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FERROELECTRIC CERAMIC ELECTROOPTIC
STORAGE AND DISPLAY DEVICES

C. E. Land

SANDIA LABORATORIES

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by

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ABSTRACT

Certain newly developed, hot-pressed ferroelectric ceramics offer an apparently practical solution to the design of extremely high-density, optically interrogated, information storage devices. In addition to optical memory applications, the materials appear to be equally useful in high resolution, controlled-persistence displays, and in both electrooptic and acoustooptic modulation and deflection devices. The potential uses of these materials in a wide variety of optical devices and systems are made possible by their unique, electrically variable optical properties.

This paper describes some of the optical and switching properties of hot-pressed lead zirconate-lead titanate (PZT) ceramics. A number of proposed optical devices are discussed, including a medium density memory which is in the research prototype stage of development.

INTRODUCTION

Polycrystalline ferroelectric ceramics can be given lasting polar properties, including pyroelectric and piezoelectric effects, by the application of dc electric fields for a short time. The process by which this result is accomplished is called poling.¹ In the virgin or thermally depoled states, the ferroelectric domains within the crystallites or grains are randomly oriented; thus, the material, on a macroscopic scale, is isotropic. When a poling field is applied, domains oriented favorably with respect to the field grow at the expense of less favorably oriented domains. This gives rise to polar effects which result in anisotropic response to small-signal electrical stimuli.^{2,3} We have recently demonstrated that this anisotropic response extends to optical stimuli as well.

We have discovered that electrically poled, thin, polished plates of hot-pressed lead zirconate-lead titanate ferroelectric ceramics have the following properties:

- (1) they transmit visible light,
- (2) they are birefringent,
- (3) their light transmission characteristics depend upon both the thoroughness (magnitude) and direction of poling, and
- (4) extremely small localized areas of the plates can be poled or switched independently without affecting the material in the surrounding area.

With normally incident plane polarized light, both unpoled and poled coarse-grained optical ceramics, i.e., with nominal grain diameters, G , of two microns or more, almost completely depolarize transmitted light by multiple scattering. Although the coarse-grained materials do not appear under ordinary microscopic examination to be birefringent because of the depolarizing effects of multiple scattering, their light transmission characteristics are, nevertheless, quite dependent upon magnitude and direction of electrical poling. This results from the fact that their scattering properties are, themselves, dependent on poling. In general, thin unpoled plates appear optically dense (translucent or nearly opaque). Plates poled normal to the major surfaces appear transparent; those poled parallel to the major surfaces appear more opaque than unpoled plates.

Fine-grained materials ($G < 2$ microns), both unpoled and poled, depolarize only part of the transmitted light. The remainder of the light retains its polarization if the material is in the unpoled state. In the poled state, fine-grained ceramics transmit light in exactly the same manner (neglecting scattering) as optically uniaxial, birefringent crystals.⁴⁻¹⁰ Poled ceramics are isotropic in the plane normal to the polar axis and birefringent in the planes parallel to the polar axis.

Both the magnitude and direction of poling can be varied in ferroelectric ceramic plates by applying external electric poling or switching fields. This property provides a means of controlling

the light transmission characteristics electrically. Of paramount importance to the design of high density information storage and display devices is the fact that the magnitude and direction of poling can be varied in small localized areas without affecting the polarization in the surrounding areas. The light transmission characteristics in the small localized areas can be controlled independently by applying localized poling or switching fields. Remanence in even very small localized areas has been found to be stable over periods of several months. Locally switched domains may be restored to their original orientations at any time by applying an electric field of proper configuration and amplitude.

Shabana's experiments^{11,12} have demonstrated that 90° locally switched domains in barium titanate single crystals are highly unstable; they relax back to their original orientation after removal of the switching field. Cummins^{13,14} has recently shown that the switching which occurs in monoclinic bismuth titanate single crystals with 180° reversal of electric field is optically detectable. Single crystal memories employing this mode of switching are, therefore, feasible. Bismuth titanate single crystals are quite difficult to fabricate, which is a major disadvantage compared to hot-pressed ceramics.

The purpose of this paper is to describe the previously mentioned optical and switching properties of hot-pressed PZT ceramics,

to explain--at least in part--some of the observed optical behavior, and to discuss how these properties may be employed in optical memory and display devices.

MATERIALS

The materials used in this study are hot-pressed, lead zirconate-lead titanate (PZT) solid solutions.¹⁵⁻¹⁷ A composition-temperature phase diagram for this solid solution series is shown in Figure 1. The compositions which appear to have the best optical properties are those in which the individual crystallites exhibit rhombohedral symmetry. Fortunately, these materials also have the best switching properties.¹⁸ For memory and long-persistence display devices, the latter property is quite important.

Ferroelectric ceramics must have the following general properties to be of good optical quality:

- (1) high density--porosity must be minimized,
- (2) homogeneity--the solid solution or composition must be uniform throughout,
- (3) optical surfaces--the material must exhibit optical quality surfaces after polishing, and
- (4) reproducible, uniform grain size--control of grain size is required in the fabrication process.

The four properties enumerated above have been achieved only by employing hot-pressing techniques in the fabrication process.

The material designations used throughout this paper are explained most easily by considering a typical example. PZT 65/35-2Bi (1300/1/3000) refers to a lead zirconate-lead titanate solid solution containing 65 percent lead zirconate and 35 percent lead titanate with 2 atom percent bismuth added as bismuth oxide. The numbers in parentheses refer to the hot-pressing parameters: temperature (1300°C), time (1 hour), and pressure (3000 psi).

OPTICAL PROPERTIES

A. Transparency

Thin plates of optical ceramics are reasonably transparent to visible light. The photograph in Figure 2 shows a ceramic plate 100 microns thick, poled normal to the surface. Ordinary type behind the plate is quite visible. Although these materials exhibit both scattering and dispersion losses, transmittances as high as 0.9 have been measured, using a Joyce-Loebl Mark III B recording microdensitometer, for some 20 to 30 micron thick plates.

When thin ferroelectric ceramic plates are heated above the Curie temperature (the ferroelectric-paraelectric phase boundary shown in Figure 1) they become considerably more transparent. In this state they resemble slightly tinted yellow glass. Incident plane polarized light is transmitted with negligible loss of polarization. Since in the paraelectric state the material is cubic

and domain structure disappears, it may be concluded that only negligible scattering is associated with the grain boundaries of the ceramic.

In the ferroelectric state, both the grain and domain dimensions are generally greater than a wavelength of visible light. As the wavelength of incident light decreases, scattering increases, and very likely some absorption occurs toward the violet edge of the visible spectrum. In Figure 3 transmittance is plotted as a function of wavelength for an unpoled ceramic plate 80 microns thick. The grain size, G , of this material was one micron. The dispersion shown in Figure 3 is characteristic of all the ceramics measured, regardless of grain size or poling condition. For example, the transmittance versus wavelength curve shown in Figure 4 is for five micron grain size material. Again, the 104.6 micron thick plate was unpoled.

B. Birefringence

All poled, optical quality ferroelectric ceramics are birefringent. The birefringence of coarse-grained ceramics, however, is obscured by multiple scattering. The effect of multiple scattering is to depolarize transmitted light to the extent that birefringence can be measured only in a narrow central beam along the light propagation direction. This narrow beam which retains its polarization is measurable only if the ceramic plate is less than about 100 microns thick.

In fine-grained ceramics the scattering properties are drastically changed so that the depolarizing effects are greatly reduced. A significant percentage of the intensity of light transmitted by fine-grained ceramic plates is either not scattered at all, or is scattered in such a manner as to retain its polarization. As a result, the light transmission characteristics of these materials strongly resemble those of optically uniaxial, birefringent single crystals. In the unpoled state, they are, on the average, isotropic; therefore, normally incident plane polarized light remains plane polarized after transmission. Furthermore, the polarization planes of the incident and emerging light are parallel. After electrical poling, the materials are isotropic only in the plane normal to the polar axis, and birefringent in all planes parallel to the polar axis. A ceramic plate poled normal to its major surfaces is isotropic to normally incident plane polarized light. It therefore resembles an unpoled plate in appearance when they are both viewed between crossed polarizer and analyzer.

If the ceramic polar axis is not parallel to the light propagation direction, the ceramic plate is birefringent and becomes an optical retarder. Incident plane polarized light is resolved into two orthogonal plane polarized components upon entering the plate. One component is aligned with the ceramic polar axis; the other is perpendicular to the polar axis. The refractive index, hence, the light propagation velocity, parallel to the polar axis is

different from that perpendicular to the polar axis. As light propagates through the ceramic, the velocity of one of the two orthogonal, plane polarized components exceeds that of the other. When the components recombine at the surface, they are, in general, displaced in phase. Unless the phase displacement is a multiple of 90° , the emerging light is elliptically polarized. If the phase displacement is an odd multiple of 90° , the emerging light is circularly polarized. If the phase displacement is an even multiple of 90° , the emerging light is plane polarized. If the phase displacement is an integral multiple of 360° , the incident and emergent light polarization planes are parallel. Phase displacements which are odd multiples of 180° shift the polarization plane of the emergent light to an angle of 2ρ with respect to the incident polarization plane. The angle ρ is the angle between the incident polarization plane and the polar axis of the ceramic plate.

The phase displacement between the two orthogonal plane polarized components of light as they emerge from the ceramic plate is called the retardation. The retardation, r , expressed in light wavelengths, λ , is the product of the birefringence $(n_e - n_o)$ and the plate thickness, t , divided by the wavelength of incident light λ .

$$r = (n_e - n_o)t/\lambda \quad (1)$$

The term n_e is the refractive index along the polar axis, and n_o is the refractive index in any direction in the plane normal to the polar axis.

Birefringence was measured in both the fine-grained and coarse-grained rhombohedral lead zirconate-lead titanate ceramics. The results were the same for the fine-grained and coarse-grained ceramics.

$$(n_e - n_o) = -0.042 \quad (2)$$

Perhaps by coincidence, this value agrees exactly with that measured by Fushimi and Ikeda¹⁹ in PZT 85/15 single crystals. Using this value of birefringence, a ceramic plate 13.1 microns thick produces one wavelength retardation for incident light of 550 millimicrons wavelength. Since the birefringence is negative, the optic axis (ceramic polar axis) is the fast axis. Any direction normal to the optic axis is a slow axis.

C. The Dependence of the Scattering Properties on Electrical Poling

The light scattering properties of thin, polished, ferroelectric ceramic plates were investigated by measuring the angular intensity distribution (scattering profile) of transmitted light. These measurements were made with a Gaertner Model L-119 Ellipsometer, shown schematically in Figure 5. The compensator was used for birefringence measurements, but removed for scattering measurements. Using a collimated, normally incident beam, the intensity

of the transmitted light was measured as a function of the angle θ , the angle between a normal to the ceramic surface, located at the center of the area from which the beam emerged, and a straight line from the same point on the ceramic surface to the detector.

A profile of the scattered light intensity was obtained by moving the detector in an arc of radius d about the center of the area from which the beam emerged at the ceramic surface. The details of the scattering profile were visible since the angular aperture was very small (0.650°).

If two sets of measurements are made of the scattering profile, one with the ceramic plate between parallel polarizer and analyzer, and the other between crossed polarizer and analyzer, an indication of the nature of the scattering is obtained. When the two measurements give the same result, the transmitted light is completely depolarized by multiple scattering. When the two measurements give different results, the transmitted light is partially plane polarized, and we may conclude that only a portion of this light has been multiply scattered. The angle ρ between the polarizer axis and the ceramic polar axis must be set at either 0° or 90° in order to assure that the transmitted light will be plane, rather than elliptically polarized.

The results of the scattering measurements described above are shown in Figures 6, 7, and 8 for a fine-grained ($G \cong 1$ micron) ceramic plate. In each of these figures, curve (1) was obtained with the polarizer and analyzer axes parallel ($\phi=0^\circ$), and curve

(2) was obtained with the polarizer and analyzer axes crossed ($\phi=90^\circ$). (The angle ϕ is the angle between the polarizer and analyzer axes.)

Assuming that the scattering is isotropic about the beam direction, the intensity $I(\theta)$ measured by the detector at the angle θ can be integrated to determine the total transmitted intensity I_T .

$$I_T = \int_0^{90^\circ} I(\theta) \sin\theta d\theta \quad (3)$$

Figure 6 represents the scattering profiles for the unpoled isotropic case. The integrated intensity of that component of the transmitted light retaining at least 90 percent of its initial polarization (exhibiting at least 90 percent extinction for $\phi=90^\circ$) will be designated I_P . The intensity I_P is given by

$$I_P \cong \int_0^{\theta_0} I(1) \sin\theta d\theta \quad (4)$$

$I(1)\sin\theta$ is shown as curve (1) in Figure 6. θ_0 is the angle at which 90 percent extinction is obtained for $\phi = 90^\circ$. For the scattering profile of Figure 6, θ_0 is 5.5° . The total integrated intensity of the transmitted light with parallel polarizer and analyzer ($\phi=0^\circ$) is given by

$$I_{T(\phi=0)} = \int_0^{90^\circ} I(1) \sin\theta d\theta \quad (5)$$

The ratio,

$$\Pi = I_P/I_T(\phi=0) \quad , \quad (6)$$

is then a measure of the fraction of transmitted light with parallel polarizer and analyzer which has not undergone multiple scattering. For the unpoled ceramic plate of Figure 6, $\Pi = 0.494$. The parameter Π is a function of grain size, G , poling magnitude and direction, P , plate thickness, t , and the optical quality of the material. The optical quality depends upon density, homogeneity, and surface quality of the ceramic plate.

Figure 7 shows the scattering profiles for the plate poled normal to the major surfaces. In this condition also, the plate is isotropic for normally incident light. The scattering curves are, therefore, quite similar to those shown in Figure 6. The transmitted light is more than 90 percent polarized for scattering angles less than $\theta_o = 4^\circ$. For this poling condition, $\Pi = 0.41$.

Figure 8 represents the scattering profiles for the plate poled parallel to the major surfaces with $\rho = 90^\circ$. Here, again the curves differ only slightly from those of Figures 6 and 7. The angle θ_o is 4.5° and $\Pi = 0.392$.

From Figures 6, 7, and 8, it is evident that θ_o is almost independent of the poling condition of the ceramic. The parameter Π is slightly higher for the unpoled than the poled ceramic, but does not appear very sensitive to the poling state. For small detector numerical apertures ($N.A. \leq 0.10$ for the sample used to obtain the results of Figures 6, 7, and 8) the transmitted

light is more than 90 percent polarized. This indicates that the ceramic plate exhibits light transmission characteristics similar to those which one would expect of uniaxial birefringent crystals. Since both magnitude and direction of poling can be varied in ceramics, thin plates of the fine-grained ceramics are electrically variable optical retarders.

As previously stated, the birefringence of coarse-grained ceramics is obscured by multiple scattering. Since transmitted light is essentially completely depolarized, optical retardation is not normally detectable except in thin plates and in a narrow beam directly along the light propagation direction. The dependence of their light transmission characteristics on electrical poling is of an entirely different nature than in fine-grained ceramics. In coarse-grained ceramics, it is the scattering properties which are extremely sensitive to the magnitude and direction of poling. This is illustrated in Figures 9, 10, and 11, which are scattering profiles for a coarse-grained ($G \approx 5$ microns) ceramic plate. The measuring techniques used to obtain the results shown in these figures are the same as those previously described for Figures 6, 7, and 8. For each figure, two sets of measurements were made: one with the sample placed between parallel polarizer and analyzer ($\phi=0^\circ$), the other with the polarizer and analyzer axes crossed ($\phi=90^\circ$).

Figure 9 is the scattering profile for the unpoled or random condition. For all practical purposes, the transmitted light is

completely depolarized ($\theta_0=0^\circ; \Pi=0$). However, a relative intensity peak occurs at an angle $\theta_1 = 9.5^\circ$. If we designate the relative intensity at θ_1 as I_M , both I_M and θ_1 are extremely sensitive to the magnitude and direction of electrical poling.

Figure 10 is the scattering profile for the same plate poled normal to the major surfaces. Some of the polar properties of the transmitted light are detectable between $\theta = 0^\circ$ and $\theta = 0.5^\circ$, but here again $\theta_0 = 0^\circ$ and $\Pi \approx 0$. The relative intensity peak I_M has increased by a factor of two (not as indicated by the normalized values shown in Figures 9 and 10), and the angle θ_1 has decreased to 2° . This represents a major change in the scattering characteristics as compared with those shown in Figure 9. Suppose one measures the transmitted light intensities with a detector numerical aperture of 0.1 (angular aperture of about 12 degrees), aligned with the surface normal, for the polar states shown in Figures 9 and 10. The ratio of the intensity with the plate poled normal to the surface to that of the unpoled plate should be

$$\frac{I_L}{I_R} = \frac{\int_0^{6^\circ} I \sin \theta d\theta \text{ (Fig. 10)}}{\int_0^{6^\circ} I \sin \theta d\theta \text{ (Fig. 9)}} \quad (7)$$

The value of this ratio, calculated by integrating the areas under the curves out to $\theta = 6^\circ$, is 6.65. Measured values of this

ratio using a lens of numerical aperture of 0.10 are shown in Figure 12 for various plate thicknesses. The value corresponding to a thickness of 80 microns (the thickness of the sample used for the measurements of Figures 9 and 10) is 6.7 which is in excellent agreement with the value calculated from the scattering curves. The scattering curves serve as a useful design tool if the desired transmitted light intensity ratio is specified for two different polar states of the material.

Figure 11 is the scattering profile for the same plate used to obtain Figures 9 and 10, poled parallel to the major surfaces with $\rho = 90^\circ$. The transmitted light is, for all practical purposes, completely depolarized. This scattering profile has essentially the same shape as for the unpoled plate (Figure 9) except θ_1 is increased to 15° and I_M is slightly less than the absolute value measured for Figure 9. Other measurements have shown that the shape of this curve depends strongly on the angle ρ .

LOCALIZED SWITCHING

In thin ferroelectric ceramic plates, both the magnitude and direction of poling can be varied in small localized areas without affecting the state of poling in the surrounding areas. The light transmission characteristics of these small areas can, therefore, be varied independently by applying localized poling or switching fields. The domains in a small area can be

switched to virtually any orientation by application of the proper field configuration, and they will remain in their switched orientation after the switching field has been removed. They may be switched back to their original orientation by applying a restoring or erasing field. This localized switching property, which exhibits true memory capability is of paramount importance in the application of ferroelectric ceramics to high density information storage devices and controlled-persistence display devices.

The diagram, Figure 13, illustrates three methods of obtaining 90° localized switching in ferroelectric ceramic plates. The plate is first poled normal to its major surfaces as shown in the first illustration at the left of the diagram. Electrodes are then affixed to the plate in one of the three configurations shown in column A. In practice, the dimension, a , is always less than the thickness t . By applying a switching voltage with the polarity shown in each row of column B, the domain dipoles in the local area are switched by 90° to a direction parallel to the major surfaces of the plate. The locally switched domain dipoles remain in their switched orientation as shown in column B until they are restored to their original orientation by applying an erasing voltage of the polarity shown in column C. The switching mode illustrated in row 2 has been applied successfully to the design of a research prototype memory which will be described later.

The diagram shown in Figure 14 illustrates three additional 90° localized switching modes for ferroelectric ceramic plates.

These differ from the modes illustrated in Figure 13 primarily by the initial poling condition of the ceramic plate. The plate of Figure 14 is initially poled parallel to its major surfaces, and then locally switched normal to the surfaces. Dimensional restrictions are $b > t > a$.

Figure 15 illustrates two types of localized switching modes investigated by Shabana^{11,12} in barium titanate single crystals. The switching modes employing c-domain single crystals are analogous to the ceramic modes illustrated in Figure 13. The modes employing a-domain single crystals are analogous to the ceramic modes illustrated in Figure 13. Shabana found that 90° locally switched domains in single crystal barium titanate were unstable with time. In the case of the c-domain crystals, they relaxed back to their original orientation in less than a microsecond after the switching field was removed. In a-domain single crystals, the relaxation time was a matter of hours. This instability of locally switched domains makes 90° localized switching in single crystals unsuitable for memory or long persistence display systems.

There are many other localized switching modes which are possible in ferroelectric ceramic plates. Almost all of these are potentially useful for special type memories or displays. For example, several modes are useful in fine-grained birefringent materials which involve localized switching of the polar axis into various directions in the plane parallel to the major surfaces. Figure 16 shows an electrode configuration suitable for

performing 90° switching in the plane parallel to the major surfaces of the plate. An x-y addressed matrix designed to employ this switching mode is illustrated in Figure 17. Figure 18 shows a possible electrode configuration for performing 45° switching in the plane parallel to the major surfaces of the plate.

DEVICES

The optical retardation characteristics, both effective birefringence and optic axis orientation, of fine-grained ferroelectric ceramics depend on the magnitude and direction of electrical poling. The light scattering properties, both amplitude and orientation of peak intensities, of coarse-grained ferroelectric ceramics are similarly dependent on the magnitude and direction of electrical poling. These first order electrically variable optical effects, coupled with unique localized switching capabilities, establish the feasibility of a new technology--ferroelectric ceramic optical devices. Two new classes of devices are suggested immediately by the combination of physical properties previously described. These are high density optical memories and controlled-persistence, high resolution displays.

A number of prototype memories of the configuration shown in the photograph, Figure 19, have been constructed for the purpose of studying a specific type of optically interrogated memory. This memory design employs the 90° localized switching mode illustrated in row 2 of Figure 13. This particular localized switching mode

has been adapted to an x-y addressed matrix configuration by the technique illustrated in Figure 20. The solidly outlined electrode configuration (y-address) is on one surface of a thin ceramic plate; the dashed outlined electrode configuration (x-address) is on the opposite surface. The device shown in Figure 19 consists of four 64-bit word arrays arranged on a ceramic plate 0.004 inch thick. The dimensions of the major surfaces of the plate are 0.20 by 0.25 inch. The information storage density is 5,120 bits per square inch.

The switching time required to switch an individual bit depends upon the amplitude of the switching field. Figure 21 shows the results of initial measurements of the relationship between bit switching time and amplitude of the switching pulse for the prototype memory configuration. It is believed that even faster switching can be achieved by modifying the design configuration of the memory.

The material used in these first prototypes is PZT 65/35-2Bi, hot-pressed at 1300°C for one hour at 3000 psi pressure. This is a coarse-grained material ($G \approx 5$ microns); hence, the optical properties of the ceramic employed for readout are the variable scattering properties. The scattering profile for the "zero" condition at each bit location is similar to that shown in Figure 10. The scattering profile for the "one" condition is similar to that shown in Figure 11. The difference sensed by a photodetector in transmitted light intensity for a binary "zero" and "one"

depends upon the detector aperture and alignment. A detector with a numerical aperture of 0.10 will "see" a difference of about 6.5 to 1 for the "zero" and "one" states, respectively. In general, smaller detector apertures produce larger transmittance ratios but less integrated intensity or signal.

Several concepts of readout systems have been considered. Recent developments in photodiode matrix arrays suggest the feasibility of the system shown in Figure 22. This system involves the use of one diode light source per word and a photodiode detector matrix containing one sensor per bit. Word selection is achieved by connecting the diode light sources in an x-y addressed array. When the selected word is illuminated, the photodiode sensor matrix is scanned serially or one row or column at a time. The photodiode sensor matrix provides the required memory-computer interface. For memories employing coarse-grained ceramics, this readout system requires only the components shown in Figure 22, with the possible addition of a mask or aperture array intermediate to the memory and photodiode sensor matrix. Fine-grained ceramic memories employing this readout system would require, in addition, a polarizer and analyzer. The polarizer would be located between the light source array and the memory; the analyzer between the memory and detector array.

A second generation prototype memory has been designed which has a storage density of 20,480 bits per square inch. Even higher density memory arrays are feasible, especially if more sophisticated readout systems are employed.

Further intensive studies of the switching properties of the newly developed ferroelectric ceramics are required before specific memory limitations can be defined. One area of this investigation must involve the "disturb" pulse problem as it affects the large variety of possible switching modes. At this time it appears that the high density memories can be employed immediately in peripheral, catalog-type memory applications.

The problems associated with the application of the x-y addressed memory techniques to high resolution displays seem at this time to be straight forward. The use of transparent electrode arrays offers further possibilities in display applications.

Applications of these materials to the design of electrooptic and acoustooptic modulation and deflection devices will be limited by the scattering properties of present materials. Further materials developments may remove this limitation.

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FIGURE CAPTIONS

1. Composition-temperature phase diagram for the lead zirconate-lead titanate (PZT) solid solution series.
2. Photograph of thin polished disk of PZT 65/35-2Bi, poled normal to the major surfaces. Nominal grain size, G , is five microns.
3. Transmittance as a function of wavelength in the visible for unpoled PZT 65/35-2Bi, with nominal grain size, G , of one micron.
4. Transmittance as a function of wavelength in the visible for unpoled PZT 65/35-2Bi, with nominal grain size, G , of five microns.
5. Schematic diagram of the optical network for birefringence and scattering measurements (Gaertner Model L-119 Ellipsometer).
6. Relative intensity of transmitted light versus θ , the angle from the surface normal, for PZT 65/35-2Bi, with nominal grain size, G , of one micron. Unpoled. Detector N.A. = 0.00568.
7. Relative intensity of transmitted light versus θ , the angle from the surface normal, for PZT 65/35-2Bi, with nominal grain size, G , of one micron. Poled normal to the major surfaces. Detector N.A. = 0.00568.

8. Relative intensity of transmitted light versus θ , the angle from the surface normal, for PZT 65/35-2Bi, with nominal grain size, G , of one micron. Poled parallel to the major surfaces. $\rho = 90^\circ$; detector N.A. = 0.00568.
9. Relative intensity of transmitted light versus θ , the angle from the surface normal, for PZT 65/35-2Bi, with nominal grain size, G , of five microns. Unpoled. Detector N.A. = 0.00568.
10. Relative intensity of transmitted light versus θ , the angle from the surface normal, for PZT 65/35-2Bi, with nominal grain size, G , of five microns. Poled normal to the major surfaces. Detector N.A. = 0.00568.
11. Relative intensity of transmitted light versus θ , the angle from the surface normal, for PZT 65/35-2Bi, with nominal grain size, G , of five microns. Poled parallel to the major surfaces. $\rho = 90^\circ$; detector N.A. = 0.00568.
12. Transmittances of poled (T_L) and unpoled (T_R) ferroelectric ceramic plates as a function of plate thickness. PZT 65/35-2Bi. Nominal grain size, G , is five microns. Detector N.A. = 0.10.
13. Diagram illustrating three 90° localized switching modes of thin ferroelectric ceramic plates. Initial poling condition: normal to the major surfaces. LPS refers to localized perpendicular switching.

14. Diagram illustrating three 90° localized switching modes of thin ferroelectric ceramic plates. Initial poling condition: parallel to the major surfaces. LPS refers to localized perpendicular switching.
15. Diagram illustrating four 90° localized switching modes for ferroelectric single crystals.
16. Diagram illustrating 90° localized switching in plane parallel to the major surfaces of a ferroelectric ceramic plate.
17. Diagram of x-y addressed matrix array of localized switching electrode patterns similar to Figure 15.
18. Diagram illustrating 45° localized switching in plane parallel to the major surfaces of a ferroelectric ceramic plate.
19. Prototype memory. The memory consists of four 64 bit words. Plate dimensions are 0.2 by 0.25 inch by 0.004 inch thick. The ceramic is PZT 65/35-2Bi, hot-pressed at 1300°C for one hour at 3000 psi pressure. Grain size is five microns.
20. Schematic diagram for "write" and "erase" circuits for the prototype memory of Figure 19.
21. Switching time versus field amplitude for the prototype memory of Figure 19.
22. Proposed readout system for ferroelectric ceramic optical memories.

THE SOLID SOLUTION PbZrO_3 - PbTiO_3 SYSTEM

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7,

Figure 3

Figure 9

Figure 10

Figure 11

Figure 12

INITIAL POLED
STATE OF THE
CERAMIC PLATE

ELECTRODE
CONFIGURATION
FOR LPS

CERAMIC PLATE
AFTER SWITCHING;
POLARITIES OF SWITCHING
VOLTAGES SHOWN

CERAMIC PLATE
AFTER ERASURE;
POLARITIES OF ERASING
VOLTAGES SHOWN

Figure 13

Figure 14

Figure 15

CERAMIC PLATE WITH ELECTRODE CONFIGURATION
FOR INDEPENDENTLY SWITCHING THE TWO SURFACES.

Figure 16

ELECTRODE PATTERN FOR A MATRIX ARRAY
OF RETARDERS ON A SINGLE SURFACE.

Figure 17

ELECTRODE CONFIGURATION FOR VARIOUS RETARDER
FAST AXIS ORIENTATIONS: (1) $\rho = 0^\circ$; (2) $\rho = 90^\circ$;
(3) $\rho = 45^\circ$; (4) $\rho = -45^\circ$.

Figure 18

Figure 19

SCHEMATIC DIAGRAM FOR "WRITE" AND "ERASE"

Figure 20

Figure 21

SCHEMATIC OF OPTICAL READOUT SYSTEM

Figure 22