), images can be projected only on screens with a surface area of a few square metres. With an arrangement comprising three tubes and three optical projection systems and using a directional screen giving a gain of approximately 3, it has been possible to project pictures in colour having a luminance of 20 cd/m² on a surface area of 7 m² [4]; however, it should be pointed out that the use of a directional screen obviously limits the useful field of observation and hence the number of viewers.

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Optical relay using a laser beam

Optical relays have been developed in the earliest days of television; a light beam from a source was amplitude-modulated with the aid of a Kerr cell, then deflected by a rotating mirror before reaching the screen. With an arrangement of this type, however, it was not possible to reproduce high-resolution and large-dimension images because the light modulators and light deflectors could only accept beams of limited solid angle and cross-section.

The recent advent of lasers concentrating the entire radiation in a beam of very small solid angle and cross-section (e.g. diameter 1 mm, divergence $10^{-3}$ rad) now makes it possible to reconsider the use of such a device to obtain high-resolution pictures. Modulation can be achieved without difficulty by means of a Kerr or Pockels cell and, so far as the problem of deflection is concerned, it can be solved either by digital deflection or by continuous scanning using ultrasonic waves or rotating or vibrating mirrors [5].

Let us compute the efficiency of the system, choosing as a source the continuous-wave laser operating in the visible region for which the efficiency and the power output are the highest, i.e. the ionized-argon laser. When a strong magnetic field, greater than 0.1 tesla (1000 gauss), is applied to its plasma, the efficiency $\eta$ can reach a value of $10^{-3}$ [6]. We list below the values of $\eta$ and the relative eye sensitivity factor $\bar{y}$ as a function of the wavelength of the emitted spectral lines:

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>$\eta$</th>
<th>$\bar{y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>488</td>
<td>$5.5 \times 10^{-4}$</td>
<td>0.18</td>
</tr>
<tr>
<td>514.5</td>
<td>$3 \times 10^{-4}$</td>
<td>0.60</td>
</tr>
<tr>
<td>498.7</td>
<td>$0.8 \times 10^{-4}$</td>
<td>0.28</td>
</tr>
<tr>
<td>476.5</td>
<td>$0.7 \times 10^{-4}$</td>
<td>0.12</td>
</tr>
</tbody>
</table>

As the value $\bar{y} = 1$ corresponds to a luminous efficiency of 680 lm/W, the sum of the light energies of the various emission lines gives an overall luminous efficiency of 0.20 lm/W. Furthermore, we must take into account the efficiency of the modulator, which is about 75%, and also the relative projection time — 0.8 times 0.92 (20% loss due to line flyback and 8% loss due to frame flyback) — with the 625-line standard. The consumption necessary to obtain a luminance of 28 cd/m$^2$ then becomes 1000 W/m$^2$ (Table I).

The efficiency of this system is therefore much too low to permit projection on large screens. In the case of reproduction of colour pictures, one might consider the use of the ionized-argon laser for the green primary (emission line 514.5 nm) and the blue primary (line 476.5 nm and, though less suitable, 488 nm) and the He-Ne laser for the red primary (line 632.8 nm, efficiency $3 \times 10^{-4}$ approximately); it will then be seen that the consumption is about 2000 W/m$^2$, i.e. 100 times higher than that for cinematographic projection.

Optical relay with electron-beam scanning (Eidophor)

The operating principles of the Eidophor were proposed by F. Fischer as early as 1939. The first practical experiments were performed in 1944 and development

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of the system was completed in about 1950 [7][8].

Its operating principle is shown in fig. 1. The light from a cinema-type projection lamp A is directed to a concave mirror C coated with a film of oil D, after reflection on a mirror B made up from strips and placed at the centre of curvature of the concave mirror (Schlieren optics). When the film of oil is perfectly uniform, the concave mirror gives an image of the strip mirror

![Diagram of Eidophor optical relay](image)

Fig. 1. Operating principle of the Eidophor optical relay; the Eidophor utilizes the deformations caused in a film of oil by the charges deposited by an electron beam. A light source. B strip mirror. C rotating concave mirror. D oil film. E electron beam. F projection lens. G knife-edge to smooth the oil film. The part of the light from A which is not reflected by the strips of mirror B is completely absorbed in H.

which is practically superimposed on itself. All the light which reaches the film of oil is then reflected towards the source. When the oil film is distorted, however, part of the light is transmitted through the strip mirror towards the objective and the projection screen. The distortion of the oil film is induced by electric charges distributed with spatially variable density and deposited on the film by an electron beam whose density is modulated at a relatively high frequency (e.g. of the order of 10 MHz). One can thus project a television picture, using the video signal to control the modulation depth of the electron beam. Erasure is achieved automatically with a suitable time constant by choosing a good compromise between the conductivity and the viscosity of the oil film, which has to be kept at a well defined temperature. This device shows the same flicker effect as conventional cathode-ray tubes and the laser projection system. To avoid permanent deformations, it is necessary to rotate the concave mirror slowly and to smooth the surface of the film with a knife-edge (G in fig. 1).

To calculate the consumption of the system, we may assume that the same light source and the same optical collection system are used as in the case of cinematographic projection. We must then take into account the fact that only 50% of the light from the lamp is usefully reflected by the strip mirror B towards the oil film [9] and that, in the return direction, this mirror transmits at most 50% of the light diffused by the oil film; besides, we may assume that the relative projection time is approximately 50% because of the exponential decay of the deformations of the film, this decay being necessary to reproduce movement. The consumption necessary to obtain a luminance of 28 cd/m² is then 53 W/m² (Table I).

In order to project colour-television pictures, a triple projector has been constructed by adding to the device shown in fig. 1 two more electron guns and placing dichroic mirrors between the strip mirror and the concave mirror; the dichroic mirrors split the incident luminous beam into three primary components, red, green and blue, which are directed towards three different zones of the concave mirror; these mirrors reconstitute the beam from the three reflected light components. In practice, the power consumption of this arrangement is about 1.5 to 2 times larger than that of the black-and-white system (Table I).

The Eidophor is the only real-time optical relay at present in use which is able to project television pictures on to a screen with an area of several tens of square metres. Pictures exhibit a flicker effect that becomes increasingly disturbing as the picture area is increased. It has the further disadvantage of being expensive, bulky and not easy to operate. In fact, it usually has to be demountable to permit replacement of the cathodes, whose life-time is limited by the presence of a residual oil-vapour pressure, and it incorporates a pumping system; it also includes rotating and cooling elements in vacuum. Attempts are at present being made to build a sealed-off model. Nevertheless, the bulkiness and complexity of the system remain and this is why a number of laboratories have tried to develop devices of smaller size based on other physical phenomena, in particular on electro-optic effects.
Relay using the Pockels effect

Operating principle

In the optical relay, which will now be described, modulation of the beam is performed by using the Pockels longitudinal electro-optic effect exhibited by a monocrystalline plate belonging to the potassium dihydrogen-phosphate family. It should be noted that the idea of utilizing the Pockels effect for the projection of television pictures is not new, having been put forward as long ago as 1936 by L. S. Kaysie [10], M. von Ardenne [11], and V. A. Babits [12]. An attempt at the realization of such a device was described in 1960 by S. Rissmann and H. Voshahlo [13] and we know that work along these lines is at present in progress in several American laboratories. To our knowledge, this work uses crystals operating at ambient temperature and it seems at the present time not to have resulted in the development of an optical relay capable of projecting high-definition images.

It is known that when a crystal of KH$_2$PO$_4$ is placed in an electric field $E$ parallel to its optical axis $c$, a difference $\Delta n$ in refractive index occurs for light components whose directions of polarization are at right angles to each other. These components, initially in phase, show a phase shift $\varphi$ upon leaving the crystal of thickness $l$. Since the effect is linear, $\Delta n$ is proportional to the field $E$ and $\varphi$ is proportional to the product $El$, i.e. to the potential difference $V$ between the input and output faces of the crystal. When the crystal is placed between two crossed polarizers, the resulting transmission is equal to:

$$T = \sin^2 \frac{1}{2} \varphi = \sin^2 kVl,$$

in this expression the parameter $k$ does not depend on the thickness of the plate. As long as $T$ remains below 75%, the characteristic is practically quadratic and similar to that of conventional picture tubes.

The sensitivity of a crystal can be characterized by the voltage $V_{\lambda/2}$ for which the phase shift is 180° and therefore the transmission is maximum. This voltage reaches approximately 8 kV in the case of ordinary potassium dihydrogen phosphate and about 3.5 kV in the case of the deuterated crystal (KD$_2$PO$_4$). If light goes through the crystal twice and if transmission is limited to 75%, in order to remain within the quadratic region of the characteristic, the maximum voltage which is necessary for KD$_2$PO$_4$ is reduced to 1.2 kV. If the dimensions of the crystal plate are of the order of 30x40 mm and if one wants to obtain a resolution of 600 lines with 800 elements per line, two points which are 50 $\mu$m apart must be able to hold potentials which differ by approximately 1 kV. It seems that this result has not as yet been reached, either because of the occurrence of leakage currents at the surface of the crystal or because of the effect of these potential differences on the trajectories of the electrons, even in the presence of high acceleration voltages (e.g. 20 kV).

The TITUS tube

A special tube based on the Pockels effect, called TITUS ("Tube Image à Transparence Variable Spatiotemporelle"), has been developed at LEP. The operating principle has been defined in cooperation with Y. Angel, professor at the Conservatoire National des Arts et Métiers in Paris, and R. Genève at LEP, and already described in a previous article [14].

When the variations with temperature of the Pockels effect in a ferroelectric crystal are examined, it is observed that the induced birefringence is not proportional to the electric field but to the electric polarization, i.e. to the product $eE$ when the crystal is operated above the Curie point. As the crystals of the KD$_2$PO$_4$ family are ferroelectric, we overcame the previous difficulties by operating the crystal at a temperature near its Curie point $t_c$. Fig. 2 shows the variation with temperature of the dielectric constant of KD$_2$PO$_4$.

![Fig. 2. Curves showing the variation of the dielectric constant of a KH$_2$PO$_4$ crystal with 90% of its hydrogen replaced by deuterium, as a function of the temperature $t$: $\varepsilon_c$ in a direction perpendicular to the optical axis; $\varepsilon_a$ and $\varepsilon'_a$ in a direction parallel to the optical axis for a free crystal and a clamped crystal.](image-url)
for a field in a direction perpendicular to the optical axis \((\varepsilon_0)\) and in a direction parallel to the optical axis; in the latter case it is shown both for a free crystal \((\varepsilon_0)\) and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\). In fact, since the Pockels effect in a free crystal is accompanied by a piezoelectric effect which might cause coupling between the different points of the picture, it is necessary to clamp the crystal plate, e.g. by gluing it; one then observes and for a clamped crystal \((\varepsilon_0')\).

The choice of the operating temperature not only modifies the sensitivity of the Pockels effect but also makes it possible to give the optical relay an important additional feature: it can reproduce television pictures without flicker, however low the scanning speed. Indeed, the discharge time constant of the crystal (equal to the product of the dielectric constant and the resistivity) becomes about 1 hour at \(-60 ^\circ C\), whereas it is about 0.1 second at ambient temperature. In our case, this phenomenon raises the problem of removal of the charges deposited by the electronic beam, while erase can be considered to be automatic in the case of operation at ambient temperature. For the removal of the charges we have made use of secondary emission from the target by employing an arrangement already used in a few storage tubes. This arrangement is shown in fig. 3, which also illustrates the principle of double-transit operation with the aid of a multi-layer dielectric mirror \(M\). The target is bombarded by an electron beam whose acceleration potential is of the order of 500 to 1000 V, so that the secondary-emission yield at saturation of the bombarded face is greater than 1; a grid \(G\) is placed in front of the target, a short distance away from it — about 50 \(\mu m\). It can be shown that, under these conditions, the equilibrium potential reached by the point of impact of the electron beam is a few volts higher than the potential of the grid; the electron beam, which has a constant intensity, then works practically as a “flying” short-circuit between the grid and the target of impact on the target. It is therefore sufficient to apply the video signal between the grid \(G\) and the transparent conducting layer \(E\) to ensure that the various points on the target get charged to the corresponding video voltage when they are hit by the beam. The erase and writing functions are therefore combined and the result is an entirely flicker-free operation; indeed, the charge at each point remains constant between two successive scans of the electron beam as well as during these scans, for points which have not moved on the image.

### Power requirements of the projection system

The \(K\)DP04 crystals belong to the tetragonal system and have an optical axis; therefore, when they are placed between crossed polarizers, one can obtain a total extinction of the transmitted light only for beams parallel to the optical axis. Operation with a light beam that has a certain amount of divergence introduces a level of unwanted light which limits the contrast. It has been calculated that, with a crystal plate having a thickness of 0.2 mm and operating in a double-transit system, it is possible to obtain a contrast of 50 for a beam whose aperture angle is about 10°. The solid angle of the light beam which can be used is therefore more limited here than in the case of cinematographic projec-

![Fig. 3. Basic structure of the TITUS tube. C monocrystalline plate of KD2PO4 exhibiting Pockels effect. M multi-layer dielectric mirror. G ground-potential collector grid placed a short distance away from the crystal. E transparent conducting electrode receiving the video signal. K cathode at a potential between \(-500\) and \(-1000\) V, which delivers an electron beam of constant intensity. For practical purposes the electron beam can be regarded as a flying short-circuit between the grid and the target. Also shown in the figure: external light source \(L\) and crossed polarizers \(P_1\) and \(P_2\); the light is projected on to the screen S.](image-url)
For an illumination of 110 lux of the screen (Table I), we thus obtain a consumption of 55 W/m², a value very close to that found in the case of the Eidophor. As in that case, the consumption is increased by a factor of 1.5 to 2 when colour pictures are projected, which can be done very simply using three relay tubes and two dichroic mirrors (as shown by the dashed portions in fig. 5).

First experimental results

The experimental realization of the optical-relay tube gave rise to many technological problems, related in particular to operation with polarized light and the need to cool the target uniformly to a temperature close to −60 °C. These problems were solved in cooperation with J. Donjon and R. Le Pape at LEP. Fig. 4 shows a tube having the dimensions of a 3-inch image orthicon in order to enable conventional deflection and focusing coils to be used; cooling of the target is achieved with two stages of Peltier cells incorporated into the tube.

The experimental arrangement is shown in fig. 5. The light from the xenon lamp is condensed by means of a concave mirror on to a polarizing calcite prism of the Glazebrook type which transmits to the tube only the light component whose electric vector is parallel to the plane of the figure. The projection lens is placed between this prism and the tube so that the luminous beam incident on the target has a mean direction which is normal to the latter; when the light beam is reflected and passes through the lens and the prism again, only the light component with its electric vector perpendicular to the plane of the figure is transmitted to the screen.

The first laboratory experiments consisted in pro-
jecting a picture on to a screen with a surface area of approximately one square metre; the resolution (750 elements per line) and the contrast obtained are satisfactory, as can be seen from the photograph in fig. 6.

**Advantages and applications**

The optical relay we have just described is a simple sealed-off tube of relatively small dimensions. Compared with existing systems of the Eidophor type, it has the advantage of being very easy to operate. Moreover, the pictures do not flicker, which is particularly important in the case of large-screen projection and which might result, for professional applications, in a reduction by almost a half of the passband needed for a television channel.

The applications of this optical relay are not restricted to conventional television. Indeed, the absence of flicker makes it particularly well suited to the reproduction of slow-scan images such as those obtained in infra-red television with mechanical scanning (one image per second approximately) or in the case of radar pictures (a few pictures per minute). Finally, it should be noted that the memory features of the tube (storage time of the order of one hour) and the feasibility of simultaneous writing and erasing — localized if needed at precise points of the image — will also make it suitable for application as a computer peripheral unit.

**Summary.** After recalling the problems involved in the projection of television pictures on large screens the author describes the solutions known at present: recording on film and projection, projection from cathode-ray tubes, use of lasers, and the Eidophor. The latter is the only real-time optical-relay system at present in use, although it has some drawbacks due to its bulkiness and complexity. Simpler solutions are possible by using a new type of optical relay based on the Pockels effect in a KD2PO4 crystal. Different varieties are under study in Europe and the United States. The characteristics of a relay tube made at LEP and known as TITUS are examined in greater detail. In this tube the crystal is brought to its Curie temperature (−60 °C) and one of its most important features is that it provides a flicker-free picture. First results show that satisfactory resolution and contrast can be obtained.