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# A SOLID-STATE SELF-SCANNING DISPLAY DEVICE

FINAL REPORT NO. RADC-TDR-62-601

M.S. Wasserman

General Telephone & Electronics Laboratories Inc.
Bayside, New York

TR 62-204.18

Contract No. AF 30(602)2524

Prepared for

Rome Air Development Center
Air Force Systems Command
United States Air Force
Griffiss Air Force Base, New York

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## PREFACE

One of the most serious obstacles to the successful realization of electroluminescence as a display mechanism is the difficulty encountered in distributing information to the display surface. Many techniques have been proposed to alleviate the problem but to date none have been highly successful. It was the objective of this effort to prove the feasibility of a novel approach to the switching problem.

This approach was based upon the launching of an acoustic wave in a piezoelectric ceramic and the utilization of the resultant moving electric field as a means of accessing the EL panel. The goal was to develop a display structure that would be suitable for either random or sequential access and be controlled by an analog input signal.

To assess the limitations of the acoustic techniques as a display access method, the contractor elected to study the various components (ceramic, non-linear resistors, phosphor layer, etc.) independent of the display and, then, to investigate the problems associated with the integration of these components into the final device. This proved to be a wise choice as it delineated the interaction effects and allowed an assessment of the properties that could be expected under optimum conditions.

Feasibility of utilizing this technique as a display method was demonstrated. In addition, considerable insight into the critical parameters of a piezoelectric self-scanning display was acquired. The research has indicated that resolution and brightness will be the limiting factors associated with this technique.

## FOREWORD

The contributors to this investigation are as follows:

| | |
|---|---|
| <u>Piezoelectric Ceramic Materials</u> | - R.N. Summergrad<br>F.J. Stiftel |
| <u>Thin Piezoelectric Plates</u> | - R. Steinitz<br>E. Mazza<br>G. Lindemann |
| <u>Electroluminescent and Nonlinear Resistor Layers</u> | - W. Zloczower<br>J. Carroll |

This report was prepared by M.S. Wasserman.

This report was approved by A. L. Solomon.

The project engineer for Rome Air Development Center was M. Kesselman.

# ABSTRACT

This report describes the second phase of an investigation of materials for use in a solid-state electroluminescent display device in which the electric field for activation of the electroluminescent layer is provided by elastic waves propagated through a piezoelectric ceramic plate which serves as the substrate for the display.

The first phase of this investigation, reported in Technical Report No. RADC-TDR-62-430, was devoted to a search for improved piezoelectric ceramics, to the development of procedures for fabrication of thin large-area piezoelectric ceramic plates, and to a search for materials for improved nonlinear resistor layers for the suppression of spurious light in the display.

In the second phase of the investigation, reported herein, part of the piezoelectric ceramic work was continued. Main emphasis was placed on an investigation of the problems associated with integration of the piezoelectric, nonlinear resistive and electroluminescent materials into complete display structures. Displays have been prepared with the following characteristics:

| | |
|---|---|
| Trace brightness: | 0.3 foot lamberts for elliptical Lissajous figure |
| Trace width: | 0.14 inch |
| Display area: | 2-1/2 x 2-1/2 inches |
| Contrast ratio: | > 100 |
| Power input: | 45 watts |

It was found that the brightness and resolution of the display are limited largely by the fact that the electroluminescent layer exhibits a nonlinear resistive characteristic at high field strength. An estimate has been made of the improvement in performance to be expected if this loss component is reduced. The expected effect of improved propagation characteristics of hot-pressed ceramics has also been assessed. Finally, it has been shown that a significant increase in brightness can be achieved if the display design is revised so that the piezoelectric ceramic plate is used as the means of access to the points on the display, but not as the source of power. Its output pulses would be used to gate power from an independent source.

**Title of Report**

RADC-TDR-62-601

**PUBLICATION REVIEW**

**This report has been reviewed and is approved.**

**Approved:** David F. Barber
DAVID F. BARBER
Chief, Applied Research Laboratory
Directorate of Engineering

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**FOR THE COMMANDER:** Irving J. Gabelman
**IRVING J. GABELMAN**
**Director of Advanced Studies**

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# 1. INTRODUCTION

The purpose of the work reported here was to investigate the material requirements and the incorporation of these materials into optimum layer structures for improvement of the performance of a unique solid-state electroluminescent (EL) display device. The work was performed under contract No. AF30(602)-2524, sponsored by the Rome Air Development center.

This new concept of a solid-state display panel is based on a combination of an electroluminescent phosphor layer in contact with a piezoelectric panel which excites and controls, point by point, the light output of the electroluminescent phosphor layer. No intricate electrode geometries are required and the electronic driving circuitry is simple. One can provide either a high-speed sequential access or a random, point by point, access to the electroluminescent phosphor layer on the surface of the display panel. Scanning and random access circuits for this purpose were designed and successfully demonstrated prior to the inception of this contract.

The basic elements of the device are:

a) An electroluminescent layer for visual output.

b) A nonlinear resistive (NLR) layer to increase the contrast of the visual image and to reduce the modulation power requirements.

c) A piezoelectric ceramic in the form of a thin sheet serving as the scanning medium.

d) A piezoelectric ceramic input transducer.

By using two orthogonal scanning electrodes on the periphery of the flat piezoelectric panel (Fig. 1), pulses of mechanical energy are injected along the x and y directions of the panel. Associated with the elastic waves propagating through the piezoelectric panel at constant velocity are electric fields which travel across the panel area. The x and y pulses will cross each other and superimpose their associated electric field amplitudes. This crossover constitutes one sharp traveling point moving along a line oblique to the axis. The position of this scanning line is precisely determined by the time relationship between the x and y pulses. Therefore, by proper variation of this time relationship, the entire face of the panel may be scanned.

By applying an electroluminescent phosphor layer to the surface of the piezoelectric panel, the scanning point can be made visible. If the brightness response of the electroluminescent layer vs electric field were sufficiently nonlinear, then only the enhanced field amplitude at the crossover would produce light. To obtain this degree of nonlinearity, a nonlinear resistive layer is used in series with the EL layer.

By means of an area electrode applied to the rear of the piezoelectric panel, brightness modulation, point by point, can be performed. In this case the nonlinear brightness response of the electroluminescent panel is designed in such a way that only a triple pulse coincidence results in light output from the phosphor, i.e., an instantaneous video voltage becomes effective only at the position of the x and y crossover point. This is equivalent to the z-axis modulated beam of a cathode-ray tube.

Random access is accomplished by applying input voltages to four scan electrodes, (Fig. 1), thus creating two pulses each in the x and y directions. These four pulses create a four-coincidence crossover point which produces a stationary "spot" of light. By varying the relative

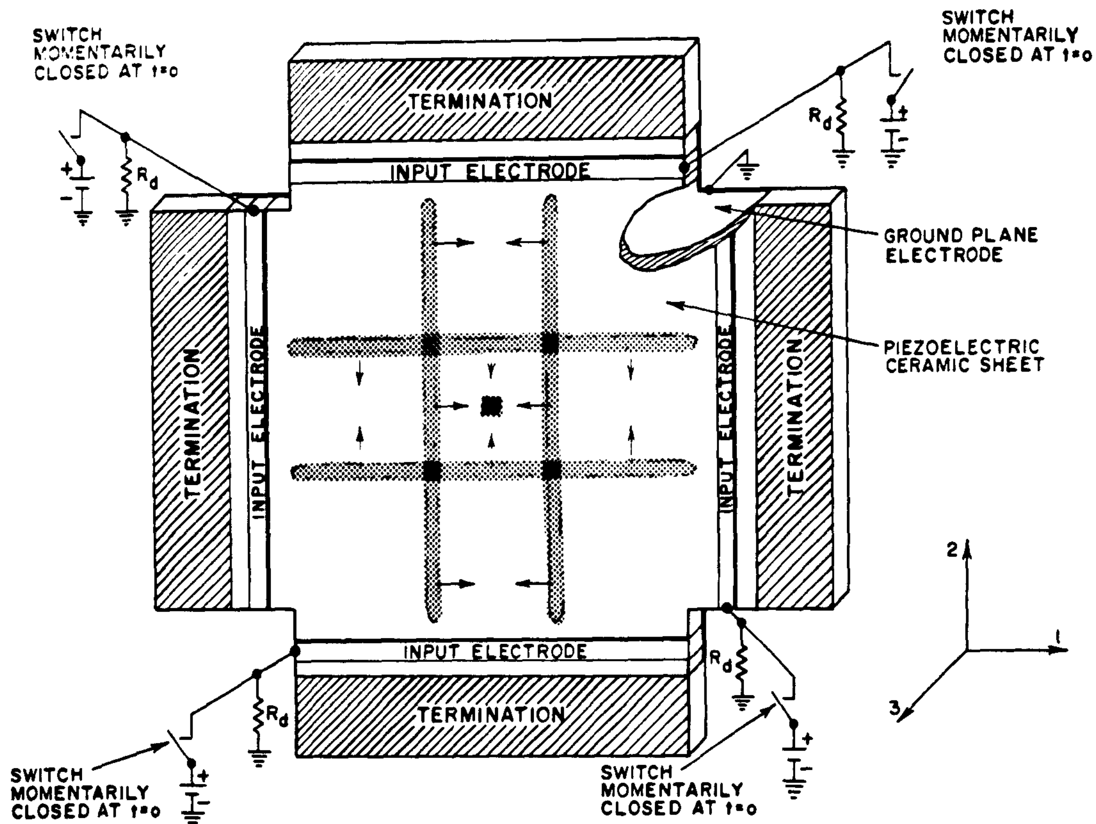



Fig. 1. Surface fields produced by four simultaneously launched elastic pulses.

timing between x and y pulses, the spot can be made to appear anywhere on the panel. By dynamically changing the timing relationships in each set of x and y pulses, the spot can produce an oscilloscope display as shown in Fig. 2. This is a photograph of an early feasibility model which does not contain a nonlinear resistor layer for suppression of background light.

Once the feasibility of this device was demonstrated, it was recognized that improvements in brightness, contrast and resolution would depend upon improved understanding and control of the pertinent characteristics of the piezoelectric and nonlinear resistor materials. In addition, the construction of the device would be simplified if the proper piezoelectric ceramics were available in the form of thin continuous sheets. The first phase of this work comprised a study of these materials. The results have been presented in RADC TDR-62-430, covering the period May 31, 1961 to May 31, 1962.

In the second phase, which is described in this report for the period June 1, 1962 to September 30, 1962, part of the materials study was continued. In addition, an investigation was made of the problems associated with integration of the piezoelectric, nonlinear resistive and electroluminescent materials into layer structures which will improve the performance of the display device.

## 2. REQUIREMENTS FOR THE COMPONENTS OF THE DISPLAY STRUCTURE

A cross-section of the four-electrode form of the display device is shown in Fig. 3. This is the form employed in the random access mode, and it is the one which has been used in this investigation. In the initial attempts to construct this device, the NLR, EL and transparent electrode (TC) layers were applied in succession to the piezoelectric ceramic plate, which served as the supporting substrate. It

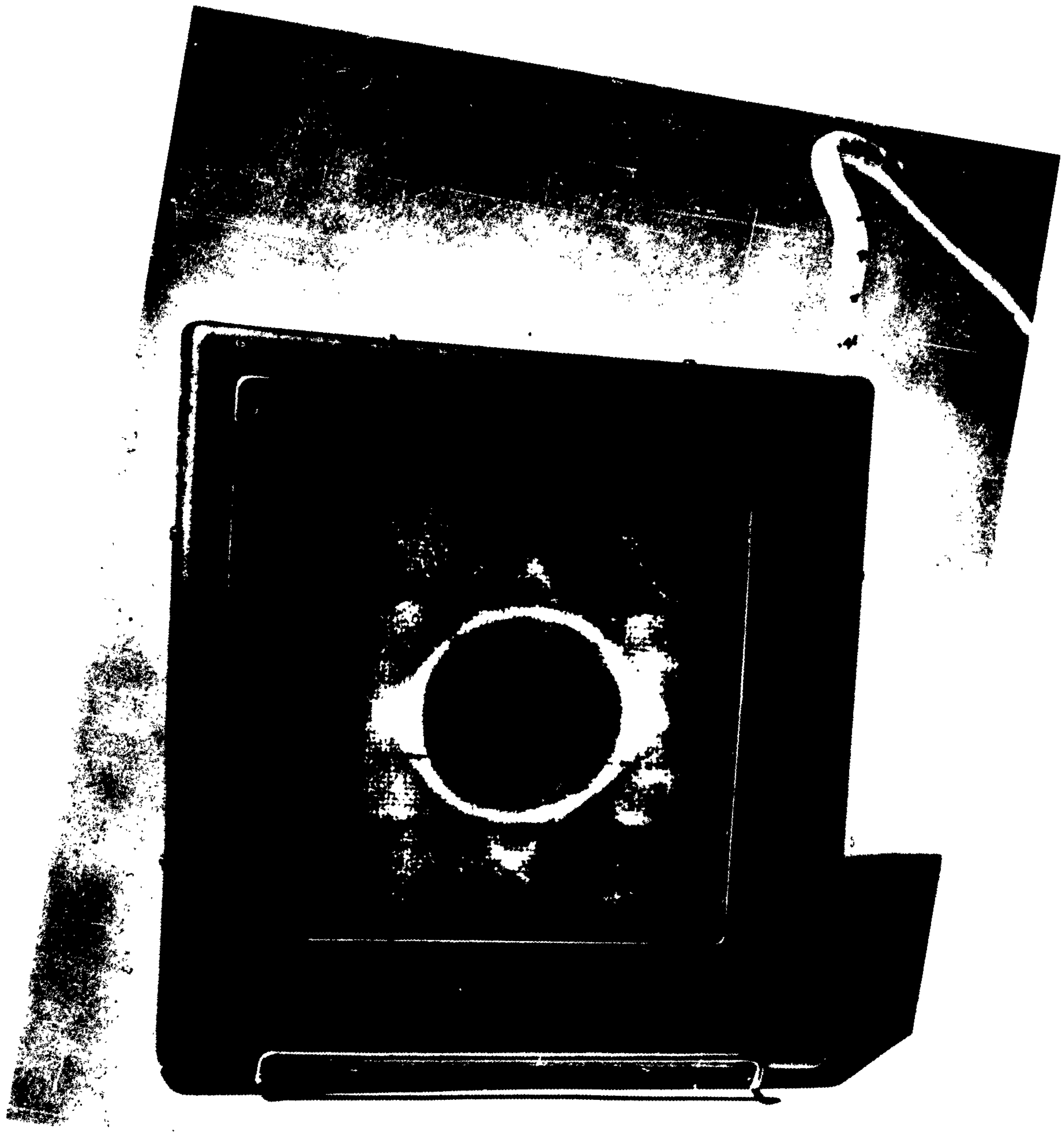


Fig. 2. Display panel showing lissajous figure resulting when X and Y signals are 1000 cps sine waves.

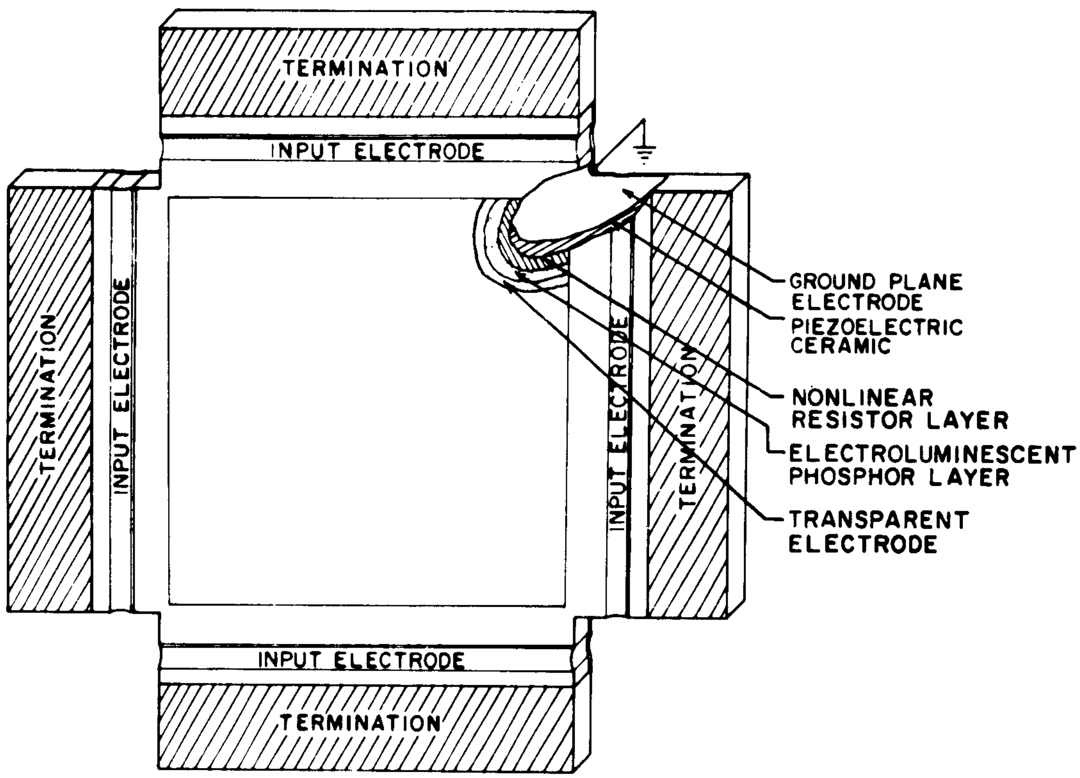



Fig. 3. Basic construction of the display device.

was found that this structure caused a constraint of the piezoelectric plate, which resulted in a serious dispersion of the elastic waves so that a well-defined voltage spot could not be obtained. This constraint was removed by using a high-dielectric-constant fluid film (e. g. glycerol) at the NLR-ceramic interface. The fluid provides effective electric coupling with no mechanical damping effect. In the present form of the device, the TC, EL and NLR layers are applied in succession to a glass substrate, and this structure is then coupled by means of the fluid film to the piezoelectric plate.

An equivalent circuit for the display is shown in Fig. 4. The voltage source $V_c$ represents the open-circuit voltage generated in an element of area of the ceramic plate when the elastic wave appears there. The internal impedance of that area of the plate can be represented by a capacitance with negligible leakage. The NLR layer acts as a capacitor for low values of $V_c$, and as a voltage-dependent resistor when four elastic waves intersect to provide the maximum value of $V_c$. The EL layer is essentially a capacitor, but it has a nonlinear leakage resistance which cannot be neglected. The series resistance of the TC layer can be neglected in most cases.

The required characteristics of the component layers of the device will be discussed in terms of the brightness, resolution, background suppression and efficiency.

## 2.1 PIEZOELECTRIC CERAMIC PLATE

The influence of the piezoelectric constants and dielectric properties of the ceramics on the display brightness was discussed in detail in the Interim Technical Report. Briefly, the material which

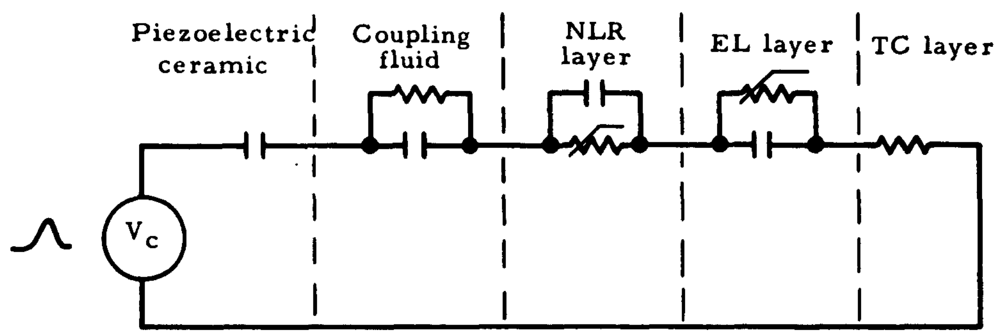



Fig. 4. Equivalent circuit of the piezoelectric-electroluminescent display device.

lies under the input electrodes should have a large value of $d_{31}$, which is the strain produced per unit field applied. The material underlying the display area should have a large value of $g_{31}$, which is the field produced per unit stress. Another factor which must be considered is the matching of the ceramic impedance with the impedance of the load for maximum power transfer. The ceramic impedance depends upon the dielectric constant and the plate thickness.

The thickness of the ceramic plate is also a determining factor in the spot size, and therefore the display resolution. This consideration dictates the need for thin plates, with the lower limit of thickness determined by structural strength and the fact that the output voltage is proportional to thickness.

Several properties of the piezoelectric ceramic influence the efficiency of conversion of input electrical energy to the electrical energy supplied to the display. The conversion from electrical to mechanical energy in the input transducer and the inverse process in the display substrate are proportional to the square of the radial coupling coefficient, $k_r$. Therefore, the overall conversion is proportional to $k_r^4$. The extent of attenuation and dispersion of the propagated waves is determined by the elastic properties of the ceramic such as mechanical hysteresis and by the direction of polarization of the ceramic.

## 2.2 FLUID COUPLING LAYER

The coupling layer between the piezoelectric ceramic plate and the NLR layer must have a low shear modulus in order that mechanical coupling to the piezoelectric plate be minimized. The introduction of the coupling layer effectively increases the driving source impedance, and thereby reduces the available output voltage. It is therefore desirable that the coupling layer have a high capacitance or a conductivity of approximately 2500 ohm cm in layers of 1 to 2 mils thickness.

## 2.3 NONLINEAR RESISTOR LAYER

The nonlinear resistor layer is employed to obtain a high-contrast image by suppressing the light emission from the EL layer other than where the light spot is to appear. The properties of the NLR layer required to perform this function are described in detail in the Interim Report. The NLR layer also serves to reduce the spot size. Since the output pulse from the ceramic plate has an approximately Gaussian distribution in space, the NLR layer suppresses light emission that might be produced by the skirts of the pulse.

## 2.4 ELECTROLUMINESCENT LAYER

Although the basic property desired of the EL layer is a high brightness for a given input voltage, other factors are important in this device. It is desirable that the brightness discrimination ratio of the phosphor layer alone be as high as possible so that the burden of background suppression will not be placed entirely on the NLR layer. Of equal importance is the current-voltage characteristic of the EL layer. A nonlinearity in this relationship that leads to a decrease in impedance at high voltage will be evidenced as a brightness-limiting effect as the voltage is raised.

# 3. EXPERIMENTAL RESULTS

## 3.1 COMPOSITE ELECTROLUMINESCENT-NONLINEAR RESISTOR LAYERS

The EL and NLR layers were prepared by similar techniques involving settling or spraying the powder in a vehicle containing an epoxy resin, and then curing the resin. In early composite structures the electrical coupling between the two layers was poor because of the roughness of the interface, which permitted intimate contact only at isolated points.

This difficulty was eliminated by interposing a vacuum-deposited aluminum electrode at the interface. This electrode was continuous in test samples, but in the display device it is in the form of an array of isolated dots, approximately 10 mils square. The improved coupling led to an approximately ten-fold brightness increase. All composite structures discussed in this report have this intermediate electrode.

The characteristic of the composite layers that is most significant in determining display brightness and the degree of background suppression is the brightness-voltage characteristics of the layers under pulsed operation. The pulse width in the display is determined by the speed of sound in the piezoelectric ceramic ($3.5 \times 10^3$ meters $sec^{-1}$), the ceramic thickness and the width of the input electrode. The currently available materials will produce pulse widths in the range 0.2 to 1$\mu$sec. The maximum repetition rate for the input pulses is determined by the time required for one set of input pulses to reach the sound absorbing terminations at the opposite edges. For a 5-inch x 5-inch display the maximum repetition rate is 14 kc. For an image composed of 100 spots, the excitation rate for each spot would be 140 pps. In much of the data presented here, rates of 400 pps and 4000 pps have been chosen for convenience, the former representing the excitation rate of a spot in the image, and the latter representing the excitation of a "dark spot."

The brightness-voltage curves in Fig. 5 are representative of EL layers containing copper-activated zinc sulfide (green at low frequency, blue at high frequency) in series with NLR layers containing copper activated cadmium sulfide. All of the 400-pps curves have the same general shape. At low voltages the brightness is approximately proportional to $V^{16}$. At higher voltages the exponent decreases to approximately 3. Therefore, the discrimination ratio decreases rapidly as the spot brightness is increased by raising the applied voltage. The curves show that

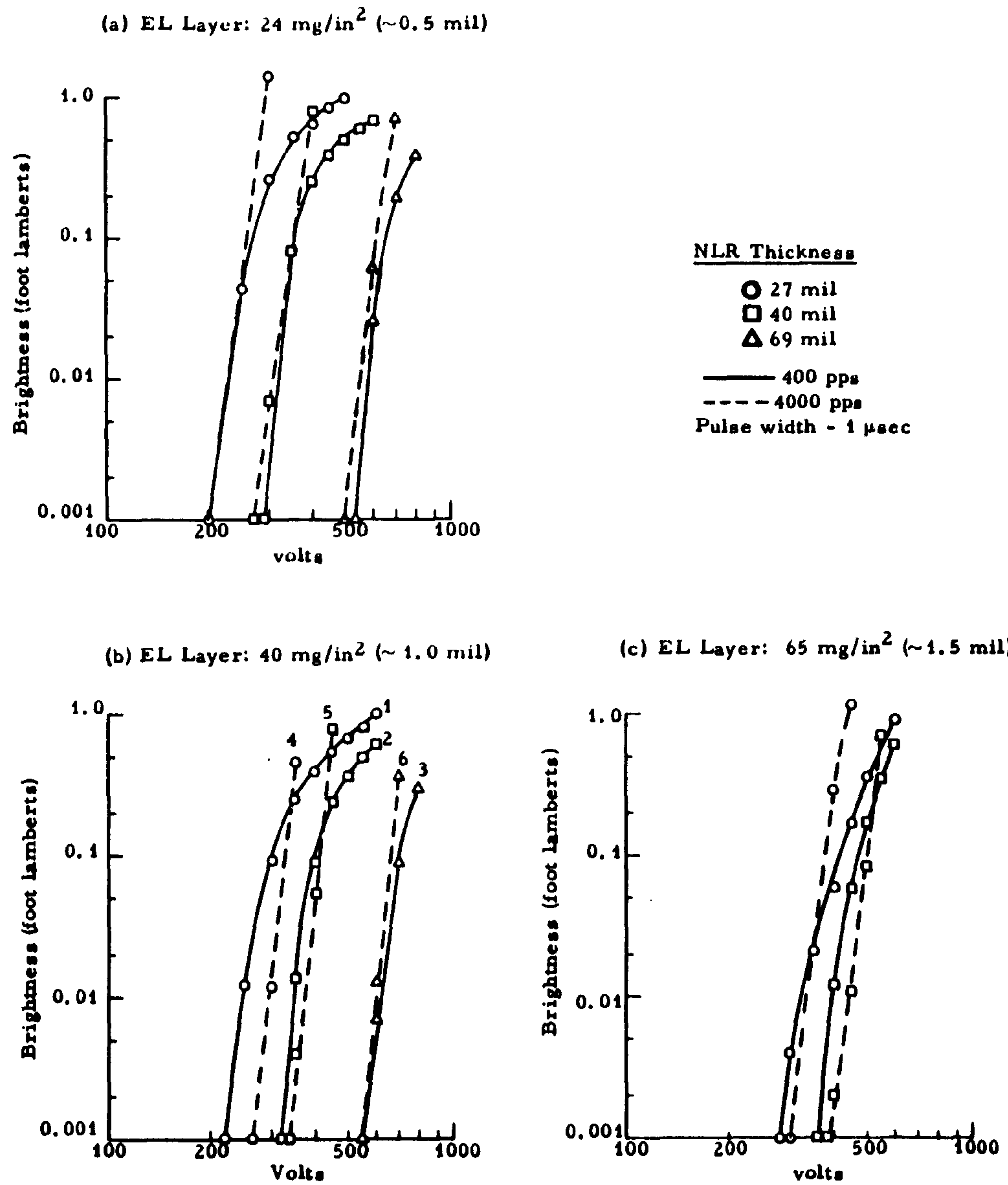



Fig. 5. Brightness-voltage characteristics of EL-NLR layers.

for a given NLR layer thickness and applied voltage, the brightness is only a slowly decreasing function of the EL layer thickness. Increasing the NLR layer thickness does not increase the exponent significantly, and only results in sharply reduced brightness at a given voltage.

When the pulse repetition rate is increased to 4000 pps, the brightness-voltage curves become steeper, especially above 0.1 foot lambert. A crossover of the 400-pps and 4000-pps curves is desirable for effective background suppression when the "dark spots" are excited at a much higher rate (at half voltage) than the bright spots. So long as the crossover point occurs at a voltage greater than that which appears at the dark spots, these spots will be more effectively suppressed as the repetition rate is increased.

The reason for the inverse relationship between brightness and repetition rate at low voltage is found in the oscilloscope traces of Figs. 6a and 6b. At the end of each applied pulse the NLR resistance, and therefore the time constant, increases. The voltage across the EL layer decays slowly. At 4000 pps (Fig. 6a) the EL voltage appears as relatively small pulses superimposed on an approximately constant background which contributes little to the light output. As the repetition rate is decreased to 400 cps, the EL voltage has time to decay to a lower level, and the effective change in EL voltage during each pulse application is greater, as may be seen in Fig. 6b. The inverse relationship does not hold at higher pulse voltages, because the steady background level becomes insignificant relative to the peak EL voltage. Brightness then increases with repetition rate. Figs. 6c and 6d show the voltage range in which this relationship pertains. Even though brightness increases with repetition rate in this voltage range, the relationship is sublinear and therefore favorable for background suppression.

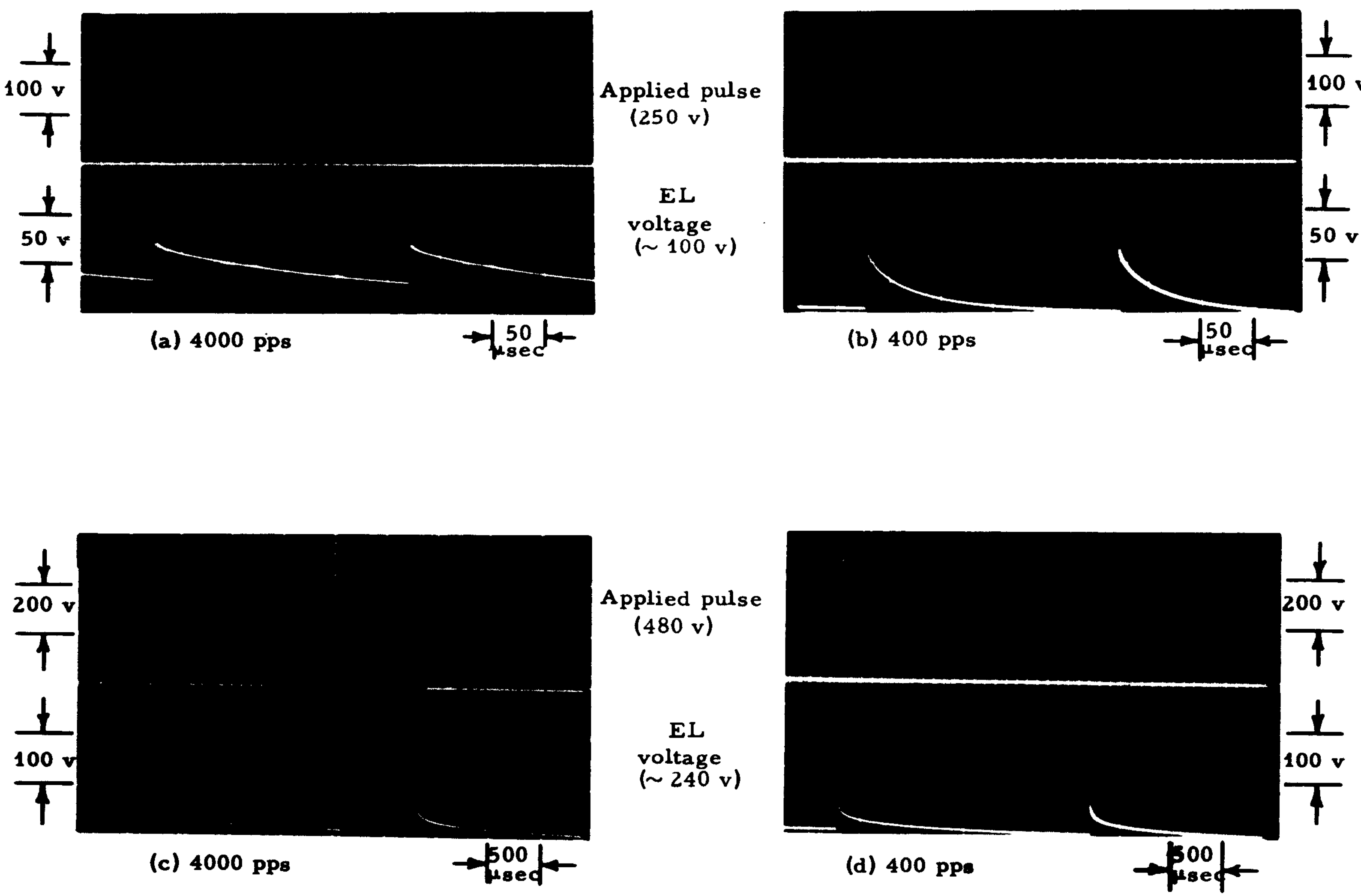
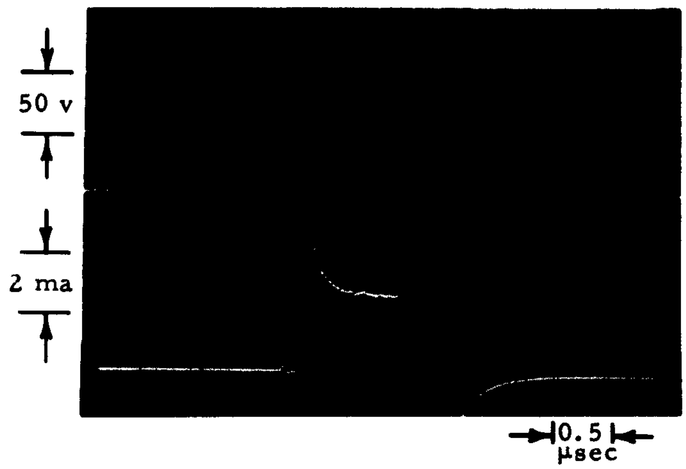



**Fig. 6. Pulse excitation of series EL-NLR circuit.**

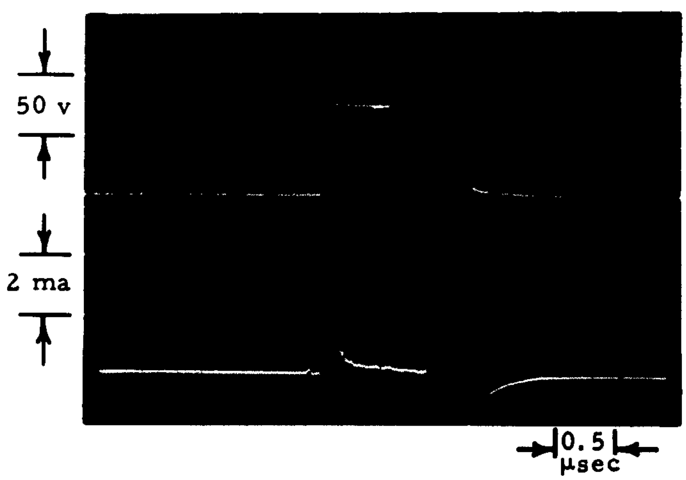
The most serious limitation on the usefulness of the EL-NLR composites is the sharp decrease in slope of the brightness-voltage curves at high brightness. As stated earlier, this implies a reduction in background suppression as brightness is increased. The main reason for the decrease in slope is that the parallel nonlinear resistive component of the EL layer impedance becomes dominant at high voltage, thereby lessening the influence of the NLR layer. The behavior of the EL layer alone at high and low voltage is shown by the current waveforms in Figs. 7a and 7b respectively. The brightness-voltage and current-voltage characteristics of EL layers alone are shown in Fig. 8. It is seen that the I-V characteristic is a 5th power relationship.

Recent investigation has shown that EL layers containing yellow, manganese-copper-activated phosphors are much less lossy than those containing the copper-activated phosphor. The yellow layers are also brighter than the blue at low repetition rate, and less bright than the blue at high repetition rate. These factors favor higher background suppression at high brightness levels, but they are offset by the fact that the brightness-voltage characteristic of the yellow layers is less steep than that of the blue layers. Past experience in phosphor preparation indicates that modifications in the preparation of the yellow phosphor can lead to higher slopes.

Reduction of pulse width from 1.0 to 0.5 μsec reduces the brightness of the EL-NLR composites by a factor of ~ 4 in the low voltage range and ~ 2 in the high voltage range. This is because the time constant is sufficiently long to prevent the attainment of full voltage across the EL layer. For EL layers alone the change in brightness is only 10% in this range of pulse widths.




(a) High voltage




(b) Low voltage

Fig. 7. Pulse voltage and current waveforms for EL layer excited with 1 μsec pulse at 4000 pps.

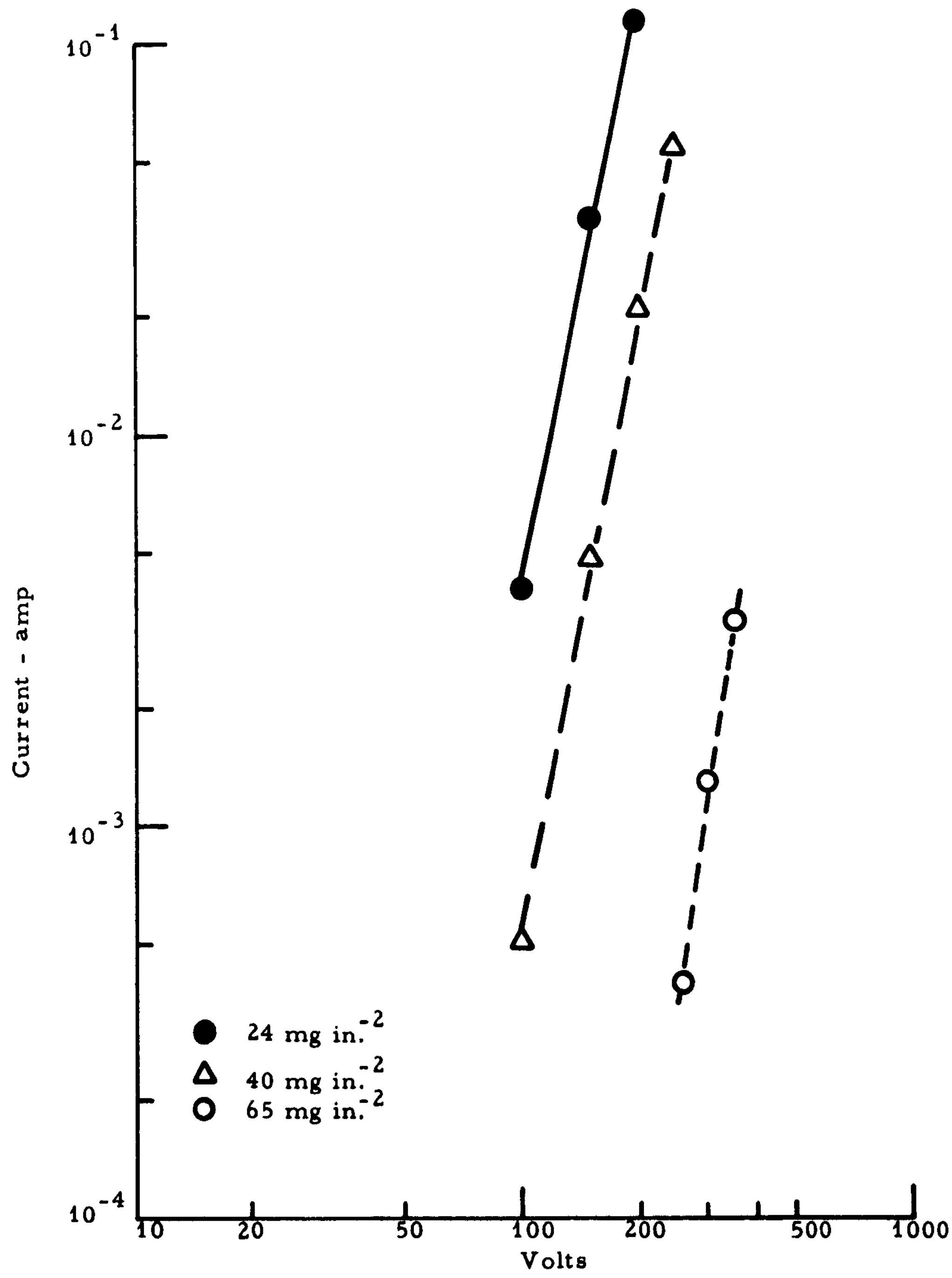



Fig. 8. Current-voltage characteristics of EL layers.

It has been found that the characteristics of separate EL and NLR layers are not reproduced when a composite layer is prepared. This has been traced to a disturbance of the EL layer when it is exposed to the solvents used for the subsequent preparation of the NLR layer. The result is a reduction in EL layer brightness by as much as two fold. Further work is required to develop more compatible techniques for the layer preparations.

Measurements were made of composite EL-NLR layers in series with a capacitor to simulate the piezoelectric plate. A serious difficulty is that the EL-NLR composite presents a voltage-sensitive impedance to the driving source, so that the output voltage at the intersection of four elastic waves is less than twice the output voltage at the intersection of two waves. In some cases the measured ratio was 3:2. This implies a sacrifice in either discrimination ratio or display brightness.

## 3.2 COMPLETE DISPLAY STRUCTURES

Consideration of the characteristics of composite EL-NLR layers and the available output voltage from the ceramic plate led to the preparation of display panels, 2-1/2 inches square, composed of 40 mg in$^{-2}$ (approximately 1-mil-thick) EL layers and 27-mil-thick NLR layers, for evaluation in the complete display structure. When the open-circuit output voltage of the ceramic was 500 volts, the brightness of a single spot excited at 4000 pps was 4.7 foot lamberts. The average brightness of an elliptical lissajous figure was approximately 0.3 foot lamberts, and the width of the trace was 0.14 inch. The power dissipation was approximately 45 watts. These layers and excitation conditions correspond closely to curve 1 of Fig. 5b. The discrimination ratio, as estimated from curve 1 for a bright spot and curve 4 for a dark spot, is greater than 5000. Figure 9 is a photograph of the displayed image.

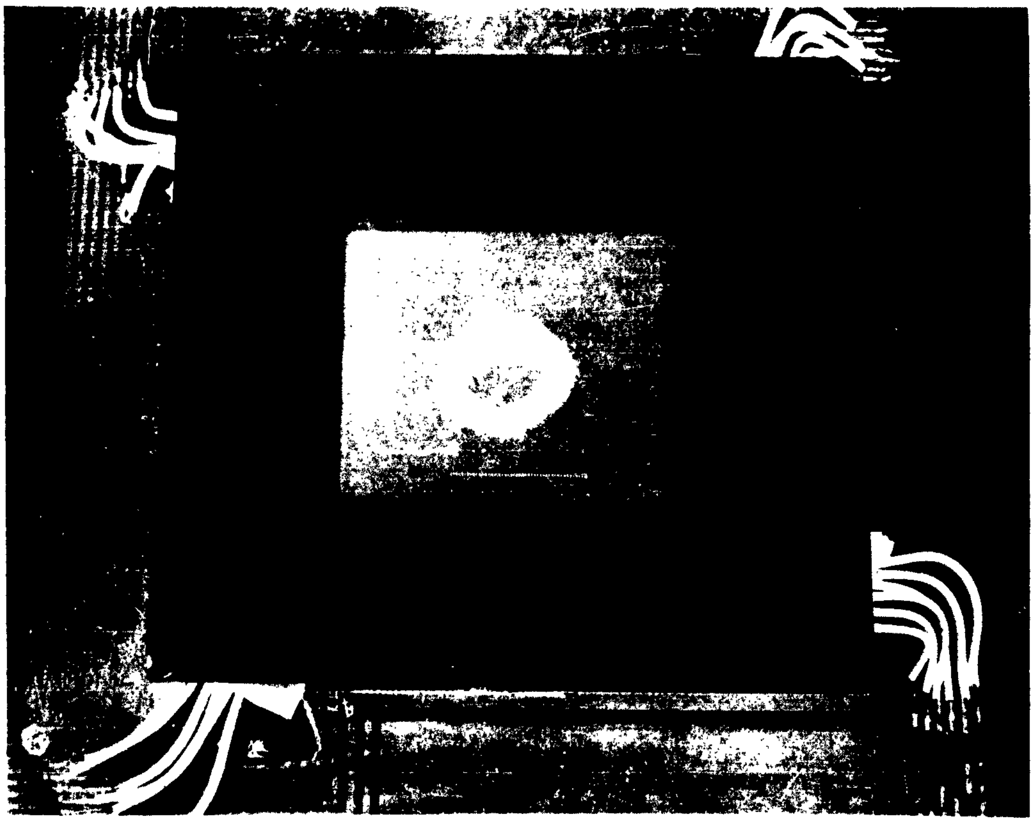


Fig. 9. Lissajous figure displayed on new panel with nonlinear resistor layer. Complete background suppression results in significant improvement in contrast.

The fluid coupling medium between the ceramic plate and the NLR layer in these tests was glycerol. A thin film of this high dielectric constant liquid provided good coupling. The extent of voltage attenuation caused by the glycerol remains to be determined.

It appears that the observed trace width of 0.14 inch is determined to a large extent by the relatively conductive state of the EL layer at high voltage. This permits some lateral spreading of the field, with consequent broadening of the trace. Aiding this effect is the fact that the brightness-voltage characteristic of the EL layer is not very steep in this voltage region. Calculations have been made of the expected trace width when the EL layer is a near-perfect capacitor. Taking the observed voltage pulse width in a 0.030-inch-thick ceramic plate after the pulse has propagated 3 inches into the plate, a trace width of 0.080 inch is obtained. The trace width can be further narrowed if propagation losses in the ceramic are reduced. This point will be further discussed in Section 3.3.1.

## 3.3 PIEZOELECTRIC CERAMICS

The study of piezoelectric ceramic materials was carried out concurrently with the work on EL-NLR structures. The hydrostatic pressing-sintering technique was developed to the extent that it can now be considered a routine procedure for the preparation of thin plates up to 5 inch x 5 inch. The polarization of these plates, however, remains to be optimized. Recent hot-pressed samples have shown superior piezoelectric properties, as well as increased density, which should contribute to improved propagation characteristics.

3.3.1 Pulse Propagation in Thin Plates

Preliminary measurements of the propagation characteristics in piezoelectric ceramic plates were made on commercially available 1-inch x 5-inch samples.

Measurements of pulse propagation have been made by applying a sawtooth signal to an input electrode near the edge of a 1 x 5-inch plate, and measuring the open-circuit output voltage as a function of time at parallel output electrodes placed along the length of the ceramic plate. The output pulse width is an increasing function of the width of the input electrode for widths greater than 1.4t, where t is the ceramic plate thickness. Reducing the width below this value has no effect on the output pulse width. The effect of plate thickness was determined by successively grinding the plate to a thinner dimension for each set of measurements. This eliminated the effect of material variations in different plates. It was demonstrated in independent measurements that the grinding operation had no significant effect on the piezoelectric constants of the plate.

The attenuation of the voltage pulses during propagation is shown in Fig. 10. The initial values of pulse height were measured at an output electrode placed very close to the input. The initial values for different thicknesses are normalized for ease of comparison, although the actual values differ very little. The curves show that the initial attenuation is greatest in the thinnest plates, but that the the influence of thickness has almost disappeared after the pulses have propagated a distance of 3 inches. At this point the output pulse height is approximately 25% of the initial value.

The behavior of the pulse width is shown in Fig. 11. In these measurements the time between the 50% amplitude points is chosen as the pulse width. As expected, the initial pulse width is an increasing function of thickness, but the relationship is not a simple proportionality. The curves show that the 0.010 inch thickness is the most desirable because it provides both the narrowest starting pulse and the lowest rate of pulse

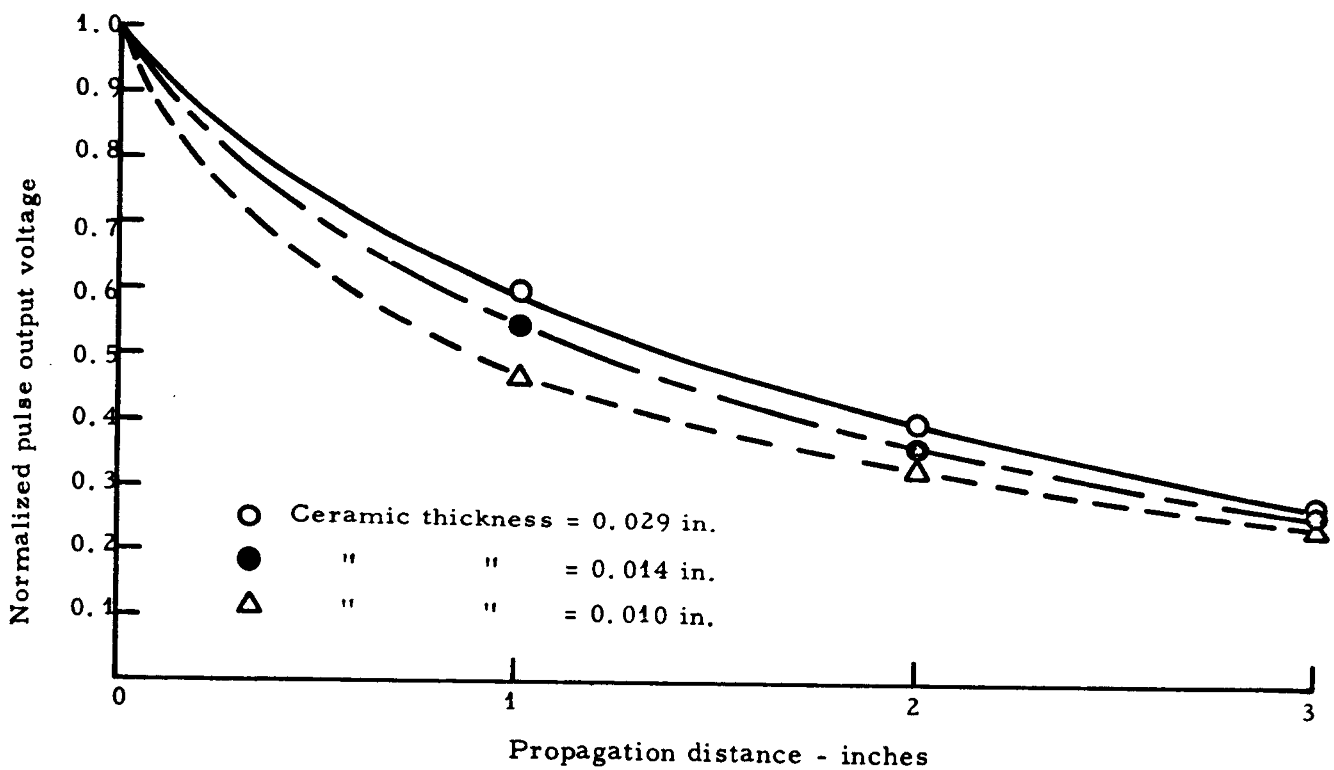



Fig. 10. Output pulse height vs propagation distance for piezoelectric ceramic plate.

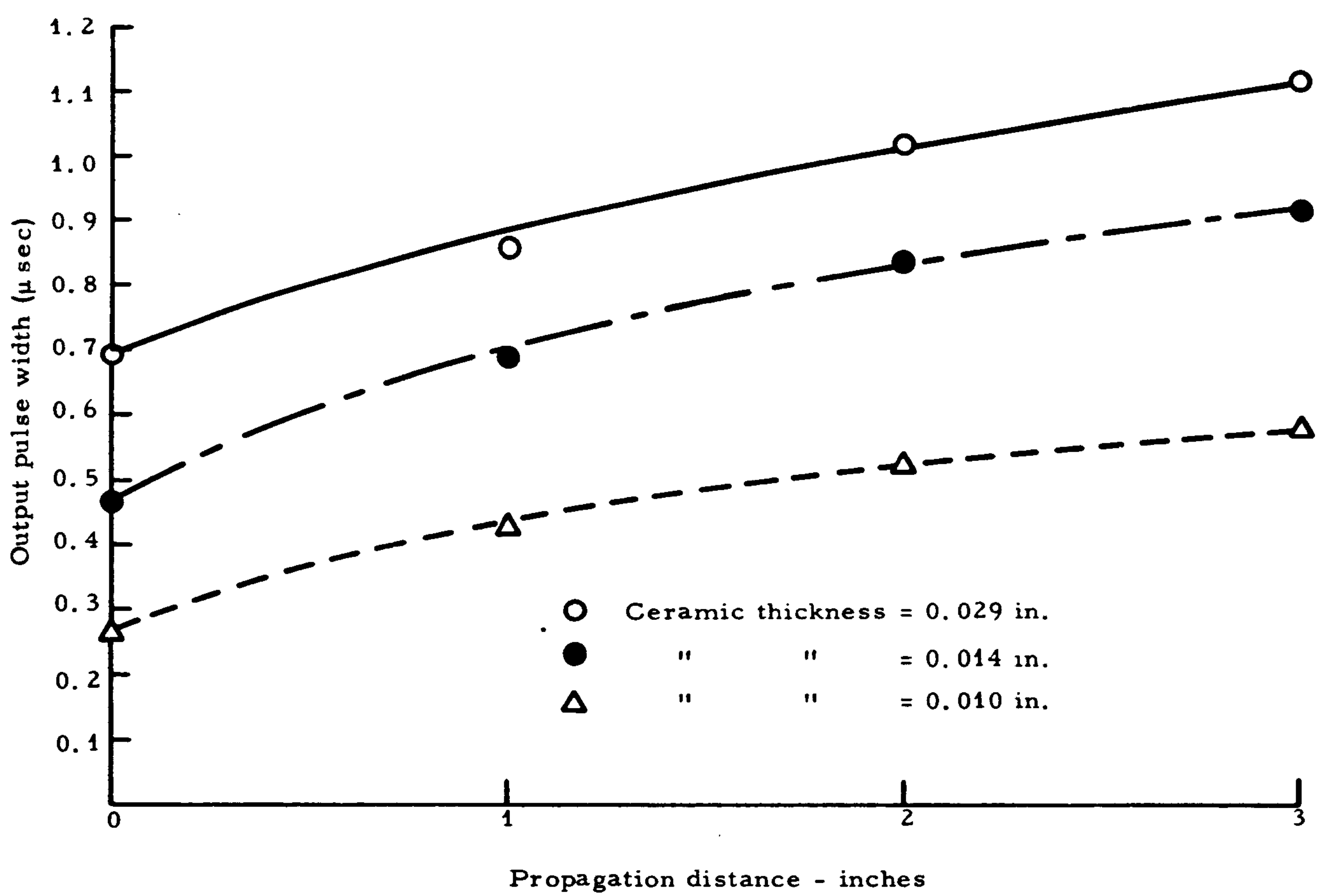



Fig. 11. Output pulse width vs propagation distance for piezoelectric ceramic plate.

broadening with propagation distance. Referring to the calculation of the display trace width which was discussed in Section 3.2, if a 0.010-inch plate thickness were used in place of 0.030 inch, the calculated trace width would be reduced from 0.080 to 0.041 inch. However, it must be pointed out that in order to maintain the same trace brightness with the thinner ceramic, correspondingly thinner EL and NLR layers would be required. The required reduction in EL layer thickness (or impedance) does not appear practical at present. Vacuum-deposited thin-film EL layers have been investigated as a possible match for 0.010-inch-thick ceramics, but it was found that their impedance is far too low. A possible alternative is the application of higher field strengths to the thinner ceramic, although problems of heating and depolarization might arise.

### 3 3.2 Preparation of Large-Area Plates

The hydrostatic pressing-sintering technique was described in detail in the Interim Report. Using the composition $Pb(Zr_{0.54}Ti_{0.46})O_3$, which is the optimum for the display substrate, 1 x 5 x 0.030 inch samples were prepared which exhibited high values of the piezoelectric constant $g_{31}$. The technique has since been extended to the preparation of 5 x 5 x 0.030 inch plates of the same composition, and also to the preparation of input transducers.

#### 3.3.2.1 Display Area Plates

A sample for slicing into large display area plates was prepared as follows:

A pliable plastic mold 7-1/2 x 7-1/2 x 3/4 inches, was loaded with prefired $Pb(Zr_{0.54}Ti_{0.46})O_3$ to which 2% of a wax binder was added, and then sealed. The assembly was then hydrostatically pressed at 17 tsi to a density of about 80% of theoretical. After removal from the mold, the compact was heated at 500°C to drive off the binder, and then sintered at 1300°C for one hour in a closed platinum boat. The final density was 93% of theoretical. Four plates, 5 x 5 x 0.030 inches, and one plate 4 x 4 x 0.010 inches were machined from the slab. One of the 5 x 5 inch plates is shown in Fig. 12. A second sample, 1-1/2 inches thick, cracked during pressing, but was processed to provide a number of 1 x 5 x 0.030 inch plates. The hydrostatic pressing operation was performed on equipment at the Sylvania Chemical and Metallurgical Division.

The piezoelectric and dielectric properties of hydrostatically pressed-sintered ceramics are given in Table I. The first group of discs listed in the table were cut from 1 x 5 inch plates and then polarized. Their piezoelectric properties compare favorably with test samples prepared during the initial phases of the ceramic work which were described in the Interim Report. The characteristics of the 1 x 4 inch strip show that the full strip can be properly polarized. The values of the coupling coefficient for the 5 x 5 inch plate are lower because the polarizing field and temperature were lower than for the small discs, in order to reduce the danger of cracking at defects in the plate. A new supply of 5 x 5 inch plates will soon be available, and the polarizing procedure will be improved to realize the properties of the small samples in the large plates.

The observed uniformity in density and piezoelectric properties of the samples cut from the large slab has been correlated with chemical and x-ray analyses. The range of lead content was 63.1 to 64.0% (calculated 63.4%). X-ray diffraction showed the presence of a single phase, and Fig. 13 shows that a fairly uniform grain size was obtained.

### 3.3.2.2 Composite Transducer-Display Area Plates

Experiments were performed to determine the feasibility of producing composite plates of transducer and display substrate material in which the two materials are sintered together, thereby eliminating the

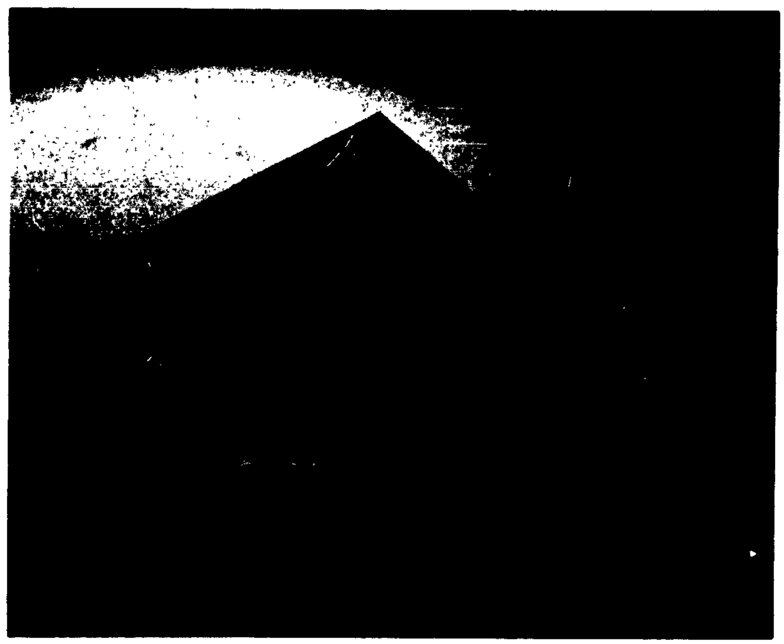


Fig. 12. 5 inch x 5 inch x 0.030 inch lead titanate zirconate plate, machined from a hydrostatically pressed and sintered block.

TABLE I

Piezoelectric and Dielectric Properties of Hydrostatically Pressed-Sintered Ceramics

| Dimensions | Dielectric Constant | Coupling Coefficient $k_r$ | $g_{31} \times 10^3$ volt meter newton$^{-1}$ | Density | | Remarks |
|---|---|---|---|---|---|---|
| | | | | g cm$^{-3}$ | % Theor. | |
| 3/4" diam. | 488 | 0.463 | 14.6 | 7.52 | 94.2 | |
| " | 484 | .447 | 13.8 | 7.49 | 93.9 | Cut from 1 in. x 5 in. plate, then polarized. Polarizing conditions: 160°C, 80 v/mil pulse, 6 min. |
| " | 494 | .447 | 13.8 | 7.45 | 92.4 | |
| " | 459 | .441 | 14.0 | 7.51 | 94.2 | |
| " | 504 | .463 | 14.2 | 7.46 | 93.5 | |
| " | 488 | .463 | 14.6 | 7.41 | 93.1 | |
| " | 470 | .407 | 13.3 | 7.56 | 94.7 | Cut from a polarized 5 in. x 5 in. plate. Polarizing conditions: 105°C, 77 volts/mil dc, 3 min. |
| " | 430 | .405 | 13.5 | 7.56 | 94.7 | |
| 1" x 4" | | .440 | | 7.42 | 93.2 | |

Fig. 13. Photomicrograph of hydrostatically pressed and sintered lead titanate-zirconate. Average grain size 10µ. Density 93% of theoretical. (750X)

need for a cemented joint. The hydrostatic pressing method was used, first filling the 1 x 3 x 3/4 inch mold to 25% of its length with a prefired powder of the composition $Pb_{0.985}Nb_{0.03}(Zr_{0.52}Ti_{0.48})_{0.970}O_3$. This formed the transducer region. The remainder of the mold was filled with the previously described display substrate material. The pressing and the sintering cycle was the same as that previously described. The slab was cut into seven plates, 1 x 4 x 0.030 inches. One of the plates is shown in Fig. 14.

The properties of 3/4-inch-diameter discs cut from the two regions are summarized in Table II. These discs were polarized after cutting. A procedure has been developed for polarizing the composite plate in two steps. The transducer region is first polarized with a dc field of 80 volts/mil at 252°C, and then the display region is polarized with a dc field of 78 volts/mil at 119°C. It has not yet been possible to achieve as high a coupling coefficient in the transducer region as the value in Table II.

TABLE II

Properties of Composite Transducer-Display Substrate Plate

| Composition | Dielectric Constant | Coupling Coefficient | $g_{31} \times 10^3$ | $d_{31} \times 10^{12}$ | Density | |
|---|---|---|---|---|---|---|
| | | | | | $g\ cm^{-3}$ | % Theor. |
| Transducer | 1245 | 0.496 | - | 114 | 7.56 | 94.5 |
| Display Substrate | 503 | 0.459 | 13.8 | - | 7.59 | 94.6 |
| Display Substrate | 509 | 0.450 | 13.6 | - | 7.45 | 93.9 |

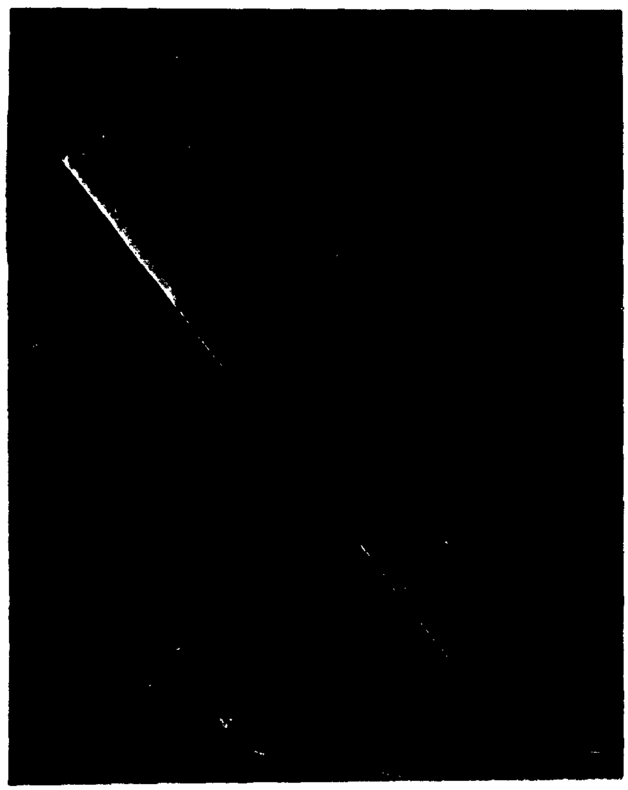


Fig. 14. Composite plate, showing 1 inch of transducer material (light area) and 4 inches of display substrate material (grey area).

Some difficulty has been encountered with breakage of the composite plates at the boundary between the two regions during polarization. This is probably related to the difference in grain size shown in Fig. 15. Since the boundary region has a niobium content between 0.03 gram atoms/mole and zero, the increase in grain size may be related to the anomalous behavior previously observed in materials containing 0.02 gram atoms/mole (cf. First Technical Report).

### 3.3.3 Ceramics Prepared by Hot Pressing

Once the hydrostatic pressing-sintering technique was established as a route to thin, large-area plates, the hot pressing technique was investigated as a possible route to ceramics with improved characteristics. This work was motivated in part by the early observations of increased density in hot pressed ceramics. The early problem of reaction between the ceramic and the carbon die was eliminated by surrounding the sample with platinum, which was in turn separated from the graphite with $Al_2O_3$ spacers. The samples prepared by hot pressing were 1-1/8 inch in diameter and 1/2 inch high. Discs 0.030 inch thick were cut from these for evaluation. The composition $Pb(Zr_{0.54}Ti_{0.46})O_3$ was used.

The marked effect of the hot pressing conditions on the piezoelectric properties is shown in Table III. A pressed-sintered sample is included for comparison. Of particular importance is the fact that it is possible to achieve higher coupling coefficients by hot pressing. The results show that an increase in hot pressing temperature and pressure results in increases in the coupling coefficient, $g_{31}$ and density. The fact that hot pressed samples show a simultaneous increase in both dielectric constant and coupling coefficient over pressed-sintered samples indicates that the hot pressed materials should lead to displays of higher brightness. Of equal significance is the

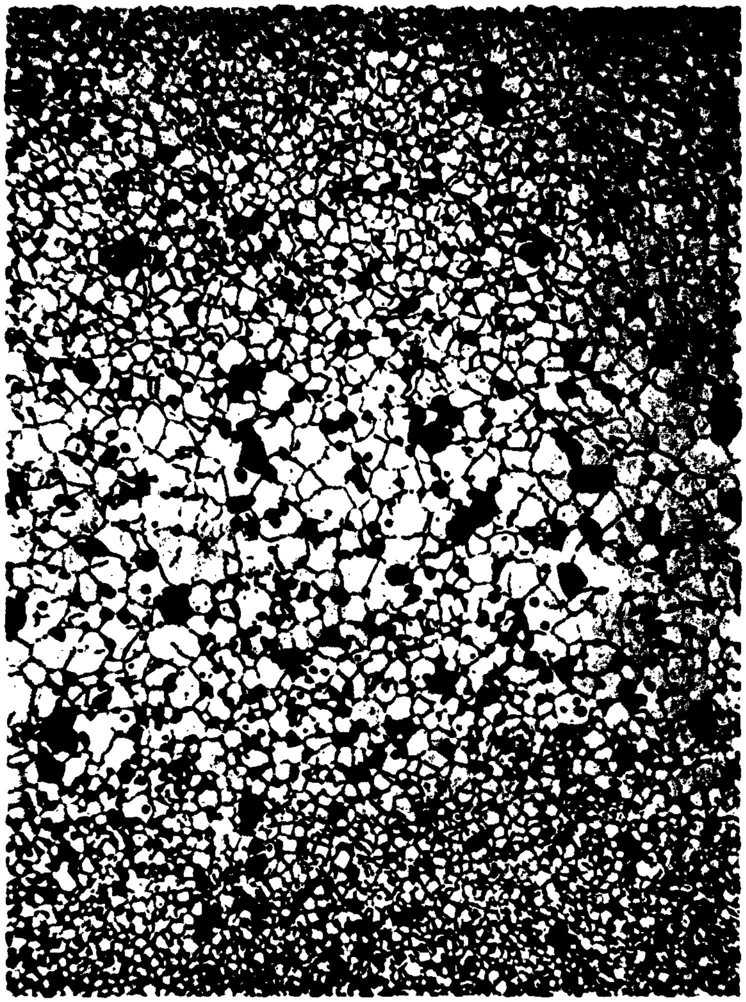



Fig. 15. Photomicrograph of boundary region in composite transducer-display substrate plate. (200X)

TABLE III

Comparison of Hot Pressed and Press-Sintered Ceramics

| Hot Pressing Condition | | | | | | | Density | |
|---|---|---|---|---|---|---|---|---|
| Temp ($^{o}$C) | Pressure (psi) | Time (min) | Dielectric Constant | Coupling Coefficient | $g_{31} \times 10^3$ | Avg. grain size | g cm$^{-3}$ | % Theor. |
| 1175 | 2200 | 6 | 647 | 0.417 | 10.9 | 3 | 7.81 | 97.6 |
| 1225 | 2500 | 6 | 649 | .486 | 12.9 | 5 | 7.82 | 97.6 |
| 1260 | 2500 | 6 | 571 | .519 | 14.4 | 7 | 7.91 | 99.4 |
| Pressed-Sintered 1300$^{o}$C | | | 477 | .468 | 15.1 | 10 | 7.49 | 93.9 |

higher density, which is expected to lead to a marked decrease in propagation losses. The plot of coupling coefficient vs density in Fig. 16 for a larger number of hot pressed samples shows a favorable trend of increasing coupling coefficient with increasing density. The highest values are favored by high values of both temperature and pressure.

The high dielectric constants obtained by hot pressing should be especially favorable for transducer materials, since $d_{31}$ is an increasing function of the dielectric constant. In this connection it has been observed that the highest values of the dielectric constant (>800) in $Pb(Zr_{0.54}Ti_{0.46})O_3$ have been obtained by annealing samples originally hot pressed at 1175$^{o}$C and 2200 psi. The coupling coefficient was also increased to 0.504.

Photomicrographs of two hot pressed samples are shown in Fig. 17. These may be compared with Fig. 13, which shows a pressed-sintered sample.

## 4. CONCLUSIONS AND RECOMMENDATIONS

The study of EL-NLR structures and their performance in conjunction with piezoelectric ceramic plates has shown that at the present time the EL layer is the least satisfactory component. In particular, the behavior of the EL layer as a nonlinear resistor at high voltage has a limiting effect on

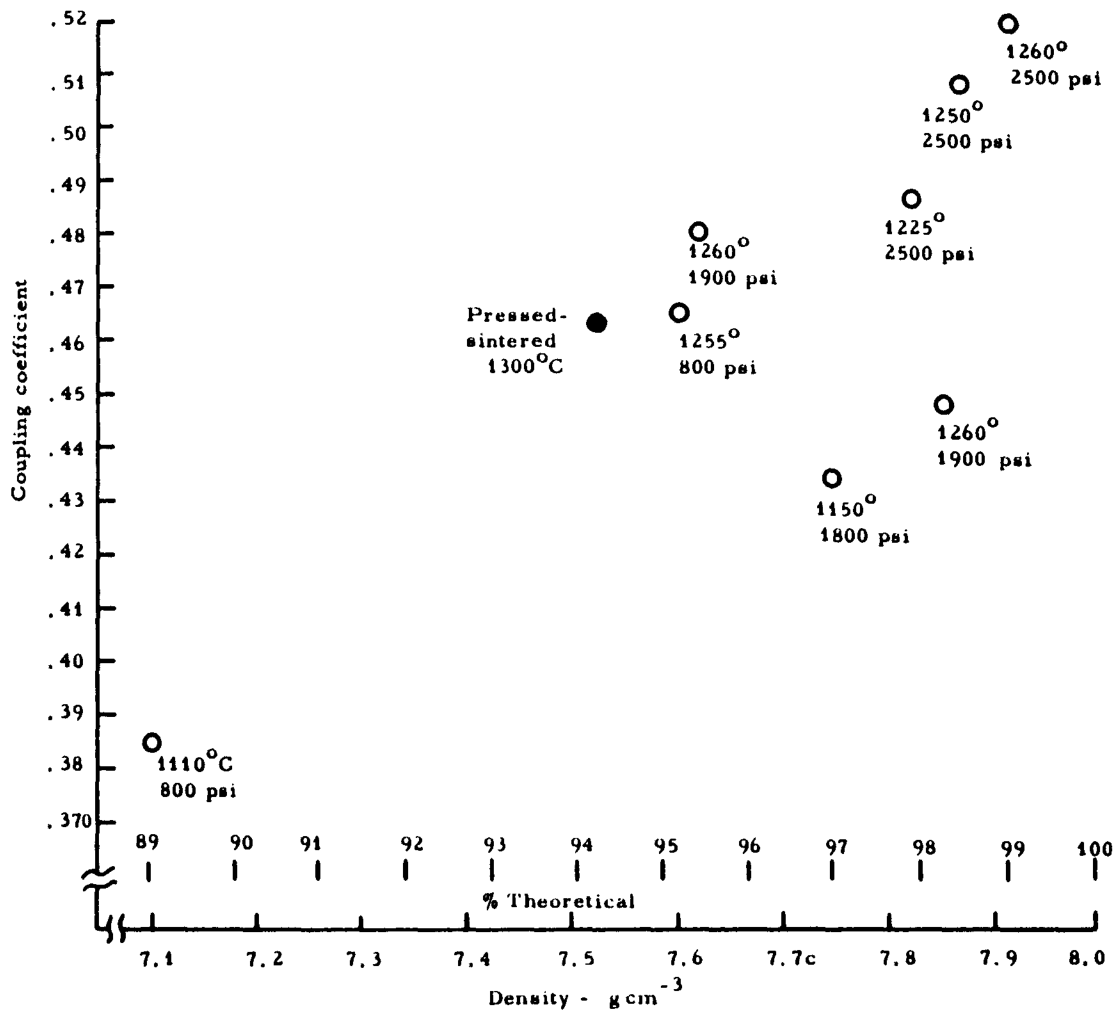
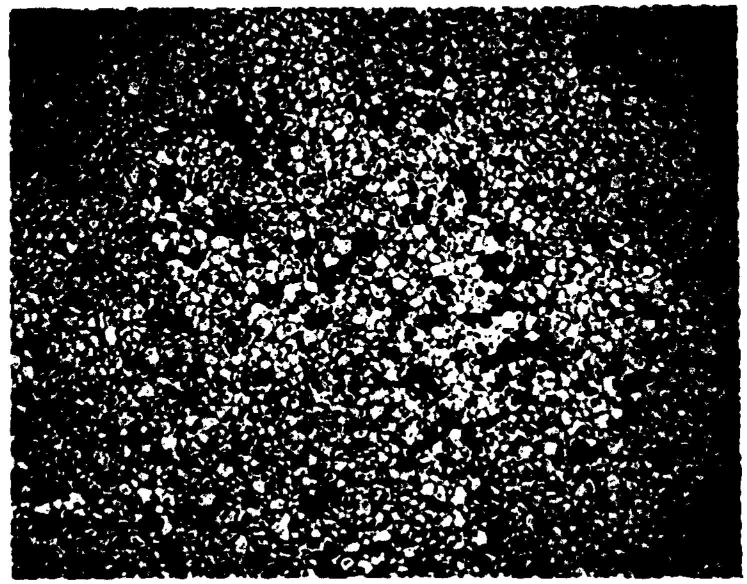
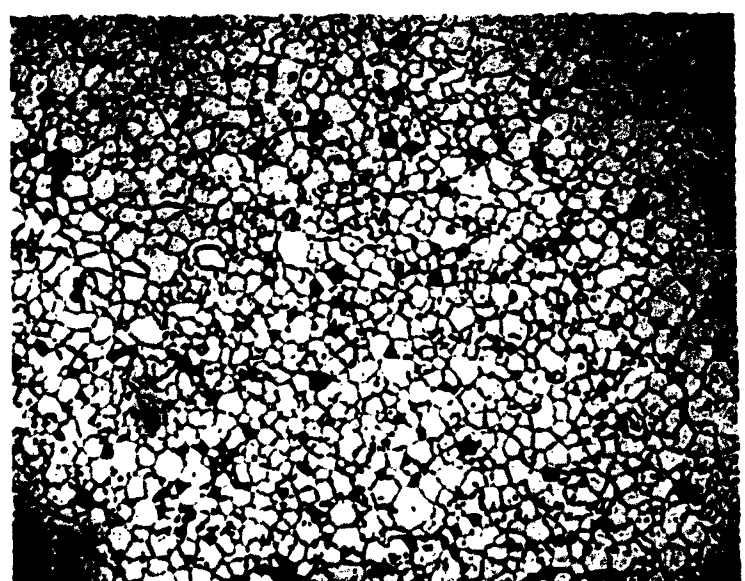



Fig. 16. Hot pressed lead titanate-zirconate relationship between coupling coefficient and density.



Hot pressed 1175°C  2200 psi  6 minutes
Avg. grain size 3μ  97.9% density  750X



Hot pressed 1260°C  2500 psi  6 minutes
Avg. grain size 7μ  99.4% density  750X

Fig. 17. Photomicrographs of hot pressed piezoelectric ceramics.

the display brightness and contrast, and contributes to the broadening of the trace. Several approaches are available for improving the EL performance, namely, the choice of phosphor, the choice of embedment medium and the application of protective coatings to the phosphor particles before embedment. Experience with the manganese-doped ZnS phosphors shows that the loss component can be reduced significantly.

Only a rough estimate can be made of the increase in brightness to be expected once the loss component of the EL layer is reduced. The maximum improvement in spot brightness is estimated to be one order of magnitude. If the improved EL layer characteristics also reduce the trace width from the observed 0.14 inch to the calculated 0.080 inch, the number of excited spots required to produce the lissajous pattern of Fig. 9 will be increased by the factor 1.75 (=0.14/0.080); the repetition rate and therefore the brightness of each spot will be reduced by the same factor. The net effect would be an increase in trace brightness from 0.3 foot lambert to a value near one foot lambert for the 2-1/2 x 2-1/2 inch display. Larger and more complex images, which require the excitation of more spots, will be of correspondingly lower brightness. For example, an increase in image complexity will increase the number of spots by a factor of approximately four; increasing the linear size of the display two fold will contribute another factor of two. Therefore the brightness of a more complex image with a 0.080-inch trace width on a 5-in. x 5-in. panel will be of the order of 0.1 foot lambert.

The remaining sources of possible improvement in display brightness are the NLR layer and the piezoelectric ceramic. The characteristics of the NLR layers discussed in this report are essentially the same as those reported in the preceding one. The extent to which they may be improved has not yet been determined. While it is true that a significant fraction of the ceramic output voltage must appear across the NLR layer to obtain background suppression, this fraction can be reduced if a steeper brightness-voltage characteristic can be achieved in the EL layer alone.

The hot pressed ceramics should contribute to both improved brightness and resolution if their higher density leads to the expected decrease in pulse attenuation and broadening. However, the system will still be limited by the power dissipation that the ceramic can withstand without depolarization.

With regard to display contrast, or background suppression, the degrading influence of the EL layer conductivity has already been discussed. Also discussed was the fact that the ratio of output voltages from the ceramic for the intersection of four and two elastic waves is less than two because of the considerable internal impedance of the ceramic. The latter situation may ultimately be improved when hot pressed ceramics of higher dielectric constant without reduction in $g_{31}$ become available.

Another approach to ceramics of lower internal impedance is through the use of thinner plates. This is also the indicated approach to displays of higher resolution. The usefulness of thinner ceramic plates will depend either upon the ability to drive them at a higher field strength than is now being used in the thicker plates, or upon the development of EL layers that can be excited with lower voltages. The lower limit of ceramic thickness is likely to be near 0.010 inch for reasons of mechanical strength. This implies an ultimate trace width of 0.041 inch if presently available materials are used, with the possibility of still lower values available through the use of hot pressed materials.

The characteristics of the solid-state display device in its present form are as follows:

| | |
|---|---|
| Trace brightness: | 0.3 foot lambert for elliptical lissajous figure. |
| Trace width: | 0.14 in. |
| Display Area: | 2-1/2 in. x 2-1/2 in. |
| Contrast ratio: | > 100 |
| Power input: | 45 watts |

The capabilities of the device with respect to brightness, resolution and contrast which have been projected here stem from consideration of the capabilities of the individual components and of the mode of operation of the device. Although the performance may be improved by about one order of magnitude as the materials and techniques are improved, the major limitation is the manner in which energy is supplied to the ceramic plate and extracted from it at only one point during each input cycle. Consideration is now being given to other modes of random access which can lead to another order of magnitude increase in brightness or efficiency.

It is recommended that the investigation of the solid-state display device be continued along the lines of phosphor and piezoelectric ceramic improvement. An investigation of more efficient modes of access should be undertaken. The goal of this extended effort will be a 5-in. x 5-in. oscilloscope display of at least 100-line resolution, capable of displaying complex oscilloscope patterns with a brightness of the order of one foot lambert and contrast ratio of 100.

Once the above goal has been reached, consideration should then be given to obtaining a significant increase in brightness. The approach would be through an entirely different mode of operation whereby the piezoelectric plate is used as the means of access to the points on the display, but not as the source of power. In this case the output pulse from the plate will be used to activate an EL layer which in turn activates a light amplifier, or will directly gate power from a separate source to the display. This approach also permits the introduction of element storage as a further means of increasing brightness.

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