Demonstration of Gray Scale in Electroclinic Liquid Crystals

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ABSTRACT

Liquid crystal (LC) materials possessing the chiral smectic A (Sm A) phase have been designed to yield high induced tilt angles and low response times. The primary objective of our work is to design materials that can provide the optimum tilt angle of 22.5° for applied voltages less than 5V/μm, making them CMOS compatible. Optical response measurements to illustrate the feasibility of obtaining 256 gray levels are presented. The gray scale capability of the material is visually demonstrated using a 1X64 array driven by a dc balanced circuit.

Keywords: electroclinic effect, chiral smectic A, electrooptic effects, gray scale applications, high resolution displays.

1. INTRODUCTION

In 1977 Garoff and Meyer first demonstrated the electroclinic effect in chiral smectic A (Sm A).[1] Since that discovery, efforts have been made to design materials with large induced tilt angles and fast response times for electrooptic applications. The possibility of achieving full gray scale capability coupled with fast response times[2-10] has made the electroclinic liquid crystal (ELC) an excellent choice for analog applications.[11-14] Interest in the ELC is rapidly expanding due to the development of spatial light modulators for optical data processors, projection displays, real time holography, smart pixel image processors, etc., where speed, high contrast and analog gray scale capability are essential. Recent studies have concentrated on the development of such materials but have not met the stringent requirements dictated by the display technology, which require Sm A materials to have large induced tilt angles at low applied voltages and field independent response times over a broad temperature range.

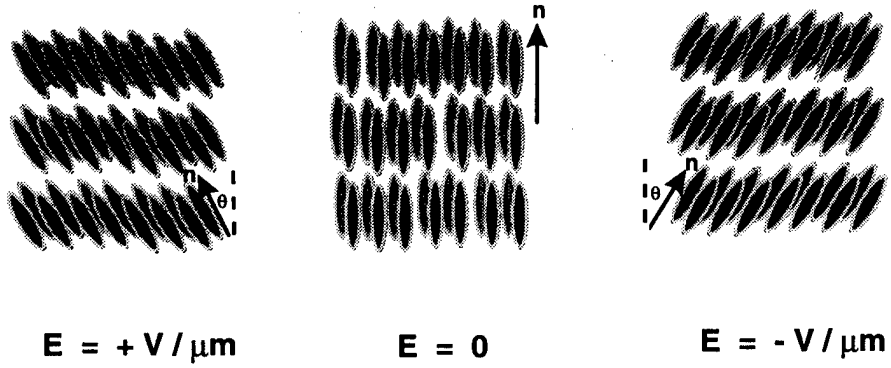

Figure 1: Schematic representation of chiral Sm A phase liquid crystal.

The tilting of the molecules with respect to the layer normal occurs in chiral Sm A, via the electroclinic effect, on the application of an electric field in the plane of the smectic layer (see Figure 1). The chiral smectic C (Sm C*) has been studied extensively in the surface stabilized ferroelectric LC (SSFLC) mode, where the LC is bistable.[15] In this case gray scale is obtained by spatial or temporal

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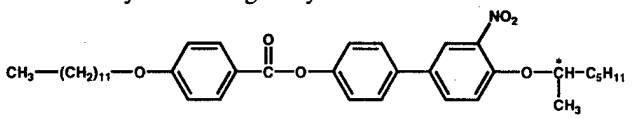
dithering with a concomitant loss in either resolution or speed, respectively. On the other hand, the electroclinic Sm A LC can be used in an analog device by continuously varying the induced tilt angle via an applied electric field. The development of materials that switch rapidly as well as possess large electroclinic coefficients is crucial to the advancement of high resolution display technology.

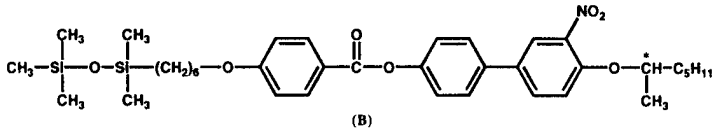
2. MATERIAL DEVELOPMENT

The materials synthesized at NRL show induced tilt angle values of 10° to 30° and fast response times in the 10-200μs range.[5,9,10] The tilt angle and response time for the ELC material are obtained using optical polarizing microscope with a photodiode to measure the amount of light transmitted through the sample. The tilt angle is measured by applying a known voltage in the form of a bipolar 100 Hz square wave across a commercially manufactured (EHC Ltd.) 2 μm cell filled with ELC material. The exact thickness of the cell is determined to be 2.0 ± 0.1μm, using Displaytech's Automated Polarizing Testbed (APT). The temperature of the sample is maintained by an Instec temperature controller connected to a circulating water bath to aid temperature regulation to ±0.01°C. The tilt angle measurement is accurate to ±0.1 degree and the applied voltage is accurate to ±0.05 volts. The angle (2θ) is determined by rotating the sample stage between crossed polarizers to determine the two minima corresponding to the V^+ and V^- states, as shown in Figure 1. The 10-90% response time between θ^+ and θ^- is measured on a 500 MHz Hewlett Packard oscilloscope after averaging over 256 cycles.

We have synthesized a series of materials[5,9,10] to achieve our goals of high induced tilt angle and low response times. One of the molecules that has been studied viz., KN125 is shown in Figure 2(A). The planar aligned ELC sample of KN125 shows a regular striped pattern when viewed between crossed polarizers.[16] The presence of the striped pattern in an ELC has been well established[17,18] and is a plaguing problem for device applications, since it affects the contrast ratio. We have shown from x-ray diffraction studies that the KN125 molecules tilt as a rigid rod upon the application of an electric field.[17] This tilt results in the buckling of the smectic layers, which is visually apparent as a striped texture. Consequently, development of materials in which the stripe behavior is inhibited is necessary for the advancement of ELC display technology. One approach to reduce the layer buckling is to design molecules which allow for the chain to reorient independent of the core such that the decrease in the layer spacing on the application of an electric field is minimized (see Figure 3). Our efforts in this direction has led to the synthesis of siloxane based liquid crystals in which the alkyl chain on the non-chiral end of KN125 is partially replaced by flexible siloxy groups. Three examples of such materials in which the number of siloxy groups has been varied from one to three are given in Table 1. The stripe texture in all these materials is almost non-existent, leading us to hypothesize that the change in the layer spacing in these materials, on application of an electric field, is very small. We are currently conducting x-ray diffraction measurements to confirm this hypothesis.



(A)



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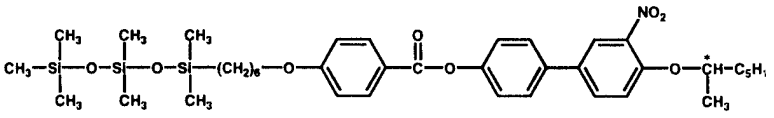

(C)

Figure 2: Structures of (A) KN125, (B) DSiKN65 and (C) TSiKN65.

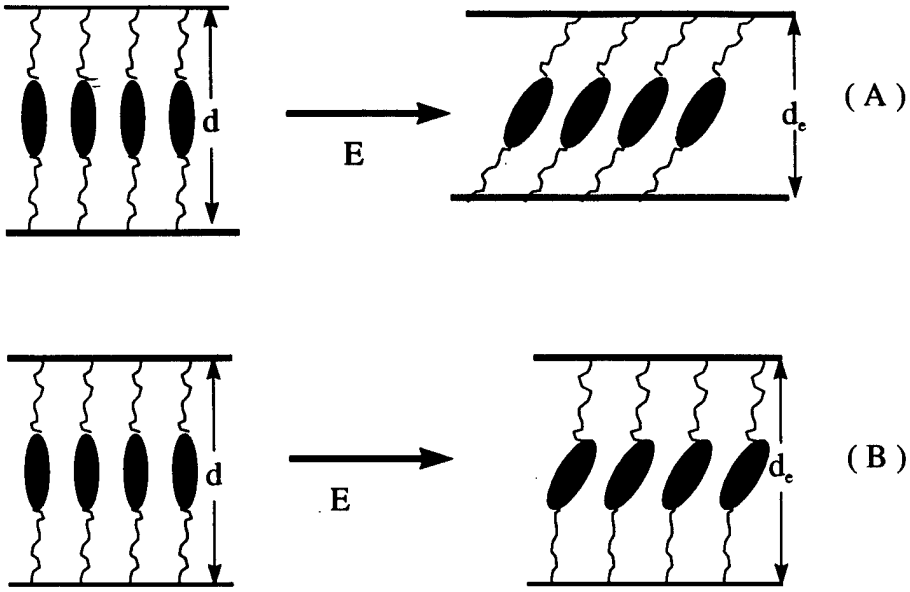

Figure 3: The effect of the electric field induced molecular tilt on the Smectic layer spacing (d). (A) Molecule tilts as a rigid rod resulting in $d_e < d$. (B) Core and chain tilt to different extents such that $d_e \approx d$.

The phase behavior of the materials presented here is shown in Table 1. The addition of siloxy groups induces a Smectic C^* phase and lowers the melting transition temperature to below -20°C, which is the limit of our Differential Scanning Calorimeter. Specifically, the addition of one siloxy group (SiKN65) results in the creation of a Sm C^* phase 3°C from the isotropic phase. The next step, therefore is to see the effect of adding more siloxy groups to this molecular design. The structures containing two and three siloxy groups are shown in Figure 2 (B) and (C) and are referred to as DSiKN65 and TSiKN65, respectively. The effect of the additional siloxy groups is two-fold: (i) the Sm A-Isotropic transition temperature increases slightly and (ii) the Sm A-Sm C* transition is suppressed. As a consequence of these two effects, the range of the Sm A phase increases to 19° and 32° for DSiKN65 and TSiKN65 respectively.

Table 1: Transition temperatures for materials under study.

Material	Phase Sequence						
KN125	Crystalline	30	---		Sm A	80	Isotropic
SiKN65	Crystalline	< -20	Sm C*	48	Sm A	51	Isotropic
DSiKN65	Crystalline	< -20	Sm C*	36	Sm A	55	Isotropic
TSiKN65	Crystalline	< -20	Sm C*	25	Sm A	57	Isotropic

The material properties of SiKN65 were not determined due to its small Sm A phase range. The electric field dependence of the induced tilt angle for the other three material is shown in Figure 4. The large induced tilt angles observed result from the presence of the sterically hindered nitro and methyl groups close to the chiral carbon atom which leads to a strong dipolar coupling with the applied electric field. The effect of adding the siloxy group to the basic molecular structure of KN125 results in an increase in the induced tilt angle via the electroclinic effect. In KN125, the induced tilt angle at 25°C is only 12.5°, but the addition of the siloxy group results in an increase of tilt angle to 21° in DSiKN65 and to 25.6°in TSiKN65 at 5V/μm. These measurements were performed at $T-T_{ac^*} = 2$ for the siloxy materials. The addition of the siloxy groups enhances the induced tilt angle and brings us closer to the goal of achieving the optimum tilt angle of 22.5° for applied voltages of less than 5V/μm.

The electric field dependence of the response time is presented in Figure 5. The increase in the response time as the field increases has been attributed to the presence of the Sm C^* phase at lower temperatures. However, the observation of a similar effect in KN125, which does not exhibit a Sm C^* phase, is not yet understood. The field dependence of the response time in DSiKN65 is almost negligible and the induced tilt angle is relatively large (close to the optimum value of 22.5°). Due to these attractive material properties, DSiKN65 is the prime component of the mixtures we are developing to produce high tilt angle materials with large Sm A ranges.

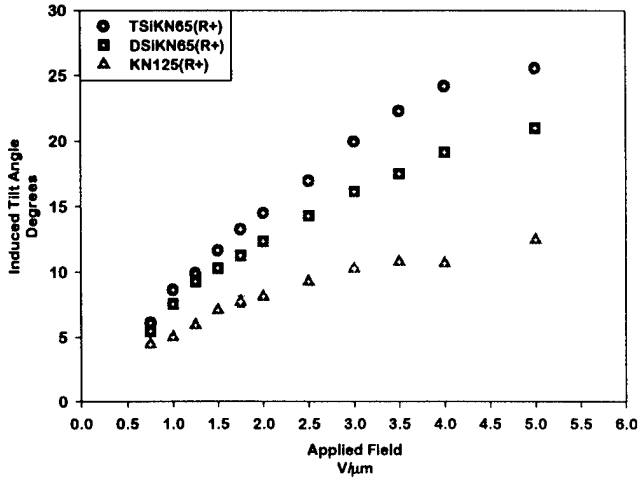

Figure 4: Induced tilt angles as a function of electric field for KN125, DSiKN65 and TSiKN65.

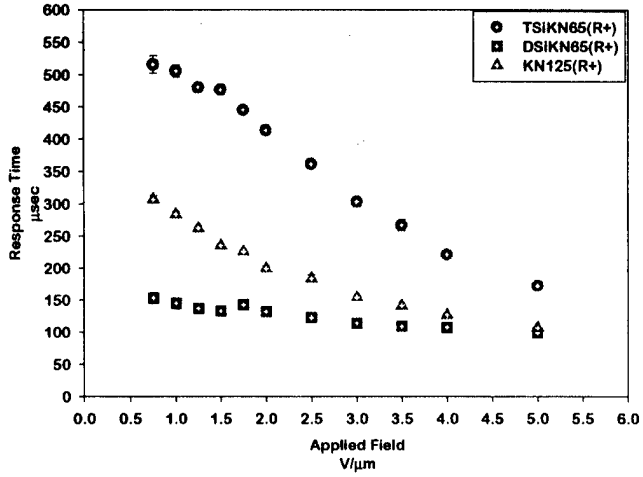

Figure 5: Response time as a function of electric field for KN125, DSiKN65 and TSiKN65.

3. DEVICE DEVELOPMENT

One of the most crucial tests of ELC for analog application is the ability to obtain accurate optical response for small changes in applied field. This is tested in our materials by observing the optical response to an applied triangular wave form. Figure 6 shows the optical response of a 2 μm thick ELC to a 64 step triangular wave form. The mimicking of the applied wave form by the electrooptic response of the ELC allows for a reasonable estimation of the possible gray levels. The additional evidence of response to small changes in applied field originates from the smooth intensity curve that results from the application of 256 different applied voltage levels as shown in Figure 7. This data clearly indicates the material has 256 possible gray levels at 25°C. The intensity vs. applied

electric field is recorded using a Helium-Neon laser with the optic axis of the ELC, in the absence of an electric field, being parallel to the polarizer. The contrast ratio measured at the highest applied field viz., 5V/μm is greater than 500, indicating the good quality of the alignment.

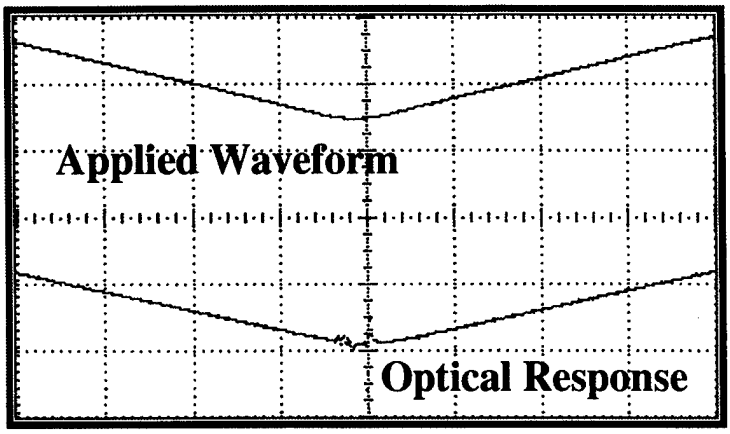

Figure 6: Linearity of optical response to an applied 64 step, 5V triangular wave form is shown for a 2 μm thick TSiKN65 sample.

Beyond the systematic experimental evidence of compatibility with the stated requirements for a display device, the construction of a device was necessary to demonstrate the functionality of our materials. We have developed a 1X64 array cell and a driving circuit to visually evaluate the gray levels and contrast ratio of our materials. The driving circuit is implemented by using commercially available integrated circuits and discrete components. To prevent the accumulation of charge in response to an applied dc field, the voltage across the cell is dc balanced. The optical response of the ELC is monotonic with the applied voltage as is observed in Figure 8. With zero field applied to each pixel, the cell is placed between crossed polarizers and is rotated until the intensity of transmitted light is a minimum. At this point the dark state is attained. The optical intensity is symmetric around the zero field resulting in the same gray level on each side of the zero point of the applied square wave that results in applying V_{LC} both positive and negative. The time constant of the optical response of the material is sufficiently fast so that a pixel can be switched between the V^+ and V^- imperceptibly over a single frame. Our next effort will be to demonstrate the high speed and color capability of our materials. We are currently developing a ½ VGA resolution reflective display using a CMOS based silicon backplane for this demonstration.

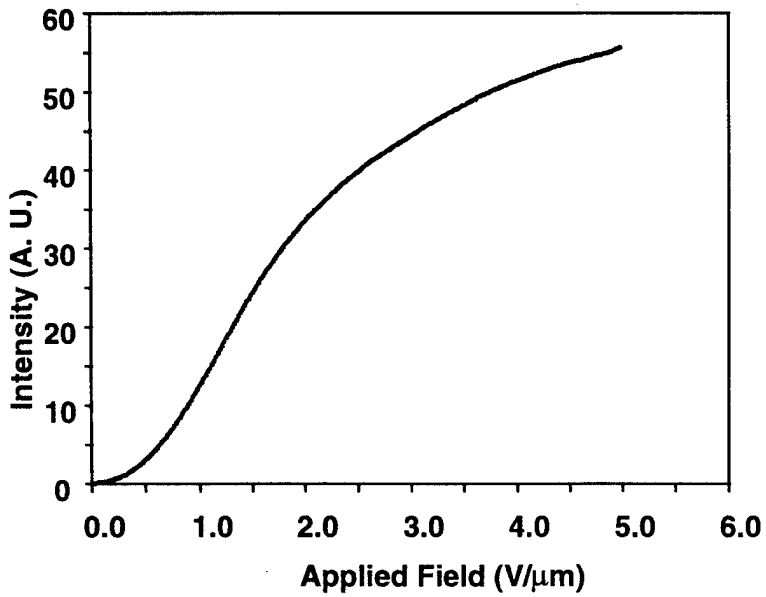

Figure 7: Continuous response of the transmitted light intensity to 256 steps of voltages between 0 and 5V/μm, indicating 256 possible gray levels in a 2 μm cell of TSiKN65 and measured at 27°C. The contrast ratio at 5V/μm is measured to be greater than 500.

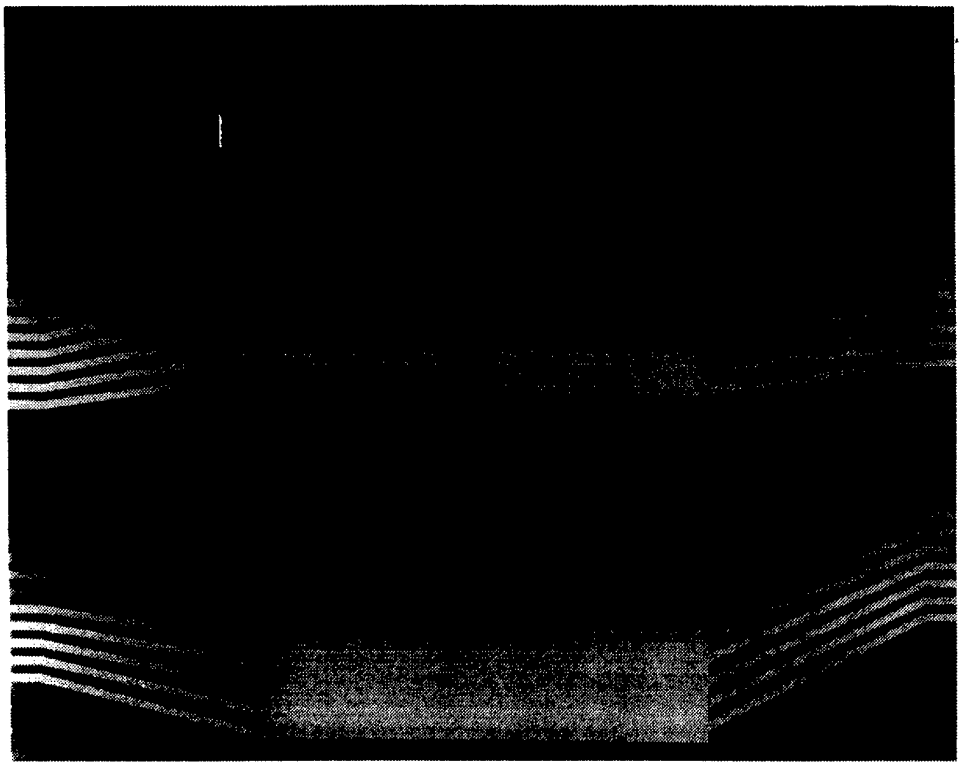

Figure 8: 1X64 pixel array showing 16 different gray levels in TSiKN65. The reproducibility of the 16 gray levels shows the continuity of the material alignment.

4. CONCLUSION

A comprehensive study of the applicability of ELC materials to display device technology is presented. The construction of a device as a demonstration tool for the gray scale capability of these materials provides additional evidence of the suitability of the under study to the development of analog display devices.

5. ACKNOWLEDGMENTS

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