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Nonlinear optics of nematic liquid crystals and characterization of a π twist nematic display

Gayathri Sundaresan
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of a π twist nematic display**

Sundaresan, Gayathri, M.S.

San Jose State University, 1991

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Ann Arbor, MI 48106**

**NONLINEAR OPTICS OF NEMATIC LIQUID CRYSTALS
AND
CHARACTERIZATION OF A π TWIST NEMATIC DISPLAY**

A Thesis

Presented to

The Faculty of the Department of Physics

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Gayathri Sundaresan

May, 1991

APPROVED FOR THE DEPARTMENT OF PHYSICS

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1. Jan. 22, 91

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Dr. Joseph F. Becker

APPROVED FOR THE UNIVERSITY

ABSTRACT

NONLINEAR OPTICS OF NEMATIC LIQUID CRYSTALS AND CHARACTERIZATION OF A π TWIST NEMATIC DISPLAY

by Gayathri Sundaresan

This thesis addresses two aspects of Liquid Crystals, their behavior as a nonlinear medium, as well as their application in a display device. The nonlinearity was observed through the optically induced Fréederickz transition in a 355 μm thick 6CB sample at a threshold intensity of 190 watts/cm^2 . The margin of error was 13%. We have conducted contrast and color measurements on a π cell as a function of viewing angle and azimuthal orientation. While the contrast was uniform at normal incidence, wide variations were observed for off axis incidence. The coupled mode theory was applied to explain light propagation through the π cell. At normal incidence, the dominant transmitted wavelength for the cell was found to be 555 ± 6 nm in the off state and 602 ± 0.1 nm in the on state, relative to the source employed. No significant changes were observed at off axis positions of up to 20° .

ACKNOWLEDGEMENTS

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I. INTRODUCTION

Liquid crystals occupy a special place in the classification of matter. It is well known that matter exists in one of three forms, viz., solid, liquid or gas. This is not entirely true; particularly, certain organic materials do not show a single transition from solid to liquid, but rather, exhibit a cascade of transitions involving new phases.¹ The mechanical and symmetry properties of these phases are intermediate between those of a pure solid and an isotropic liquid. For these reasons, they are referred to as "*Liquid crystals*." This singular behavior of liquid crystals (also referred to as "mesomorphic phases") is of immense interest in furthering knowledge on ordering and phase transitions.²

Liquid crystals are broadly classified as lyotropic or thermotropic, depending on the principal way in which the parent solid state is altered. In lyotropic materials, this is achieved by the action of a solvent on a solid, while thermotropic substances form over specific temperature ranges. Molecular shape also plays an important role in determining liquid crystal phases.³ Depending on their shape, they are classified as spherical, rod-like, disc-shaped, bowlic, etc.

Rod shaped thermotropic liquid crystals are further classified as:

* *nematic*, in which the molecules align preferentially in one direction. In this phase, they are positionally disordered, but orientationally ordered. Above the transition temperature the molecules undergo a phase change to that of an isotropic liquid.

* *smectic*, in which the molecules exhibit a higher degree of ordering, by preferential alignment occurring in planes with well defined spacing.

* *cholesteric*, in which the alignment in individual planes also follows a twist with respect to adjacent planes. These three types are illustrated in Figure I.1 at the end of this chapter.

Liquid crystals have been an active subject of research since the late 1800s. Although they exhibit certain aspects of both solids and liquids, liquid crystals also possess certain unique properties that are not those of the two pure states. For example, the orientational properties can be manipulated by magnetic and electric fields. Some of them have optical properties of enormous magnitude, not easily found in any solid, liquid or gas. Additionally, some of them change the color of polarized light transmitted through them as a result of their molecular orientation. All of these properties show extensive potential for device development.

Early research on liquid crystals (LCs), was focussed on the isotropic phase of nematogens^{4,5} - compounds that give rise to the nematic type of mesophase.

However, due to the strong correlation between individual molecules, the optical properties of Lcs in the *mesophases* are vastly different, giving rise to extremely large nonlinearities. This fact has been well established in a number of experiments referred to in the following pages.

The experiments detailed and discussed in the following chapters are the first of their kind to be conducted at San Jose State University. The first of these experiments, on the nonlinear response of nematic liquid crystals, involves basic physics of molecular reorientation under the influence of optical fields. The second experiment, on the other hand, involves a major application of liquid crystals, that of display technology.

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Figure I.1

II. NONLINEAR OPTICS OF NEMATICS

II.A. Introduction

Nonlinear optical effects arise from the interaction of electromagnetic radiation with a medium in which the medium offers a nonlinear response to the incident field. Expanding the induced polarization $\mathbf{P}$ as a power series in terms of the incident electric field, $\vec{E}$, and the dielectric tensor $\chi^{(x)}$ of rank x , viz.,

$$\mathbf{P} = \epsilon_0 \chi^{(1)} \vec{E} + \epsilon_0 \chi^{(2)} \vec{E} \cdot \vec{E} + \epsilon_0 \chi^{(3)} \vec{E} \cdot \vec{E} \cdot \vec{E} + \dots$$

we see that the first term of the series corresponds to the induced linear polarization, giving rise to linear optical effects such as refraction, absorption, etc. The other terms of the series represent the nonlinear polarization induced in the medium, classified as second or third order, respectively, according to their dependence on the electric field. While second order effects are seen only in media that lack a center of symmetry, third order effects are seen in all media.

The nonlinearly induced polarization can manifest itself as an intensity-dependent refractive index change, thereby greatly influencing the propagation characteristics of the incident beam. It is thus desirable to work with materials that have a very large nonlinear response. Several such materials have been observed, which exhibit changes

in refractive index at very large intensities.^{9,21} Among liquids, the mesophases of liquid crystals are especially attractive since it is possible to create large changes in their refractive index with cw laser beams of modest intensities.⁶

Liquid crystals exhibit such a large nonlinear response due to their strong molecular anisotropy and correlation in molecular motion under the influence of optical fields.¹⁷ In experiments, the nonlinearity is effected by reorientation of their molecular alignment. Many interesting phenomena have been observed,^{14,19} of which the propagation of a gaussian beam through a nematic cell itself offers a rich field of study.²⁰ Liquid crystals generally exhibit nonlinear effects of the third order.

II.A.1. Fréederickz Transition³

Molecular reorientation of the sample occurs above a certain threshold intensity of the incident light beam, giving rise to changes in refractive index and, thus, birefringence of the material. This is referred to as the optical field induced "Fréederickz transition." In general, Lcs are used with prescribed orientation of the molecules, usually accomplished by substrate surfaces. At threshold, the torque due to the electric field of the light beam competes with the torques due to the elastic forces dictated by the surface treatment in influencing the reorientation. For materials with positive dielectric anisotropy, the molecules reorient themselves along the direction of the incident electric field. The intensity threshold depends on material

parameters such as elastic constants, dielectric anisotropy, thickness of the sample cell and also on experimental parameters such as the size of the laser spot on the sample and the temperature of the experimental environment.

As mentioned earlier, molecular reorientation manifests itself in terms of birefringence of the material, thus providing very interesting modulation of the propagating light beam. Fréederickz threshold transition induced by optical fields has been very successfully observed in the nematic phase of liquid crystals and has given rise to such fascinating experiments as optical transistor action,¹⁴ transverse bistability,¹⁶ and spatial self-phase modulation.⁴

II.B. Objectives

The aim of this experiment was to construct a uniformly aligned homeotropic nematic film and to observe and study the optical field induced Fréederickz transition in the same. The induced refractive index change was observed in the case of spatial self-phase modulation, where the propagating laser beam emerged from the sample as a set of conical shells, observed as diffraction rings on a screen.

II.C. Sample preparation

Two kinds of nematic alignment are frequently encountered:

- * *Homogeneous*, in which the molecules lie parallel to the substrate and,
- * *Homeotropic*, in which the molecules lie perpendicular to the substrate.

The experimental cell consisted of two glass plates between which the sample was sandwiched. The plates were treated for homeotropic alignment of the nematic molecules.

Sample preparation was done in the following steps:

- * Cleaning of the glass plates,
- * Treating the glass plates for homeotropic alignment,
- * Filling with nematic compound and sealing.

The glass plates were initially cleaned with a soap solution. They were then placed in a magnetically stirred acid bath made up of 140 cc distilled water, 1 cc concentrated sulfuric acid and approximately 0.6 gms of NOCHROMIX, (a glass cleaning agent). Each of the glass plates was cleaned in this fashion in an ultrasonic cleaner (for a period of 2 minutes) in order to remove any trace of oil deposits and rinsed twice in distilled water. They were then dried in a continuous stream of nitrogen.

Surface anchoring of the molecules was effected by the choice of DMOAP¹ (N,N-dimethyl-N-octadecyl-3-aminopropyltrimethoxysilyl chloride), a silane compound favoring homeotropic alignment. This was done by soaking the glass plates in a magnetically stirred mixture consisting of 50 cc distilled water, 1.5 cc acetic acid and 1 cc DMOAP for approximately 15 minutes. After this, the plates were removed, rinsed gently with distilled water and dried in nitrogen. The plates were placed in a preheated oven at 105°C and baked for 1½ hours. The treated plates were then stacked together with 355 µm thick mylar spacers in between them and partially sealed using an epoxy glue.

The sample, K18, a 4-cyano, 4'-hexyl, biphenyl (6CB) compound, was then drawn out into a syringe, heated into its isotropic phase and slowly introduced in between the sandwiched plates, the plates tilted to facilitate easy flow of the nematic sample. On cooling, the remaining sides of the cell were sealed using the same glue.

Alignment was verified using the method of conoscopy, viz., looking at the transmission of a He-Ne laser through the cell placed between two polarizers. Uniform brightness and darkness on rotation of the analyzer confirmed uniform alignment. The cell showed very little absorption at visible wavelengths longer than 500 nm, as shown in Figure II.1.

II.D. Experimental Setup

A schematic of the experimental setup is given in Figure II.2. Light from a cw Argon Ion laser operating at 514.5 nm was sent through two polarizers. The first polarizer controlled the intensity incident on the sample while the second polarizer was used to provide the needed linear polarization of the beam. The laser light was focussed by an uncoated lens with a focal length of 50 cms, giving a e^{-2} spot diameter of 280 μm (along the horizontal plane) on the sample. The transverse profile of the laser output was elliptical, with an eccentricity of 0.73. The cell was held at normal incidence in a steady stream of air, to avoid any hot spots on the sample. The direction of propagation of the laser beam was along the homeotropic alignment of the molecules. The laser was operated under light regulation, i.e., the output power was maintained as a constant. A screen was placed 55.5 cms from the cell to facilitate the observation of the diffraction rings. The experiment was done at room temperature, 24.1°C (4.9°C less than T_{NI} , the nematic to isotropic transition temperature of the sample).

II.E. Data acquisition and analysis

II.E.1. Calibration of polarizers

Initially, the transmitted intensity through the polarizers was calibrated. This was done by application of Malus' law to the transmission of the laser light through the two polarizers. For this, the transmitted intensity was noted at various angles between parallel and crossed configurations of the polarizers. Data was taken without the lens at the position of the sample. The data and theoretical curves obtained during a typical run are given in Figure II.3. Data was fit to a straight line using linear regression and this was used to arrive at the intensity values later.

II.E.2. Data acquisition

The calibration was followed by actual data acquisition. The experimental cell was placed in position, beyond the lens. The second polarizer was adjusted so that the incident beam was linearly polarized in the vertical direction. Starting from crossed configuration of the polarizers, the first polarizer was rotated by 1° at a time and the screen was visually inspected for signs of reorientation, the pattern expected being well documented in literature.⁵

At a particular position of the first polarizer, the beam emerging from the cell gave rise to a distinct diffraction pattern that took a couple of minutes to stabilize.

Stabilization was faster at higher intensities. Data consisting of the number of rings and the diameter of the outer ring was taken as a function of orientation of the front polarizer and the polarizer rotated by another degree for the next set of data. At each of these positions, data was taken after the pattern stabilized. This procedure continued until distortion set in, at very high intensities. The spot diameters along two orthogonal directions were measured at the position of the sample cell using an electronic scanning instrument, *BEAMSCAN*, made by Photon Inc. A second calibration of the polarizers was done in order to average the data obtained.

II.E.3. Data analysis

Results from the two calibrations were used to arrive at the transmitted intensity values at various positions of the polarizers, in terms of watts. The area of the spot incident on the sample was approximated to that of an ellipse, since the beam profile was elliptical. From the information above, we arrived at the intensity of light incident on the sample.

Data is presented in the form of a plot showing the evolution of rings, as illustrated in Figure II.4, using the results of the final calibration.

Figure II.5 shows the increase in the half angle of the outermost ring as a function of incident intensity. Both plots qualitatively follow earlier results.⁴

II.F. Results and discussion

From the measurements and analysis described above, we calculated the average threshold intensity as 190 watts/cm². Corrections were made to the intensity values to account for an overall 16% loss at the lens and front glass plate to arrive at the above figure for threshold intensity. The associated experimental error margin was 13%. The evolution of the diffraction rings has been attributed to a case of spatial self-phase modulation of the laser beam within the sample.^{4,6} Following threshold conditions, the electric field of the laser beam reorients the director leading to a change in the local refractive index $\Delta n(\rho, z)$, where ρ is the transverse position vector in the beam. For a given incident gaussian beam, the phase retardation $\Delta \Psi$ between extraordinary and ordinary beams assumes a gaussian variation in the sample, given by

$$\Delta \Psi(\rho) = \Delta \Psi_0 \exp(-2\rho^2/a^2),$$

where a is a constant. As illustrated in Figure II.6, for every point ρ_1 on the $\Delta \Psi(\rho)$ curve, there exists another point ρ_2 having the same slope.⁴ Since the slope represents the rate of change of phase across the sample plane, it is proportional to the transverse component of the wave vector $k_\perp$, viz.,

$$\frac{d\Delta \Psi(\rho)}{d\rho} = k_\perp$$

Thus, radiation from the regions around ρ_1 and ρ_2 have the same wave vector, and interfere. Maximum constructive or destructive interference takes place when

$$\Delta\Psi(\rho_1) - \Delta\Psi(\rho_2) = m\pi, \text{ (m = even or odd integer)}$$

giving rise to the diffraction ring pattern. Multiple rings are expected if $\Delta\Psi_0 \gg 2\pi$.

Hence, for increasing intensities beyond threshold, the induced phase retardation also increases, showing more rings in the diffraction pattern. The outermost ring arises from radiation around a region ρ , the inflection point on the $\Delta\Psi(\rho)$ curve, and the half cone angle β_m is given by

$$\beta_m = \frac{[d\Delta\Psi(\rho)/d\rho]_{\max}}{2\pi/\lambda}$$

increasing with higher incident intensities beyond threshold.

The threshold intensity I_{th} itself is calculated by minimization of the free energy of the system,⁴ leading to

$$I_{th} = \frac{c K_{33} \epsilon_1 \pi^2}{n_o \Delta \epsilon d^2} \text{ where}$$

c = speed of light in vacuum,

K_{33} = bend elastic constant,

ϵ_1 = dielectric constant corresponding to extraordinary refractive index,

n_o = ordinary refractive index,

d = thickness of the sample cell.

Using appropriate values, viz., $K_{33} = 0.85 \times 10^{-6}$ dynes, $n_o = 1.54$, $n_e = 1.732$, the predicted value is found to be 61.8 watts/cm², much lower than the observed value. The above derivation assumes the incident field to be an infinite plane wave along with the approximation of geometrical optics. By using a self-consistent geometrical optics approximation and making corrections for the exact constant of the electromagnetic energy density given by Ong,¹⁰ we arrive at a threshold intensity which is only slightly higher, being 78.2 watts/cm².

The size of the converging laser spot plays an important role in defining the threshold behavior.¹⁵ This is because molecules outside the laser beam exert torque on those in the central region of the beam, either in competition, or conjunction with the torque exerted by the surface treatment. Typical examples are also available,^{4,11} which illustrate the variation of threshold intensity¹⁵ with spot size of the incident beam (Figure II.8).

A very important parameter that was not controlled in our experiment was the temperature of the sample. Temperature also influences the threshold intensity through the variation of birefringence²² of a liquid crystal material with temperature, as depicted in Figure II.7.

Thus, a wide variation in experimental results is observed in the literature, due to differences in material parameters, temperature, thickness of sample and incident spot sizes, making comparison of data very difficult. A summary of various results with available parameters is given in Table II.1.

To summarize, the observed threshold intensity was 190 watts/cm² for a 355 μm thick 6CB sample, at approximately 24.1°C, at an average spot diameter of 236 μm .

II.G. Conclusions

We have successfully fabricated a nematic liquid crystal cell with homeotropic alignment and used it as a medium to conduct an experiment in nonlinear optics. We have observed the Fréederickz transition, through the phenomenon of spatial self-phase modulation. Our results qualitatively follow the results of earlier experiments. We have observed the threshold intensity for a $355\text{ }\mu\text{m}$ thick sample to be 190 watts/cm^2 .

Table II.1 shows the results of similar experiments conducted on different liquid crystalline materials, as well as that of ours. It should be noted that the elastic constants of the materials listed are not vastly different from each other. However, the threshold intensity takes on a broad range of values depending on the thickness of the sample and the size of the laser spot on the sample. Therefore, further study is needed to ascertain the dependence of the threshold intensity with laser spot size, which may, in turn, lead to better agreement with theoretical predictions.

Since the threshold intensity varies as $1/d^2$, it would be a further check to conduct similar experiments on cells of different thicknesses.

The cells used in this experiment were done with plain glass. It would be interesting to make the cells using conducting glass, such as glass coated with Indium Tin Oxide. The reorientation could then be controlled with two fields,²⁰ namely the optical and electric field applied to the conducting glass. This would lead to either enhancement or suppression of the diffraction pattern.

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II. Figure captions

- II.1. Absorption spectrum of the sample cell.
- II.2. Schematic of the experimental setup for nonlinear optics.
- II.3. Calibration curves of the polarizers. The asterisk corresponds to data obtained while the line denotes the theoretical curve.
- II.4. Dependence of the number of rings on intensity.
- II.5. Dependence of the half angle of outer ring on intensity.
- II.6. Schematic profile of induced phase retardation.
- II.7. Variation of birefringence of K15, a liquid crystal material, as a function of temperature. n_o , n_e represent the ordinary and extraordinary refractive indices respectively. I represents the refractive index of the isotropic phase.
- II.8. Variation in Threshold intensity with respect to the ratio ω_0/d . Results shown are predicted and observed curves for a $100\mu\text{m}$ E46 sample. d is the thickness of the cell, ω_0 is the incident laser waist.

II. List of tables

- II.1 Comparison of various experimental results.

II. List of equipment and materials

Laser: Coherent INNOVA 90 ion series Argon⁺(extended).

First polarizer: Newport Broadband polarization beamsplitter, Model 10FC16PB.3

Second polarizer: Specifications not available.

Lens: KPX 211, Newport Corporation.

Beam profile: Beamscan, by Photon Inc., Model 1080.

Power meter: Newport Model 820, driven by 25 volt Hewlett-Packard d.c supply
Model 6102A.

K18: Catalog no. 58301 2R from EM Industries, 5, Skyline Dr., Hawthorne, NY
10532.

DMOAP: Petrarch systems Inc., 2731 Bartram Road, Bristol PA 19807.

NOCHROMIX: Godax Labs Inc., New York, NY.

Figure II.1

Figure II. 2.

Figure II.3

Figure II. 4.

Figure 11.5.

Figure II.6

Figure II.7

Figure 11.8

Reference	Sample	Temperature (deg.C)	Diameter (μm)	Thickness (μm)	Threshold (watts/cm ²)
15	E 46	22	variable	100	varies with spot size
14	5CB	-	-	60	1.8×10^3
11	5CB	24.6	200	250	550
10	MBBA	-	-	250	120.6
10	PAA	-	-	250	149.0
10	MBBA	20	-	100	1000
10	MBBA	21.5	65	150	1070
10	5CB	26	-	250	133.4
10	5CB	26	-	250	116.8
10	8CB	34	-	250	127.9
9	MBBA	20	-	75	180
8	OCBP	-	50	150	9.7×10^2
				50	3×10^3
6	5CB	24.9	960	340	130
5	5CB	-	800	250	155
SJSU	6CB	24.1	236	355	190

Table I. I

III. TWISTED NEMATIC DISPLAYS

III.A. General principle

In twisted nematic liquid crystal display (LCD) cells, a thin layer of liquid crystal material of positive dielectric anisotropy is sandwiched between two glass plates coated with transparent conducting material such as Indium Tin Oxide.³ Patterns may be etched onto the coated surfaces. The glass plates are treated for unidirectional homogeneous alignment of the liquid crystal molecules which are introduced inbetween the sealed plates. The layers of molecules close to the glass surfaces are strongly anchored in the direction of homogeneous treatment, while the layers in between adopt an arrangement determined by the distance between the plates. The term "Twisted Nematic" comes from the fact that each layer is twisted through a certain angle with respect to its preceding layer, either clockwise or anti-clockwise, such that the final layer is twisted through an angle of 90, 180, etc., degrees from the initial layer as shown in Figure III.1. The 90° twisted nematics are called " $\pi/2$ " cells, while the 180° twisted nematics are called " π " cells.

III.B. Mode of operation

This section describes the operation of a LCD as is normally used in digital watches, laptop computer screens, etc.

Liquid crystals being birefringent, each layer acts as a birefringent sheet. This structure, consisting of birefringent piles (each pile twisted with respect to its preceding pile), can rotate the plane of polarization of light. The structure and operational principle³ of a $\pi/2$ twisted nematic cell is shown in Figure III.2.

In the case when no voltage is applied to the cell, the "off" state, the unpolarized beam of light after passing through the front polarizer gets polarized along its polarization axis. The plane of this polarized beam rotates as it travels through the twisted nematic cell.³ In $\pi/2$ twisted nematics, the plane of polarization is rotated through 90° within the cell. If the plane of polarization of the second polarizer is 90° to that of the first polarizer, the light beam, coming out of the cell with the same direction of polarization as the second polarizer, passes through the second polarizer and the cell looks clear. In reflective type cells, a reflector is placed behind the second polarizer to reflect this outgoing light in the forward direction.

However, on application of voltage, known as the "on" state, the molecules align themselves in the direction of the electric field, because of the positive dielectric anisotropy and lose the property of guiding and rotating the plane of polarization of the light beam. The light beam thus travels through the cell without rotation of its plane of polarization and consequently is blocked by the second polarizer. No light is reflected by the reflector and the cell looks dark in the areas where the electric field is applied.

Voltage from the circuitry is applied on the desired electrode patterns and the characters look dark on a light background. By keeping both polarizers parallel to each other, one may get transparent digits on a black background.

III.C. The π cell

Conventional liquid crystal switching devices are constructed with a surface alignment that promotes uniform alignment in the completely relaxed state. This is accomplished by causing the directors close to the surface to align in opposite directions at the two surfaces. The electro-optic response² of such a cell is given in Figure III.3. The response of the cell clearly indicates that immediately after the driving voltage is switched off, the optical transmission drops, but is followed by an increase in transmission, known as the "optical bounce." This causes a delay in the switching time. Thus, clearly, the first and most critical disadvantage of the conventional cells was the slow turn-off time. The other problem was the limited cone of view. Both of these drawbacks can be overcome with the π cell.

The cause of the optical bounce is described by van Doorn² to be due to fluid motion taking place within the relaxing cell. As illustrated in Figure III.4a, the torque applied to the local directors,¹ near the center of the cell, results from fluid flow dictated by the surface treatment. The effect of this torque is to tilt the directors in a direction opposite to that desired, forcing a delay in the switching time. This problem is solved in the π cell through a surface treatment that causes the flow direction to be the same along both surfaces. This is illustrated in Figure III.4b. This way, no backward torque is applied to the directors in the center and the cell quickly relaxes to

its off state. In the desired off state, the molecules are assumed to be roughly coplanar. Thus, the π cell switches faster than the conventional cells.

Another convenient and useful feature is the larger cone of view. Figure III.5 illustrates that, for normal incidence, the π cell has an effective birefringence (Δn) and thickness (d) such that the product, $d \cdot \Delta n = \frac{1}{2}\lambda$. For obliquely incident light, the light ray in the lower half of the cell is nearly parallel to the optic axis, while in the upper half, it is at a greater angle to the optic axis formed by the local directors. Thus, the cell presents a lower effective birefringence in the lower half and a correspondingly higher effective birefringence in the upper half. Due to this self compensating feature, the cell offers a wider cone of view.

The π cells were provided to us by Kaiser Electronics, San Jose, CA. These cells were 5 μ ms thick, the thickness maintained by glass bead spacers of the same diameter. The molecules were at a tilt angle of 1 to 5° to the glass surfaces. The cells were filled with a Phenyl Cyclo-Hexane compound, being a liquid crystalline material, having an effective birefringence of 0.13 and viscosity of 19 centipoise. The cells studied were 6" $\times$ 6" in size and were provided with gold contacts for applying the driving voltage.

III.C.1. Characterization of π cells:

The aim of this project was to characterize the performance of the π cell as a display device. This was done in two steps:

III.C.1.a. Contrast measurements. In a display, the detection of a particular information by the eye and its readability depend on the contrast between the information and its background. In LCDs, the more popular term is the contrast ratio, which is computed using the formula,

Contrast = $[I_{\text{on}} / I_{\text{off}}] - 1$, where,

I_{on} = Transmitted intensity in the on state,

I_{off} = Transmitted intensity in the off state.

The contrast is dependent on various factors, such as viewing angle, azimuthal orientation, and driving voltage. The experiments detailed below focussed on the dependence of contrast on parameters such as viewing angle and azimuthal orientation for a certain driving voltage.

III.C.1.b. Color measurements. The complete characterization of the LCD also involves the evaluation of its spectral characteristics, namely its dominant transmitted wavelength. In colorimetric terms, this pertains to the plotting of the

color coordinates of the display, since they are as important as the contrast parameters in order to judge the visual performance of the display. It was the goal of these measurements to compute the color coordinates of the display and to plot them on the chromaticity diagram, in order to determine its dominant transmitted wavelength. The various colorimetric terms are explained in section III.E.1 of this document.

III.D. Contrast measurements

In order to evaluate the contrast of the LCD, a measurement of its transmission characteristics of the cell is essential, as outlined earlier. The transmission of the cell was measured for the on and off states, being the times at which the voltage was applied or not, respectively. The contrast was then computed using the definition given in the previous section.

III.D.1. Experimental setup

A schematic of the experimental setup is given in Figure III.6a. Light from a slide projector lamp assembly was incident on the LCD unit, after passing through a beam controlling aperture and a mechanical chopper. The transmitted light was collected by the detector placed close to the display unit and fed to the Lock-in Amplifier. The amplified signal was sent to a computer which performed data acquisition and analysis.

III.D.2. Experimental Details

The slide projector lamp system consisted of a GTE 300 watt 120 volt Tungsten-Halogen lamp and projection optics. The beam size was controlled by means of an aperture in the object plane. The aperture gave a beam size of approximately 2 mm at the image plane of the projection optics.

Following the source was a mechanical chopper, which provided the reference signal for the phase sensitive detection employed. The chopper was driven by a 12 volt d.c supply, yielding an a.c reference signal at 80 Hz.

The LCD unit was placed at the image plane of the aperture. The unit consisted of the experimental π cell, sandwiched between two polarizers. The polarizer close to the source was a neutral one, while the polarizer on the detector side was "chromatic" - a pair of crossed red and green polarizers. The transmission axis of each polarizer was at an angle of 45° to the buff direction (direction in which the glass plates are rubbed for unidirectional homogeneous alignment of the molecules) of the π cell (Figure III.22).

The cell was driven by a potential divider circuit, the schematic of which is given in Figure III.7. This circuit generated a 2 KHz a.c signal switching between 80 volts (peak to peak) in the on state, and 5 volts (peak to peak) in the off state. The frequency of switching was 0.2 Hz. The duration of the off state was intentionally made short, so as to avoid the complete relaxation of the LCD. The chromatic polarizers were arranged so that the transmission was "Red" in the on state and "Green" in the off state.

The unit was mounted on special holders which allowed azimuthal angle (α) and viewing angle (β) variation (Figure III.6b). This was necessary since the contrast was studied as a function of these parameters.

The detector was a silicon PIN photodiode, with an active area of 1 cm², equipped with a photometric filter. It was used in the photovoltaic mode, generating a current proportional to the input light level, linear over several decades of input power. The photometric filter was used to mimic the response of the human eye, a crucial factor in the characterization of the LCD display. The response of the photometric filter is given in Figure III.8.

The photocurrent was converted to voltage by a preamplifier and sent to the lock-in amplifier. Amplified voltage was digitized by the Analog/Digital converter, the output of which was used for the computerized data acquisition system.

III.D.3. Data Acquisition and analysis

Data Acquisition. The A/D converter was triggered by the 5 volt square wave used in the voltage divider circuit, so that the data acquisition run always started at the same switching state of the display.

A BASIC program was written to drive the data acquisition software. Data was taken at a sampling speed of 15 Hz for a duration of 15 seconds. At this rate, data was averaged over two switching cycles for every position of the display. The acquired data was simultaneously stored in the computer for analysis.

The LCD was positioned at normal incidence initially, and data was taken for every 10° azimuthal rotation ($\alpha = 10^\circ, 20^\circ, 30^\circ$, etc) covering 360°. The display was then moved to another angle off axis and the experiment repeated. Data was taken for normal incidence ($\beta = 0^\circ$) and for $\beta = 12.5^\circ, 20^\circ, 25^\circ, 30^\circ, 35^\circ$ measured on both sides off axis (Figure III.6b). Signal from a typical data run is shown in Figure III.9.

Data Analysis. A BASIC program was used to analyze the data, which consisted of two cycles of transmitted intensity values in terms of voltages. Each cycle contained data representing one on and off state of the display. The program

used only the stable portions of the switching cycle and averaged the transmitted intensity for the two states of the cell for both switching cycles. Thus, for every position of the cell, the program evaluated the average value of the transmitted intensity in the on and off states. The contrast was then computed for each position using the earlier definition. The contrast values for all the azimuthal orientations at a particular viewing angle were stored in a file and the process of analysis continued in the same fashion for other viewing angles.

III.D.4. Results

The values of contrast for cell# 218a are presented in the form of polar plots, in Figures III.10 - III.20, the results corresponding to data taken from one cell. In the plots, care was taken to make sure that the buff direction of the display coincided with the zero of the azimuthal orientation.

III.D.5. Discussion

The propagation of light through a twisted nematic layer can be analyzed using the coupled mode theory.⁴ The geometry of the system is given in Figure III.21. The twisted nematic cell is considered as a stack of birefringent plates, each of thickness δz , each plate rotated through an angle $\delta\Omega$ with respect to the preceding plate. An incident linearly polarized beam becomes elliptically polarized as it traverses an anisotropic medium. Further, if the medium twists about the direction of propagation

of the beam, the polarization ellipse rotates as the wave advances through the medium.

The electric field at position z in an anisotropic medium with a constant rate of twist ξ about the z axis and propagation constants β_x, β_y for light polarized along two, orthogonal, twisting unit vectors $x(z), y(z)$ fixed in the medium is given by⁵

$$\vec{E}(z) = A_x(z)x(z) + A_y(z)y(z)$$

where the amplitudes along the $x(z)$ and $y(z)$ axes are given by,

$$A_x(z) = [p \cos \tau + \sqrt{F} (ipX + q) \sin \tau] e^{i\beta_s z}$$

$$A_y(z) = [q \cos \tau - \sqrt{F} (iqX + p) \sin \tau] e^{i\beta_s z} \text{ where}$$

$$\tau = \xi z(1 + X^2)^{1/2},$$

$$F = 1/(1 + X^2)$$

$$X = (\beta_x - \beta_y)/2\xi = \pi \cdot \Delta n / \xi \lambda$$

$$\beta_s = (\beta_x + \beta_y)/2$$

$$p = A_x(0); q = A_y(0)$$

The equations above follow these assumptions:

1. $|\xi| \ll \beta_s = 2\pi n_s / \lambda$, where n_s is the average refractive index of the medium.
2. $\Delta n \ll n_s$.

Choosing the direction of the LC molecules at the incident plane to be along $x(0)$, we may infer that at any z , $x(z)$ follows the twist of the molecules. The orientation of the

polarizers and the twisted nematic display cell in our system is shown in Figure III.22. The LC molecules were at 45° to the transmission axis of the front polarizer. Two chromatic polarizers were used at the exit plane. These polarizers had their transmission axes at right angles to each other and each of them was at 45° to the LC molecules at the exit plane. Applying the above results to the off state of the cell, we have

$$p = A_x(0) = \sqrt{2} \cos(\phi)$$

$$q = A_y(0) = \sqrt{2} \sin(\phi)$$

where ϕ is the angle between the front polarizer and $x(0)$.

Since $\phi = 45^\circ$ in this geometry, we have $p = q = 1$.

If d is the thickness of the cell, then the components of the electric field A_x , A_y at $z = d$ are

$$A_x(d) = [\cos\tau + \sqrt{F} (ix + 1) \sin\tau] e^{i\beta_{sd}}$$

$$A_y(d) = [\cos\tau - \sqrt{F} (ix + 1) \sin\tau] e^{i\beta_{sd}}$$

Power transmitted P_t through one of the polarizers aligned along unit vector $\mathbf{a}$ at the exit plane is given by

$$P_t \propto |\bar{\mathbf{E}}(d) \cdot \mathbf{a}|^2$$

Since the electric field $\bar{\mathbf{E}}(z) = A_x(z)\mathbf{x}(z) + A_y(z)\mathbf{y}(z)$, the electric field at $z = d$ has two components given by

$$\bar{\mathbf{E}}(d) = A_x(d)\mathbf{x}(d) + A_y(d)\mathbf{y}(d).$$

At the exit plane, the LC molecules are along $x(d)$. The orientation of the two chromatic polarizers at the exit plane is shown in Figure III.23, where

$$\mathbf{a} = x(d)\cos(45) - y(d)\cos(45)$$

$$\mathbf{a}' = x(d)\sin(45) + y(d)\sin(45).$$

Power transmitted along $\mathbf{a}$ is then given by

$$\begin{aligned} P_{t1} &= \frac{1}{2} |\bar{\mathbf{E}}(d) \cdot \mathbf{a}|^2 \\ &= \sin^2(\tau) \end{aligned}$$

and similarly, power transmitted along $\mathbf{a}'$ is

$$\begin{aligned} P_{t2} &= \frac{1}{2} |\bar{\mathbf{E}}(d) \cdot \mathbf{a}'|^2 \\ &= \cos^2(\tau), \end{aligned}$$

giving a total transmission, $P_{t1} + P_{t2} = 1$.

Hence, there is no minimum in transmission in the off state, for normal incidence. In the on state, the molecules no longer rotate the plane of polarization of the incident light and transmission is only along that exit polarizer that is parallel to the front polarizer. Our results show that the contrast is uniform for all azimuthal orientations, without any minima, for the case of normal incidence (Figure III.15). For positions off axis, the contrast does show variations, with well defined maxima and minima occurring at specific azimuthal orientations of the display. This could be handled theoretically by taking into account the relevant components of the electric field incident on the front polarizer.

III.D.6. Conclusions

We have studied the contrast of a π twist LCD as a function of variations in viewing angle and azimuthal orientation. The contrast is uniform at normal incidence over all azimuthal angles. This can be explained in the following manner:

- i. The cell together with the polarizers, rotates azimuthally as one unit.
- ii. The cell receives the same contribution from the incident unpolarized light through the front polarizer for all azimuthal angles.

For angles off axis, the contrast does show definite maxima and minima over azimuthal variation, registering a zero minimum for angles as large as 35° . This is to be expected, since, in this case, the cell receives unequal amounts of light through the front polarizer as it is azimuthally rotated.

It was observed that the maximum contrast obtained for angles off axis was higher than the contrast at normal incidence. We have applied the coupled mode theory (to explain the propagation of light through the twisted nematic cell) to our system for normal incidence. The same theory could be extended to account for off axis behavior through suitable modification of the formulation.

III.E. Color measurements

III.E.1. Colorimetry

Color has always been a source of fascination and joy. Evidence for color consciousness in humans is obtained from archaeological studies.⁷ For a long time, the only colored materials available were mineral colors, vegetable dyes, and a few dyes obtained from insects. The synthesis of mauve from coal tar by Perkin opened the way for the discovery of new and exciting dyes and pigments. This, in turn, led to another problem, that of specification of colors! When the number of synthesized materials was few, the colors were designated by reference to their origin. But, with the ever increasing choice of colors, it became necessary to have an international system of representing any color on a uniform scale.

With this in view, *The Commission Internationale de l'Eclairage* (CIE - The International Commission on Illumination) recommended data that characterize a standard observer for colorimetry, related to which, a coordinate system for map-like representation of color measurements was suggested in 1931. The methods employed for specifying numerically the color of a physically defined visual stimulus constitutes the subject of Colorimetry.

III.E.2. Basic colorimetric quantities

Trichromatic generalization. This provides the experimental rules of color matching, which are indispensable for any system of Colorimetry. It states that most color stimuli can be represented by additive mixtures of any three primary stimuli, whose radiant powers have been adjusted. The primary stimuli may be chosen from any set of three stimuli such that none of them can be matched by a mixture of the other two.

A set consisting of red, green and blue colors is an example of primary stimuli, since any unknown color in the visible spectrum can be matched by a certain combination of the above. The unknown color could then be numerically specified by the amounts of each primary stimulus. These values, given to any color, are known as the "tristimulus values" for that color.

The tristimulus values constitute a color specification for a given test sample and for the observer who performs the experiment. Therefore, another observer, working with the same test sample, may also obtain a valid specification, which may or may not be different from that of the previous observer. In order to characterize any color, a large group of observers have to be employed, to average the results.

The CIE recommended the use of spectrophotometric data, together with data

The CIE recommended the use of spectrophotometric data, together with data obtained from a large group of observers, to standardize the specification of colors. About 1928, Wright and Guild⁷ independently redetermined the fundamental data, each employing carefully selected observers. Since both results were in good agreement with each other, the CIE, in 1931, recommended international agreement on them.

The primaries employed by Wright were spectrum colors of 650, 530 and 460 nm, while in Guild's experiments, the primaries were produced by passing incandescent light through red, green and blue filters.⁶ However, Wright and Guild both realized that they had to use negative amounts of primaries to match certain colors. Hence, the data obtained by them contained positive and negative numbers. The problem, however, was solved by the use of linear transformation, to another set of primaries. Mathematically, this can be expressed as follows:

$$r' = k_1r + k_2g + k_3b,$$

$$g' = k_4r + k_5g + k_6b,$$

$$b' = k_7r + k_8g + k_9b,$$

where r, g, b are tristimulus values based on one set of primaries, and r', g', b' are tristimulus values based on another set of primaries, and $k_1, k_2, \dots, k_9$ are the transformation coefficients.

The tristimulus values that were adopted by the CIE are given in abridged form in Table III.1, and the graphical representation of the same is given in Figure III.24. The values of x , y , and z in Table III.1 indicate the amount of each primary that is required to match the color of one watt of radiant power of the indicated wavelengths. The tristimulus values, X , Y , Z , of an illuminant can be determined by a numerical procedure explained in the Appendix.

Chromaticity coordinates. The chromaticity of a source can be determined from a knowledge of its tristimulus values, given by,

$$x = X / [X + Y + Z] ,$$

$$y = Y / [X + Y + Z] , \text{ and}$$

$$z = Z / [X + Y + Z] .$$

These three quantities are known as the chromaticity coordinates. Just two of these quantities are sufficient to describe any stimulus, since, $x + y + z = 1$, regardless of the values of X , Y , and Z .

Chromaticity diagram (color coordinates). Presentation of the tristimulus values would require a three dimensional domain of representation. However, the chromaticity coordinates can be conveniently represented on a graph, known as the chromaticity diagram. This has been done for certain colors of interest and is presented in Figure III.25. The solid curve is the locus of the spectrum colors, the

chromaticity coordinates being calculated from the tristimulus values of each spectrum color given in Table III.1. The graph also shows the color position of a source, illuminant C, which is a tungsten lamp with a filter, operated at a specific temperature and identified by the CIE as a simulator of daylight.

Dominant wavelength and purity. Any color can be represented as a mixture of the source illuminating the colored object and a particular wavelength, known as the Dominant wavelength. In our case, the Dominant wavelength was measured with respect to the source employed, namely, the projection lamp. The color coordinates for the source and the display were evaluated, in order to compute the Dominant wavelength. Further, the ratio of the distances of the sample point, (the display), and the dominant wavelength for the same, measured on the chromaticity diagram with respect to the illuminant, gives a quantitative measure of the purity of the sample.

III.E.3. Experimental procedures

The experiments and procedures explained in the following pages involve:

- ★ Initial calibration of the monochromator.
- ★ Evaluation of the response function of the system.
- ★ Computation of color coordinates of the projection lamp.
- ★ Preliminary investigation on a test filter of known specifications.
- ★ Computation of the color coordinates of the LCD cell.

★ **Calibration of the monochromator.** It was necessary to ascertain the accuracy of the monochromator, before using it for the actual data acquisition. This was done using a He-Ne laser as the source, since the emission wavelength, 632.8 nm, was known. The schematic of the experimental setup used for the calibration is given in Figure III.26.

Light from the laser was focussed onto a diffuser. The scattered light from the point source was imaged by another lens onto the entrance slit of the monochromator. The second lens was chosen to match the $f_{\#}$ of the monochromator, such that the collected light completely filled the diffracting grating. The entrance slit was 0.5 mm wide, selected for better resolution.

The spectrum was scanned manually and the transmitted intensity values were observed. Data was averaged over several runs and the monochromator was found to be accurate to +1 nm. This difference of 1 nm was corrected for in all subsequent colorimetric calculations.

★ **Response function of optics.** Before proceeding with the actual experiment of plotting the color coordinates of the LCD, it was necessary to get the response function of the optics used, so as to arrive at the true spectrum of the source used. To do this, we used a standard lamp whose spectrum was already calibrated.

By replacing the source with the standard lamp and using the same optics, we arrived at the response function of the optics as detailed below. With the response function of the optics known, the same procedure was employed, this time with the projection lamp, to arrive at the true spectrum of the same.

Experimental setup. The schematic of the experimental setup is given in Figure III.27. Light from the source (projection lamp/standard lamp) was incident on a telescope, after passing through a beam controlling aperture and mechanical chopper. The nearly collimated beam emerging from the telescope was focussed by the lens onto the entrance slit of a monochromator. A radiometric detector was fixed to the exit slit of the monochromator to collect the diffracted light. The photo current generated by the detector was sent to a lock-in amplifier through a pre-amplifier. The amplified output was sent to a computer for data acquisition and analysis.

Experimental details. A standard lamp was used as the source of light to determine the response function of optics. The lamp was of tungsten filament type, issued as a standard by the National Bureau of Standards and was calibrated in the wavelength interval of 225 to 2400 nms. The graphical representation of the spectral radiance of the lamp is given in Figure III.28. The current through the tungsten filament was regulated at 35 amperes.

The same projection lamp used in the contrast measurements was used as the source after the response function was evaluated and its true spectrum was obtained.

The beam size was controlled by means of a 0.5 cm diameter aperture, placed close to the source, giving a spot size of 3 mm at the entrance slit of the monochromator.

The telescope used was of Newtonian type, with a 32 mm diameter achromatic objective and Kellner eyepiece in focussing mount. The collimated beam emerging from the telescope had a diameter of 3.5 cm.

The telescope was followed by a focussing lens, with a focal length of 40 cms, selected to match the $f_{\#}$ of the monochromator for maximum light collecting efficiency.

The monochromator was fitted with an aberration-corrected, concave, holographic diffraction grating and was used with a 1 mm slit at the entrance aperture. The spectral range of the monochromator was 200 to 800 nm, with an accuracy of 1 nm.

A photodetector with a radiometric filter provided a flat response in the spectral range from 450 to 950 nm. The response of the radiometric detector is given in Figure III.29. The filter was necessary since the measurements involved the spectral characteristics of sources. Following the detector was the lock-in amplifier, the output of which was sent to the computer via the Analog to Digital converter.

The optics were aligned initially using a He-Ne Laser, with a neutral density filter to reduce the intensity of light received by the detector. The same setup was retained for both runs.

Data acquisition. The standard lamp was put in as the source. A BASIC program was written to drive the data acquisition software, which took data at pre-determined wavelengths. Data consisted of transmitted intensity values of the lamp, seen through the system at each wavelength, measured in terms of digitized voltage generated by the A/D converter.

The spectrum was scanned between 375 and 800 nm, at intervals of 25 nm. No triggering was used since the LCD was not part of the setup and consequently, there was no switching in the signal. Data was taken for a duration of 15 seconds at every wavelength, using a sampling rate of 15 Hz., and was stored in individual files for later retrieval and analysis.

Analysis. Using the LOTUS 123 software the data files were read into spreadsheets, and the average value of the transmitted intensity at corresponding wavelengths was computed.

Radiometric calculations were done to quantify the amount of light passing through the system.⁸ Using the Lagrange Invariant and knowing the various parameters such as areas of apertures and the distances between them, the spectral "Radiance" of the standard lamp, $L(\lambda)$, was converted into "Power" units, $S(\lambda)$, incident on the detector, along with the response of the system. Therefore, the power available at the detector, $D(\lambda)$, was given by:

$$D(\lambda) = S(\lambda) \times R(\lambda),$$

where, $R(\lambda)$ is the required response function of the system, given as a function of wavelength.

The photocurrent generated by the detector, $i(\lambda)$, depends on the radiometric detector response, $\eta(\lambda)$, and is written mathematically as

$$i(\lambda) = D(\lambda) \times \eta(\lambda)$$

Thus, the response function of the system can be computed from a slight rearrangement of the above relationships as

$$R(\lambda) = \frac{i(\lambda)}{S(\lambda) \times \eta(\lambda)}$$

The known data tables of radiometric detector response and radiance of the standard lamp were used in the above expression. The photocurrent, $i(\lambda)$, was represented via the voltage generated by the A/D converter. Thus, the response of the system was obtained, a graphical representation of which is given in Figure III.30.

★ *True spectrum and color coordinates of projection lamp.* Data was recorded in a procedure identical to that explained for the standard lamp, the important difference being that the source was replaced with the projection Lamp. The experimental setup was unchanged, and data was taken at the same wavelength intervals.

The acquired data was analyzed as before, and the average values of transmitted intensity, $X(\lambda)$, were calculated for corresponding wavelengths. Since the response of the system was known, the true spectrum $P(\lambda)$ of the projection lamp was obtained by directly dividing the transmitted intensity by the response function of the system. Mathematically, this can be expressed as follows:

$$P(\lambda) = \frac{X(\lambda)}{R(\lambda)}$$

where, again, $R(\lambda)$ represents the response function of the system. A graphical representation of the same is given in Figure III.31.

Knowing the true spectrum of the lamp, the color coordinates of the same were computed according to the procedure outlined in the Appendix, using the 1931 CIE standard observer data. The values obtained are given below:

$$x = 0.38, y = 0.41.$$

Figure III.32 depicts this result on the CIE chromaticity diagram, together with the corresponding data for a blackbody radiator.

★ *Preliminary run on a test filter.* To establish the accuracy of the colorimetric measurements, we conducted an experiment initially on an interference filter of known spectral characteristics. The experimental setup used for this purpose is given in Figure III.33a. Data was taken in the same fashion as explained in previous sections, in the wavelength interval of 567 to 607 nm , every 0.5 nm. At other wavelength selections, we had no detectable signal through the filter.

Following the same procedure outlined earlier, the color coordinates pertaining to the filter were calculated to be:

$$x = 0.35, y = 0.36.$$

The color coordinates of the projection lamp, P, (found earlier), and the coordinates of the filter F, were plotted on the chromaticity diagram. The procedure employed to deduce the dominant wavelength of the filter is illustrated in Figure III.33b. The intersection of the line through the two points P and F, and the locus of the

chromaticity diagram, gave the dominant wavelength of the filter, viz., 572 nm. As a further check, the transmission spectrum of the filter was measured using a UV - Visible spectrophotometer. The spectrum obtained from the same is given in Figure III.34.

The spectrum obtained from the spectrophotometer shows a peak at 589 nm, giving an error of 2.8%. The performance and validity of the spectrophotometer itself was checked out using standard filters supplied by Newport Corporation. The transmission spectra obtained, for filters spanning the visible spectrum, are given in Figure III.35, followed by those supplied by the manufacturer, in Figure III.36.

III.E.4. Color coordinates and dominant wavelength of the LCD cell.

Having done the preliminary test runs, we proceeded with the actual experiment on the π cell. The experimental arrangement used for the same is given in Figure III.37. It was the aim of this exercise to study the dependence of the color coordinates, again, on the angle of incidence and azimuthal orientation of the cell.

The experimental arrangement was very similar to that used for the interference filter, with the introduction of the LCD in the path of the collimated beam emerging from the telescope. The same projection lamp was used as the source and the mechanical chopper provided the reference signal of 82 Hz. The LCD unit

consisted of the same elements as used for the contrast measurements.

As before, data consisted of transmitted intensity values in the form of digitized voltage generated by the analog to digital converter. The lock-in amplifier was used at a sensitivity of 10 millivolts. The trigger from the voltage divider circuit was such that the data run always started during the on-off transition of the display. Data sampling speed and duration were identical to the contrast measurements.

Data was taken at normal incidence (0°), and at 20° off axis. At each of these positions, data was taken at every 45° azimuthal orientation of the LCD unit, in the wavelength interval 350 to 800 nm, in steps of 10 nm. A BASIC program was written explicitly for this purpose, taking care of the position, orientation of the unit and the wavelength employed for the data run. Each set of data was stored in files for later retrieval and analysis.

Again, the orientation of the polarizers was such that the transmitted light was "Red" in the on state of the cell and "Green" in the off state of the cell.

III.E.5. Analysis

Analysis of the spectrophotometric data was accomplished by means of a BASIC program, designed to calculate the average transmission values of the display,

in the on and off states, at a specific wavelength, for a given angle of incidence and azimuthal orientation of the same. This way, the analysis proceeded, for all azimuthal orientations of the display and also for the off axis positions.

For a particular position of the display, the data was read into spreadsheets and segregated into two sets, one containing data corresponding to the on state, while the other corresponded to the off state of the display. Each set was then treated individually for the calculation of the dominant wavelength.

Again, the procedure outlined in the Appendix was employed to calculate the chromaticity coordinates of the two states of the display. It was repeated to arrive at the chromaticity coordinates for all the acquired data. The results obtained are given in Table III.2, in which x_r, y_r and x_g, y_g denote the color coordinates obtained for the on (red) and off (green) states of the display, respectively. The coordinates were plotted on the chromaticity diagram, along with that of the projection lamp. From these values, the dominant wavelength of the display was deduced following the same procedure as that employed for the filter. Thus we arrived at the dominant transmitted wavelength of the display in both states of its switching cycle.

III.E.6. Results

The dominant wavelength calculated for the display was 555 nm in the off state and 602 nm in the on state. The above results correspond to the normal incidence position of the display, with the azimuthal orientation such that the buff direction of the display was at 45° to the axis of the front polarizer. The dominant wavelength was the same when the display was placed 20° off axis, too, for the same azimuthal orientation.

The known values of the dominant wavelength were nominally, 561 nm in the off state and 606 nm in the on state, showing an error margin of 1.1% for the off state, and 0.66% for the on state.

III.E.7. Discussion

The variance in the chromaticity coordinates for the data analyzed is given below:

Incidence	x_g	y_g	x_r	y_r
0°	14.9%	9.7%	3.8%	3.4%
20°	13.7%	9.6%	3.9%	2.6%

As shown above, the chromaticity coordinates do not show a significant change in the range of values calculated, going from normal incidence to off axis incidence. This indicates that the color response of the display is satisfactory.

It should be noted that the color coordinates and consequently, the dominant wavelength values obtained for the display, correspond strictly to the source employed, namely the projection lamp. Moreover, the source was not current regulated, which may contribute toward the errors in characterizing the source.

III.E.8. Conclusions

The experiment worked very well. Good agreement with known data was obtained. The colorimetric performance of the display did not change appreciably for the angles studied. It would be interesting to make measurements to study the behavior of the display for larger angles off axis! Results would be more meaningful if the experiment is done using the source to be used in the actual application.

APPENDIX: CALCULATION OF TRISTIMULUS VALUES AND COLOR COORDINATES OF AN ILLUMINANT⁶

The tristimulus values and color coordinates of any source with spectral distribution $S(\lambda)$ are computed using the following procedure:

The transmitted intensity values $S(\lambda)$ of the source at well defined wavelength intervals $\Delta\lambda$, and the color matching functions $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ are recorded. The calculations done for this experiment used the 1931 CIE color matching functions given for a standard observer. The first step is to form products of $S(\lambda)$ with each of the three color matching functions at the corresponding wavelengths. Following this, the summation of these products are taken over the entire spectrum of data. The normalization is done with respect to $y(\lambda)$, viz.,

$$\text{Normalizing factor } K = \frac{100}{\sum_{\lambda} S(\lambda) y(\lambda)}$$

The tristimulus values are then computed using:

$$X = K \sum_{\lambda} S(\lambda) x(\lambda)$$

$$Y = K \sum_{\lambda} S(\lambda) y(\lambda)$$

$$Z = K \sum_{\lambda} S(\lambda) z(\lambda)$$

yielding the chromaticity coordinates,

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

The same procedure was followed for calculating the chromaticity coordinates of the source, (projection lamp), the test filter, and the display.

III. References

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III. List of equipment

Projector System: Kodak Ektagraphic Model number AF - 2.

Power Supply: LAMBDA Model number 11 - 902 - 0V, capable of supplying 0 - 20 volt D.C

Telescope: Edmund Scientific, Model Number 60,941.

Lenses:

1. Newport Corporation KPX 208
2. Newport Corporation KPX 211
3. Newport Corporation KPX 091.AR 14
4. 7.56 focal length lens.

Neutral Polarizers: Specifications not available.

Chromatic Polarizers: Specifications not available.

Detector: United Detector Technology model 40X Optometer fitted with photometric and radiometric filters.

Lock-in Amplifier: EG & G model 5205.

A/D converter: Metrabyte Corporation DAS 16 Board.

Computer: AT & T 286 Personal Computer.

Data Acquisition Software: LABTECH NOTEBOOK, menu driven data acquisition and analysis software from Laboratory Technologies Corporation and LOTUS 123.

Oscilloscope: Tektronix, Model Number 2213, 60 Mhz oscilloscope.

Sine wave generator: Hewlett Packard Model number 200 AB audio Oscillator,
capable of supplying upto 40,000 Hz, 100 volt signal.

Square wave generator: Hewlett Packard Model number 3311A function generator.

D.C. Power supply: LAMBDA Model number LA-250.

Special Mounts: Newport Model Number 471 rotation stage,
Newport Model Number 420 translation stage.

Filters: 1. Newport Corporation color filter GG 400.

2. Newport Corporation color filter OG 515.

3. Newport Corporation color filter RG 610.

Diode Array Spectrometer: Hewlett Packard Model number 8451A.

Monochromator: Instruments SA, Inc., Model number H - 20, serial number 6809 -
1-84, 1200 UV _ V.

Lasers: Uniphase He-Ne Laser Model Numbers. 1107 & 1101-P, equipped with
power supply, Model Number 1205-1

Figure III.1.

Figure III.2

Figure III.3

Figure III.4

Figure III.5

Figure III. 6a

Figure III.6b.

Figure III.7.

Figure III.8

Figure III.9

Figure III.10

Figure III.11

Figure III.12

Figure III.13

Figure III.14

Figure III.15

Figure III.16

Figure III.17

Figure III.18

Figure III.19

Table III.20

Figure III.21.

Figure III. 22.

Figure III.23.

Figure III.24

Figure III.25

Figure III.26.

Figure III.27

Figure III.28.

Figure III.29.

Figure III.30.

Figure III.31.

Figure III.32

Figure III.33a.

Figure III.33b

Figure III.34

GG 400

OG 515

RG 610

Figure III.35

Figure III.36

Figure III.37.

Wavelength [nm]	$\bar{x}$	$\bar{y}$	$\bar{z}$
400	0.0143	0.0004	0.0679
410	0.0115	0.0012	0.2071
420	0.1344	0.0010	0.6456
430	0.2839	0.0116	1.3856
440	0.3483	0.0230	1.7471
450	0.1362	0.0380	1.7721
460	0.2908	0.0660	1.6092
470	0.1954	0.0910	1.2876
480	0.0956	0.1390	0.8130
490	0.0320	0.2080	0.4652
500	0.0049	0.3230	0.2720
510	0.0093	0.5030	0.1582
520	0.0633	0.7100	0.0782
530	0.1655	0.8620	0.0422
540	0.2904	0.9540	0.0201
550	0.4334	0.9950	0.0087
560	0.5945	0.9950	0.0039
570	0.7621	0.9520	0.0021
580	0.9163	0.8700	0.0017
590	1.0263	0.7570	0.0011
600	1.0622	0.6310	0.0008
610	1.0026	0.5030	0.0003
620	0.8544	0.3810	0.0002
630	0.6124	0.2650	0.0000
640	0.4479	0.1750	0.0000
650	0.2835	0.1070	0.0000
660	0.1649	0.0610	0.0000
670	0.0874	0.0320	0.0000
680	0.0468	0.0170	0.0000
690	0.0227	0.0082	0.0000
700	0.0114	0.0041	0.0000

Table III.1

Azimuthal angle	x_r	y_r	x_q	y_q
0°	.59	.37	.36	.52
45°	.59	.37	.35	.51
90°	.6	.37	.39	.48
135°	.59	.37	.38	.49
180°	.58	.37	.35	.51
225°	.59	.37	.35	.51
270°	.61	.37	.4	.47
315°	.59	.37	.38	.49

Table III.2