Image Storage and Display Devices Using Fine-Grain, Ferroelectric Ceramics

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Thin plates of ferroelectric ceramic in combination with transparent conductive and photoconductive films have been used to form device structures that can store a real image as a spatial variation in birefringence. This image can be viewed directly by suitably polarized transmitted light or projected onto a viewing screen. The stored image is erasable by the application of appropriate combinations of light and electric fields.

I. INTRODUCTION

Recent publications have called attention to the usefulness of fine-grained, lead zirconate-lead titanate ferroelectric ceramics in several kinds of electro-optic devices.[1–3] This paper reports initial experimental results from ferroelectric picture devices (ferpics) based directly on the electro-optic properties of these new materials. In addition, this paper discusses how the basic device may be used to advantage in several types of display systems.

II. BASIC PRINCIPLES OF OPERATION

A thin, transparent plate of lead zirconate-lead titanate ceramic, as it is initially formed, is optically isotropic. By the process of poling, it can be given a condition of uniaxial birefringence dependent upon the remanent polarization of the material. The poled material has its optic axis parallel to the polarization direction. Figure 1(a) shows how, by means of electrodes applied to its edges, a plate is poled so that the remanent polarization lies unidirectionally in the plane of the plate. In this condition (L-state) the plate exhibits uniform birefringence for polarized light incident normally. An image is stored by switching at least a portion of the domain polarization vectors in the areas where the plate is illuminated to a direction perpendicular to the plane of the plate (T-state), thus reducing the birefringence of these regions. The

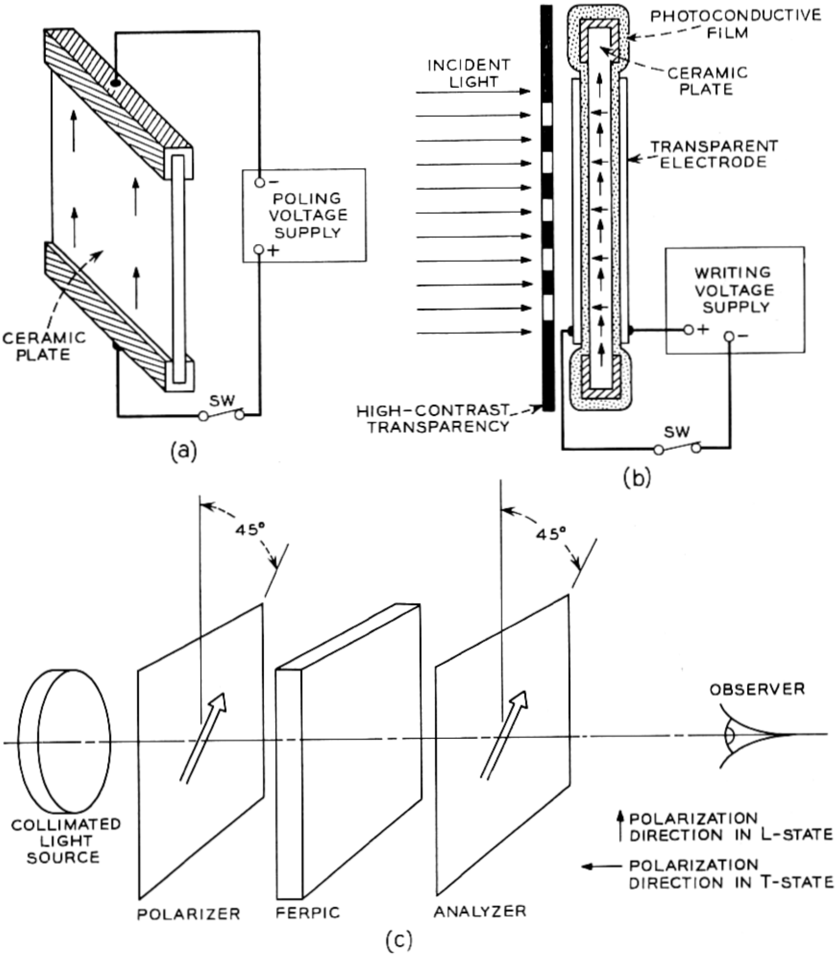


Fig. 1—Construction and operation of an elementary ferpic: (a) poling the ceramic plate, (b) storing an image, (c) observing the recorded image.

required perpendicular switching field can be obtained by means of the arrangement shown in Fig. 1(b). The ceramic plate is coated on both sides with a photoconductive film and sandwiched between transparent electrodes. In front of the ferroelectric picture device (ferpic) is placed a high-contrast transparency illuminated by a beam of collimated incident light. When voltage is applied to the transparent electrodes, the high impedance of the *dark* photoconductive regions prevents the field inside the ceramic from reaching a value producing a significant amount of switching. In the *illuminated* regions, however, the impedance of the photoconductor is reduced and the field in the ferroelectric increases to the point that appreciable domain switching is produced causing the ceramic underlying the illuminated areas to be switched to the T-state. Thus a stored image is obtained as a spatial modulation of the birefringence of the ceramic. The image can be made visible by inserting the ferpic between a polarizer and analyzer as shown in Fig. 1(c). The image can be erased either by poling the sample in the plane (L-state) or by thermally depoling the material.

III. EXPERIMENTAL RESULTS FROM AN ELEMENTARY FORM OF FERPIC

The details of an experimental device structure that operates in this manner are shown in Fig. 2. The device uses a 50 μm thick plate of ceramic* having 65 percent lead zirconate and 35 percent lead titanate with two atom percent of lanthanum (designated 65/35-2 La). The grain size of this material is approximately one micron. Originally, the plate is poled to have a remanent polarization in the plane of the plate (L-state) by means of an applied field of approximately 20 kV/cm. The sample is poled before the photoconductive film and the transparent electrodes are applied. The specific poling conditions used for a given plate are adjusted to give a state of remanent polarization causing a half-wavelength of phase retardation when polarized light is transmitted at normal incidence through the plate.

After the plate is initially in a condition such that all regions of the plate in the area used for storing the picture are in the L-state, the photoconductive film and transparent conductive films are applied. In the version of a ferpic outlined in Fig. 2, the photoconductive film is PVK† applied simultaneously to both sides of the plate by a dip-coating technique. Transparent conductive electrodes are next applied. In our experimental devices, half-transparent films of Cr-Au are vapor deposited on the two surfaces; in practical devices, more transparent electrodes of tin oxide or indium oxide would be preferred. Fine wire leads are attached to these electrodes and used to connect the device to the voltage source used to supply a switching field in the thickness direction.

Figure 2, in addition to showing the structural features of the

* The ceramic used in our experiments was produced by Clevite Corporation, Cleveland, Ohio 44108.

† The abbreviation PVK stands for polyvinyl carbazole. The material used was obtained from Polyscience, Incorporated, P. O. Box 4, Rydal, Pennsylvania 19046.

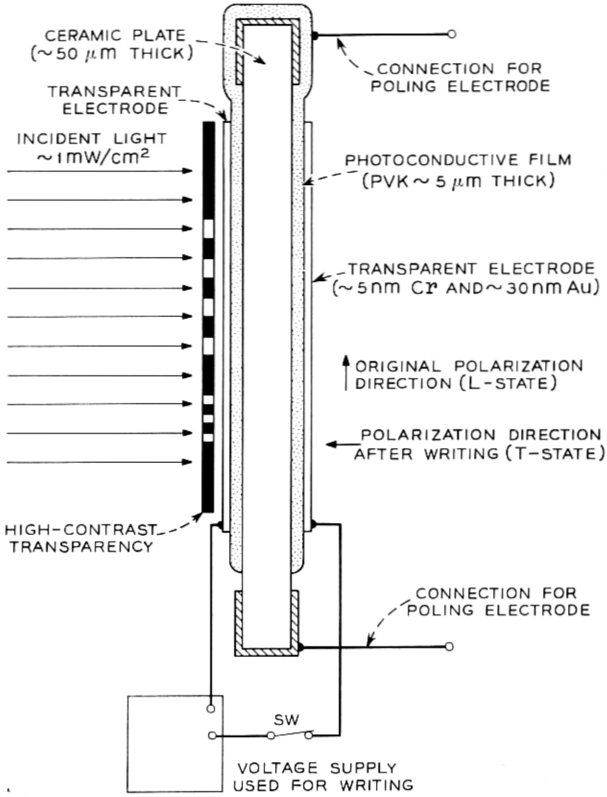
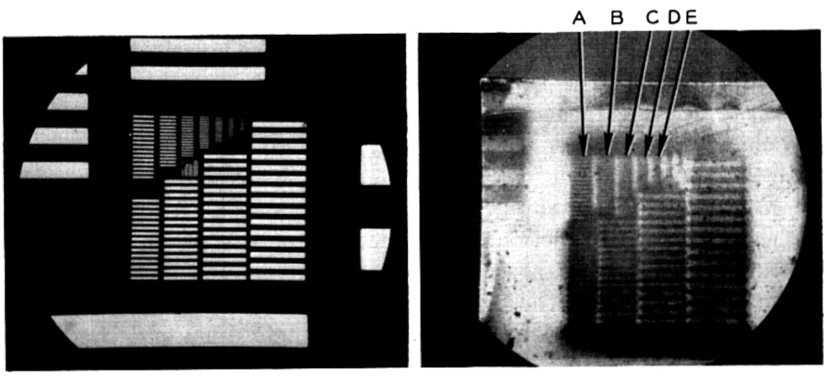


Fig. 2—Construction details of an elementary ferpic and experimental arrangement used to store an image.

device, shows the arrangement used to write the picture information into the ceramic plate. A high contrast transparency is placed immediately in front of the ferpic and illuminated with collimated light. The voltage supply is pulsed on. In the regions where the light passes through the transparency, the photoconductive film becomes conductive and the field in the ceramic becomes large enough to produce switching in the form of 90° polarization rotation. (This mode of operation is described by Land and Thacher in connection with light gate structures using various configurations of metal electrodes.[1] In ferpic devices, the 90° polarization-rotation mode of operation is obtained by the use of photoconductive films and transparent conductive films working in combination with metal electrodes.) Localization of the switching field requires that the dielectric constant of the ceramic, K_{CER}, be much larger than the dielectric constant of the photoconductor, K_{PVK}. For the materials used in our experimental devices $(K_{CER}/K_{PVK}) \approx 400$. For a 50 μm thick ceramic plate, the writing conditions were the following: (*i*) a white light flux of 2 mW/cm^2, (*ii*) a 200 V supply, and (*iii*) a voltage pulse duration of approximately 1 minute.

As already described, the stored image can be made visible by inserting the ferpic between a polarizer and analyzer, as indicated in Fig. 1(c), and illuminating it with light from a collimated, monochromatic light source. (The degree of collimation and monochromaticity involved are not critical. Most of our experimental work is done using white light from ordinary incandescent sources and, in fact, the two photographs included with this report were made with this sort of light.) If the phase retardation produced by regions in the L-state is $\lambda/2$, efficient use of light is obtained when polarizer and analyzer are set parallel to each other and at an angle of 45° to the electric polarization vector in the ceramic. The regions in the L-state appear opaque; the regions switched to the T-state present no birefringence to the incident light and appear as bright areas to the viewer.

The ferpic just described can be used as a kind of photographic plate capable of two-level (black and monochrome) image storage with a respectable degree of resolution. Figure 3 shows photographs made



(a) (b)

LINES/mm

A–25.1 B–31.6 C–39.8 D–50.1 E–63.1

Fig. 3—(a) The original resolution test chart as seen with a microscope using low power magnification.
(b) The resolution test chart image stored in a ferpic and rendered observable by means of a polarizer and analyzer used with the microscope.

using a low power microscope to view a pattern from a resolution test chart stored in a 50 μm thick ceramic plate. The number of lines/mm in the individual columns marked A, B, C, D, and E is indicated in the figure.

This photograph demonstrates that resolutions better than 30 lines/mm are obtainable under the described conditions of operation. A number of experiments have been carried out to establish the principal factor limiting the resolution. Fringing fields within the 50 μm thick plate appear to be the principal factor, since both the optical techniques and the photoconductor used have been demonstrated to have at least an order of magnitude finer resolution capabilities. The present observed resolution is already equivalent to 2 to 3 cycles of variation over a distance equal to the thickness of the plate.

The device described in Fig. 2 has limited usefulness since, like a photographic plate, it can be used only once. The transparent electrodes on the surface prevent the polarization vector under these electrodes from being switched back to the L-state when a voltage is applied to the poling electrodes. We will next consider a form of ferpic that offers the capability of being electrically changeable.

IV. AN ELECTRICALLY CHANGEABLE FERPIC USING AN INTERDIGITAL ELECTRODE ARRAY

An interdigital electrode array deposited on one side of a ceramic plate provides in principle a means of switching the polarization vectors back into the plane of the plate after they have once been switched normal to it. An exploded view of the layer structure proposed for use in a changeable ferpic is shown in Fig. 4. In addition to enabling the plate to be switched into the L-state, use of the interdigital array has the great practical advantage of reducing the voltage required to pole in the longitudinal direction. As already indicated, 20 kV is required to pole over a 1 cm distance. If the line elements have the same spacing as the plate thickness, the same voltage supply ($\sim$200 V for a 50 μm thick plate) can be used to establish both longitudinal and transverse switching fields. The obvious disadvantage to this approach is that the stored image will now be broken into a number of discrete lines. The extent to which the presence of the lines is evident and objectionable will depend on the details of use.

The ferpic structure shown in Fig. 4 constitutes an electrically changeable image storage and display device that functions in three steps: (*i*) RESET, (*ii*) WRITE and (*iii*) VIEW. The first two steps are illustrated

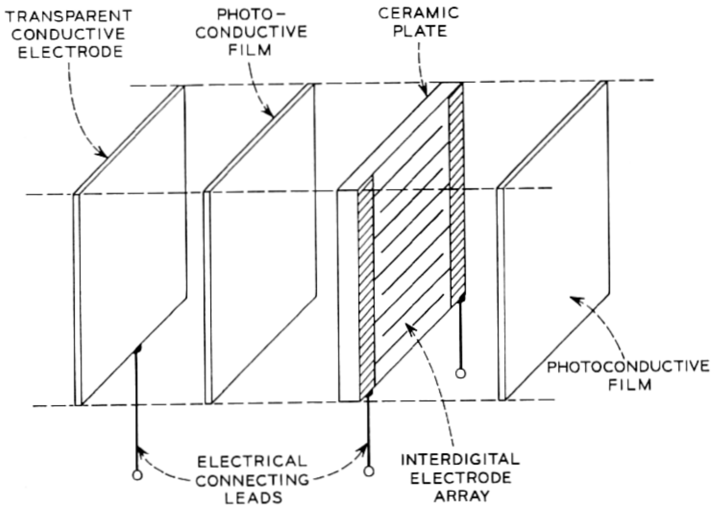


Fig. 4—Exploded view of the layered structure used to form an electrically changeable ferpic.

in Fig. 5(a) and (b); the third step involves essentially the same elements shown earlier in Fig. 1(c). In the RESET step the electrodes of the interdigital array are connected to the voltage supply and the resulting field switches the remanent polarization vectors predominantly into the plane of the plate. In this condition of polarization (L-state), every region of the plate has maximum birefringence for linearly polarized light incident normally. In the WRITE step, the elements of the array are connected in parallel to one terminal of the supply and the other terminal is connected to the transparent conductive electrode. Light is directed at the area to be switched causing the photoconductive layers to conduct and the electric field in the ceramic under the illuminated area to exceed the coercive field.

If the image to be stored in the ferpic is broken into elements, the spacing between lines of the interdigital array should be less than or equal to the size of an element. Writing the image an element at a time, as in a television picture, can be accomplished by modulating either the addressing light beam or the power supply. It is equally conceivable that the picture could be formed all at one time by projecting some desired image on the plate and switching the illuminated elements.

The basic ideas of the interdigital array device were first demonstrated in a device structure using PVK films. The details of this interdigital-

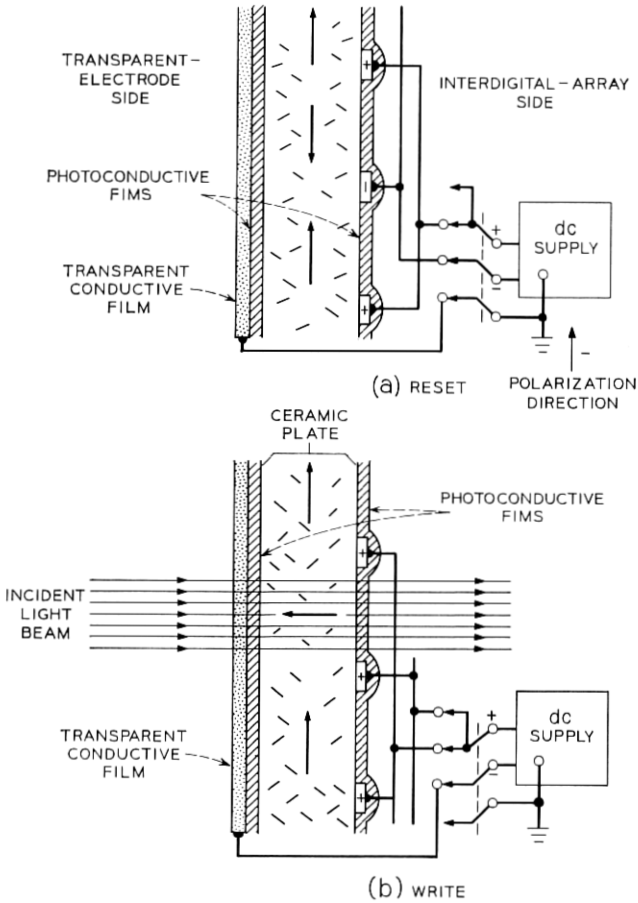


Fig. 5—Details of the RESET and WRITE steps of operation for a ferpic utilizing 90° polarization rotation in the ceramic plate.

array ferpic are shown in Fig. 6, and an example of the image storage obtained is shown in Fig. 7. The upper part of Fig. 7 shows the original, simple, high-contrast image. The lower part shows the image observed through a low-power polarizing microscope. The image was stored in a 50 μm thick ceramic plate with a square working area 0.8 cm on a side.

The experimental structure of Fig. 6 differs from the original structure described in Fig. 4 by the inclusion of an additional transparent conductive electrode on the array side of the ferpic. This additional film is needed because the PVK films do not have a high enough conductivity

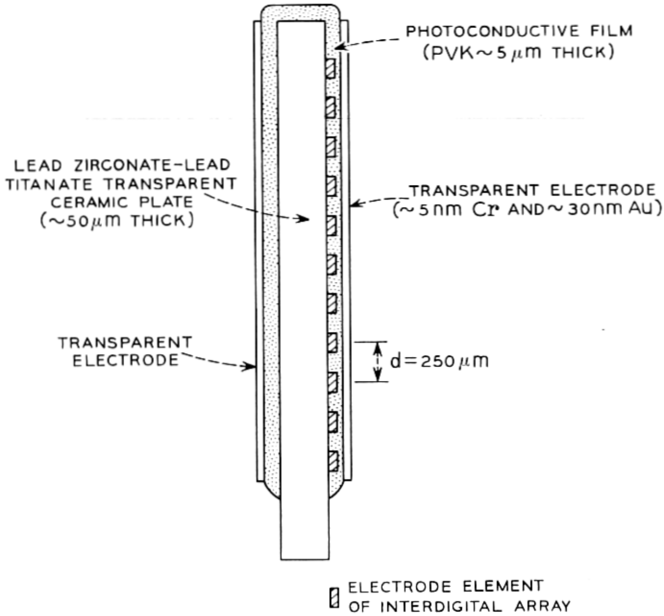


Fig. 6—Construction details of a ferpic using an interdigital array to switch the polarization into the plane of the plate.

when illuminated to establish an equipotential region between the elements of the electrode array. While the addition of the transparent conductive electrode to the array side of the ferpic solves the problem of the low conductivity in the PVK, this modification has the disadvantage that it hinders erasure. The PVK film between the transparent electrode and the array is now subject to breakdown field strengths when the RESET voltage is applied. In addition, experiments with PVK films on devices using the 90° polarization rotation have indicated that the PVK film constrains the motion of domains, probably through a mechanism of trapping polarization charges at the ceramic-PVK interface.

Our most recent experimental efforts have resulted in two significant developments, one related to the performance of photoconductive films used in interdigital-array ferpics and the other related to a new version of a ferpic.

In connection with photoconductive films, we have been successful in realizing CdS films with a high light-to-dark conductivity ratio and a high conductivity when illuminated. These films have been sputter

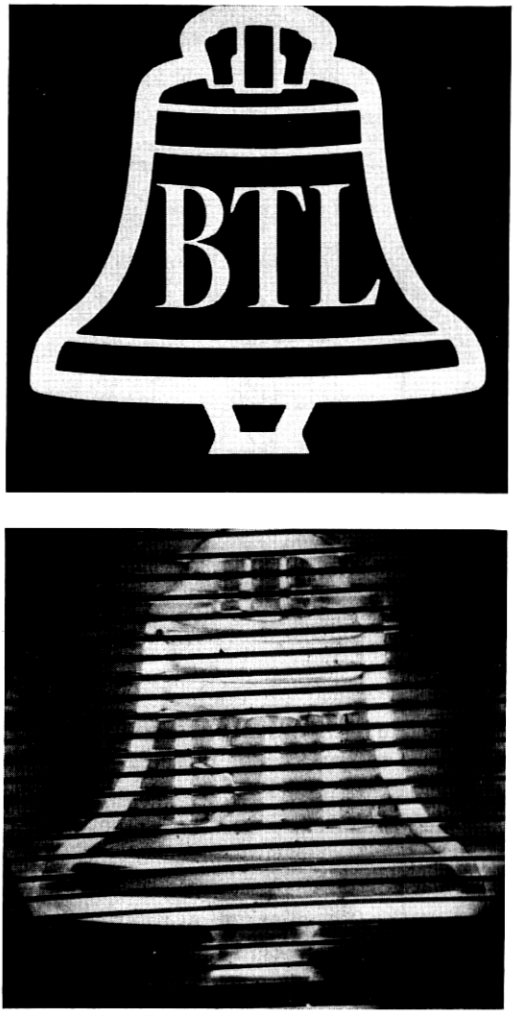


Fig. 7—A simple, high-contrast image stored as a variation in birefringence in a ferpic using an interdigital electrode array: upper, the original image; lower, the image viewed in the ferpic by means of a polarizing microscope. (The horizontal lines apparent in the photograph are formed by the electrodes of the interdigital array and these are spaced 250 μm apart on the actual device.)

deposited on device structures consisting of ceramic plates with interdigital arrays vapor deposited, in registration, on both surfaces. Images with nearly the quality of that shown in Fig. 7 have been successfully stored in the CdS film devices, and, what is more important, these devices have demonstrated a significantly greater degree of changeability than interdigital devices using PVK films. The experiments with these devices demonstrate that the ceramic and the CdS films can work together successfully with interdigital arrays to provide the intended mode of operation.

In connection with the new form of ferpic, a refined structure has been developed which eliminates the necessity of having a separate set of electrodes or interdigital arrays in order to switch the ceramic into the L-state. In this new device structure, a thin ceramic plate and photoconductive film are sandwiched between transparent electrodes, and the stack is bonded to a relatively thick, transparent substrate. The ceramic plate is put in tension along one direction by slightly flexing the substrate. The direction of the tension axis in the ceramic becomes a preferred direction along which the polarization vectors in individual domains tend to align. (Because of the use of a permanent strain to establish this preferred direction, the device is called a "strain-biased ferpic.") In the strained condition, the ceramic can be switched between two states, corresponding to an L- and T-state, by the application of fields in the thickness direction. As in the earlier versions of the device, only the illuminated regions can be switched to the T-state. In order to reset the whole device to the L-state, the whole active area is flooded with illumination while the reset voltage is applied. An important feature of the new device is that its structure permits localized switching to the L-state as well as to the T-state. A paper describing in detail the structural and performance features of the strain-biased ferpic is presently in preparation and will be published at a later time.

V. OPTICAL DISPLAY SYSTEMS WITH LASER BEAM ADDRESSING

Figure 8 shows the essentials of a projection display system using a ferpic in combination with a laser beam addressing module and a source of viewing light. A dichroic mirror that transmits at the projection wavelength and reflects at the write wavelength is used to enable the laser subsystem to be positioned off the main axis. The arrangement shown in the schematic drawing is intended to be an electronically changeable, projection display. In this display system, there are three stages to a complete cycle of operation: (*i*) RESET, (*ii*) WRITE and (*iii*)

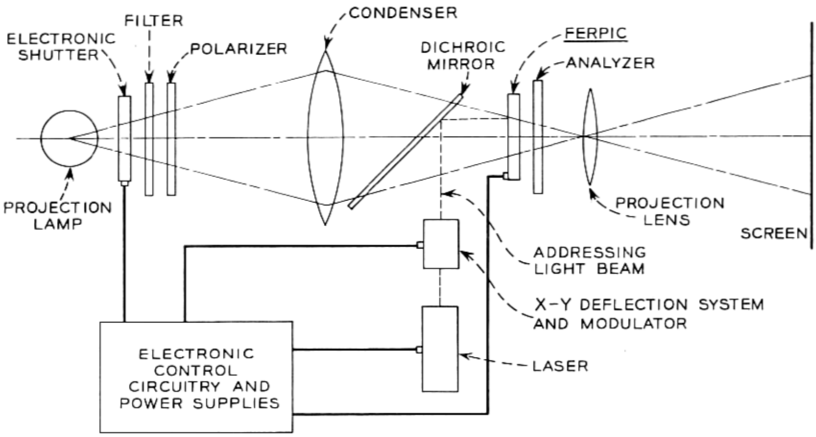


Fig. 8—A projection display system using a ferpic in combination with a laser beam addressing module and a source of viewing light.

VIEW. During the RESET stage, the viewing light and laser beam are off and the whole ferpic is switched to the L-state. During the WRITE stage, the viewing light remains off while the picture is formed an element at a time by moving the laser beam successively through all the address points. The laser beam is steered by an X-Y deflection system which could be an ultrasonic light deflector system of the sort recently developed for use in an optical memory system[4] or a mechanical scanning system. The choice exists of controlling the switching of a picture element by modulating either the intensity of the laser beam or the intensity of the voltage pulses supplied to the electrodes of the ferpic.

Once the picture has been formed, the viewing source is flashed on. An important advantage of this display system is that, once written, the picture can be held without any further expenditure of electrical power. This feature would make a ferpic display attractive for many applications now met using storage cathode-ray tubes. The fact that the basic light controlling element has intrinsic memory has important implications for practical applications. As a consequence of this intrinsic memory the display is able to hold a given picture for an indefinitely long time. Furthermore, the picture is not volatile in the sense that it is retained in the event of a power failure. Depending upon the details of construction and associated circuitry, it may be possible to break up the stored picture into individual lines or elements and use a "periodic update" mode of operation of interest in connection with bandwidth-reducing techniques of picture transmission.

In the display system proposed here, the image is formed one picture element at a time by a scanned laser beam, but is viewed or projected as a whole using incoherent light in a conventional projection system. This separation of the scanning and viewing functions allows a relatively low-power laser, in any convenient wavelength range, to be used for the scan, while a powerful, efficient incoherent source provides the actual viewed light.

We are not able at the present stage of the device development to state whether or not the device will have the lifetime and switching speed capabilities required to make it useful in real-time display systems. (For this sort of application, ferpics would be in competition with devices like the TITUS tube[5] and the EIDOPHOR tube.[6]) However, there are applications that can make use of a slowly-scanned, high-resolution image storage device that can hold an image for an arbitrarily long time and either continuously display it by an optical projection system or project it onto some form of hard-copy print-out. This sort of application would not require the high cycling rates or extreme lifetimes of a device used in real-time display systems.

With regard to obtaining maximum lifetime in a ferpic, there is an important point that deserves explicit statement: It is not necessary to rotate the polarization vector through a full 90° in order to obtain a useful effect. Operation under conditions producing full 90° polarization-rotation provides the means of obtaining the maximum birefringence change with a minimum material thickness.* On the other hand, such a large change in polarization direction produces strains that could lead to premature failure of the ceramic. In devices using ceramics with sufficiently low optical loss,† there exists the alternative of switching the average polarization through an angle much less than 90°, and then using increased thickness to obtain the desired half-wavelength retardation change.

VI. REFINING THE BASIC DEVICE TO OBTAIN GRAY-SCALE AND COLOR CAPABILITIES

A ferpic, as described in this paper, is basically a two-level (black and monochrome) image storage and display device. However, modification of the device structure and system configuration to include color

* According to Land and Thacher,[1] a Δn of -0.022 is obtained in 65/35 − 2 La ceramic at maximum remanent polarization. This Δn requires only 16 μm of material to produce a half-wavelength of retardation for 6328 Å light.

† A new hot-pressed, lead zirconate-lead titanate ceramic composition has been developed at Sandia Laboratories with lower optical loss and improved electrical switching characteristics.[7]

and a gray-scale appears to be straightforward. For example, the system of Fig. 8 can be modified for color by using a sequential-field, color-scan technique. Instead of one source illuminating the ferpic, there would be three light sources (red, blue, green) with appropriate means to strobe these in sequence. The ferpic would operate as already described except that there would now be three different RESET operations per frame, with a voltage applied to produce a retardation of a half-wavelength for the color flashed during the VIEW stage. In practice the operations RESET-WRITE-VIEW would be repeated in sequence for each color.

Modification of the basic system of Fig. 8 to obtain a gray scale requires that intermediate states of birefringence—and hence polarization—be reproducibly attainable, so that the ceramic plate functions as an intensity modulator and not just as a simple shutter. Experiments[3] with elementary, light-gate devices using the fine-grain ceramic have shown that it is possible to obtain reproducible partial switching with suitable circuitry. The development of a ferpic with gray-scale capability will depend strongly on the switching properties of the ceramic and the photocurrent response characteristics of the photoconductive films with which the ceramic is used. It is still too early to state uniquivocally that a gray-scale device can be obtained with all other desired characteristics, but the possibility is certainly there.

VII. CONCLUSION

The recent development of fine-grain, electro-optic ceramic materials has provided the means of realizing ferroelectric devices capable of storing high-contrast images under the control of electrical voltages. The image is stored as a variation of birefringence in a thin, ceramic plate and can be viewed directly by suitably polarized transmitted light or projected onto a viewing screen. Experimental devices have demonstrated a resolution capability of approximately 50 lines/mm in 50 μm thick ceramic material and have been able to hold the image with no apparent change for times of the order of several months. While our early experimental devices have had only limited electric changeability, the basic material system is certainly capable of providing this essential feature. Images stored in these devices have been projected and viewed by means of simple, desk-top, commercially available, 35 mm projection displays (modified by the inclusion of a polarizer and analyzer). Display systems of the sort considered appear to be well-suited to applications such as high-resolution, slow-scan, and document display.

VIII. ACKNOWLEDGMENTS

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