LAB MODULE 1 OF 4: LCD PIXEL

Fabrication and Characterization of a Liquid Crystal Display Pixel

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Abstract

This lab experiment is designed to help you understand the inner workings of a modern **Liquid Crystal Display** (LCD). You will learn the importance of the components and layers that comprise a typical LCD in the process of fabricating and characterizing your own single pixel LCD. Starting from the transparent and conductive Indium Tin Oxide (ITO) electrodes, you will create the liquid crystal alignment layers. You will then use spacers and adhesive to create a cell of uniform thickness, measure that thickness with a spectrometer, and fill it with liquid crystal material. Finally, using a simple photodiode arrangement, you will measure the transmittance of the LCD pixel as voltage is applied.

Part 1	Part 2	Part 3	Part 4	Part 5
Alignment Layers	Assembling the Cell Gap	Measuring Cell Gap Thickness	Filling the LC Cell	Transmittance Measurements

Write-up Instructions

Your lab report (Lab Notebook) will minimally consist of the following *for each part*:

A. Statement of experimental objective
B. Sketches of experimental setup
C. Record of all measurements
D. All requested calculations

The following lab procedure will indicate specifically what to include and where. The purpose of this style of write-up is to force you to keep a technical record of your experiments in the way that many engineers and scientists are required to do (in industry and universities). The lab director(s) will provide you with blank technical notebook sheets in the lab (also available on the website). You are expected to follow the lab notebook guidelines introduced by the lab director(s) (also see the Appendix), and your lab grade will depend both on your experimental procedure and on how well you follow these guidelines. Note that the same pages you use during the lab experiment should also be the ones you complete at home and hand-in as your write-up — do not rewrite them.

A Brief History of LCDs

Even though liquid crystals (LCs) were discovered and thoroughly studied by Otto Lehmann in the late 19th century, the credit must go to G. Friedel for understanding and classifying LCs at the molecular level [1]. Following this, the subject remained untouched until the mid 20th century when Pierre-Gilles de Gennes laid down the theoretical foundations. Liquid crystal materials have been described as mesophases that constitute a genuine state of matter whose molecular properties share characteristics of crystals and ordinary liquids.

Almost all applications employing liquid crystals operate by manipulating the polarization state of light. Liquid crystal displays (LCDs) are by far the most significant contribution of liquid crystal materials. The success of the LCD industry is based upon three important factors. First was the discovery of electro-optical effects in liquid crystal materials. Second, and probably the most important, was the successful search for those liquid crystal materials that met the necessary requirements. As an aside, since the first successful demonstration of the LCD, the improvement in liquid crystal materials has directly resulted in improvement of the number of pixels by a factor of about 40,000. Third was the successful development of technological tools for manufacturing these displays [1 – 3].

Figure 1 presents the construction of a modern LCD pixel. Typically a fluorescent lamp serves as the unpolarized backlight. More modern displays are being powered by LED backlights, reducing overall power consumption. The analyzer polarizes this incoming light, which then passes through the LC layer. Here, the alignment polymer dictates the orientation of the LC molecules at the surfaces. Based on these boundary conditions, the molecules in the bulk choose the configuration that results in the lowest overall energy. Applying a voltage across the electrodes can alter this configuration. Thus, the light intensity can be electrically modulated just by changing the orientation of the liquid crystal molecules, resulting in high power efficiency.

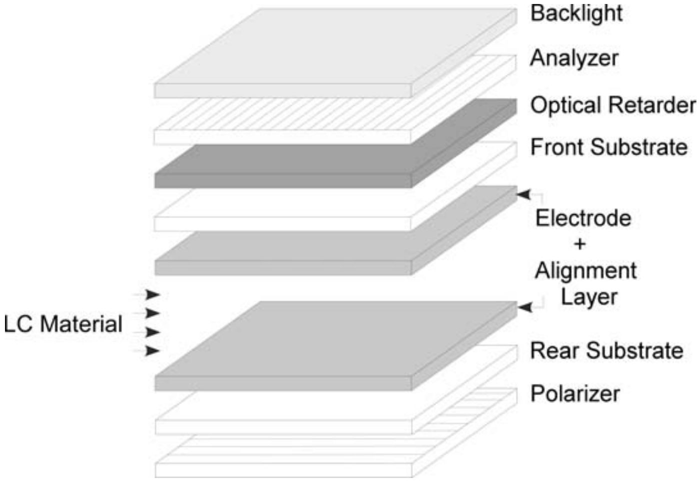


Figure 1. The basic construction of a typical LCD pixel.

The Twisted Nematic Display Mode

The most historically important LCD pixel type is the twisted nematic (TN) structure as shown in Fig. 2, where the LC layer is arranged in a twist deformation [3]. In the example sketched, the alignment polymers must be patterned such that the LC molecules align along the *y*-direction at the top substrate, and along the *x*-direction at the bottom substrate. In addition, the polarizers enclosing the substrates may be crossed, i.e., arranged to have orthogonal optical axes. This results in a normally “Bright” display mode where light is passed in the “OFF” state and blocked in the “ON” state as depicted in Fig. 2(a).

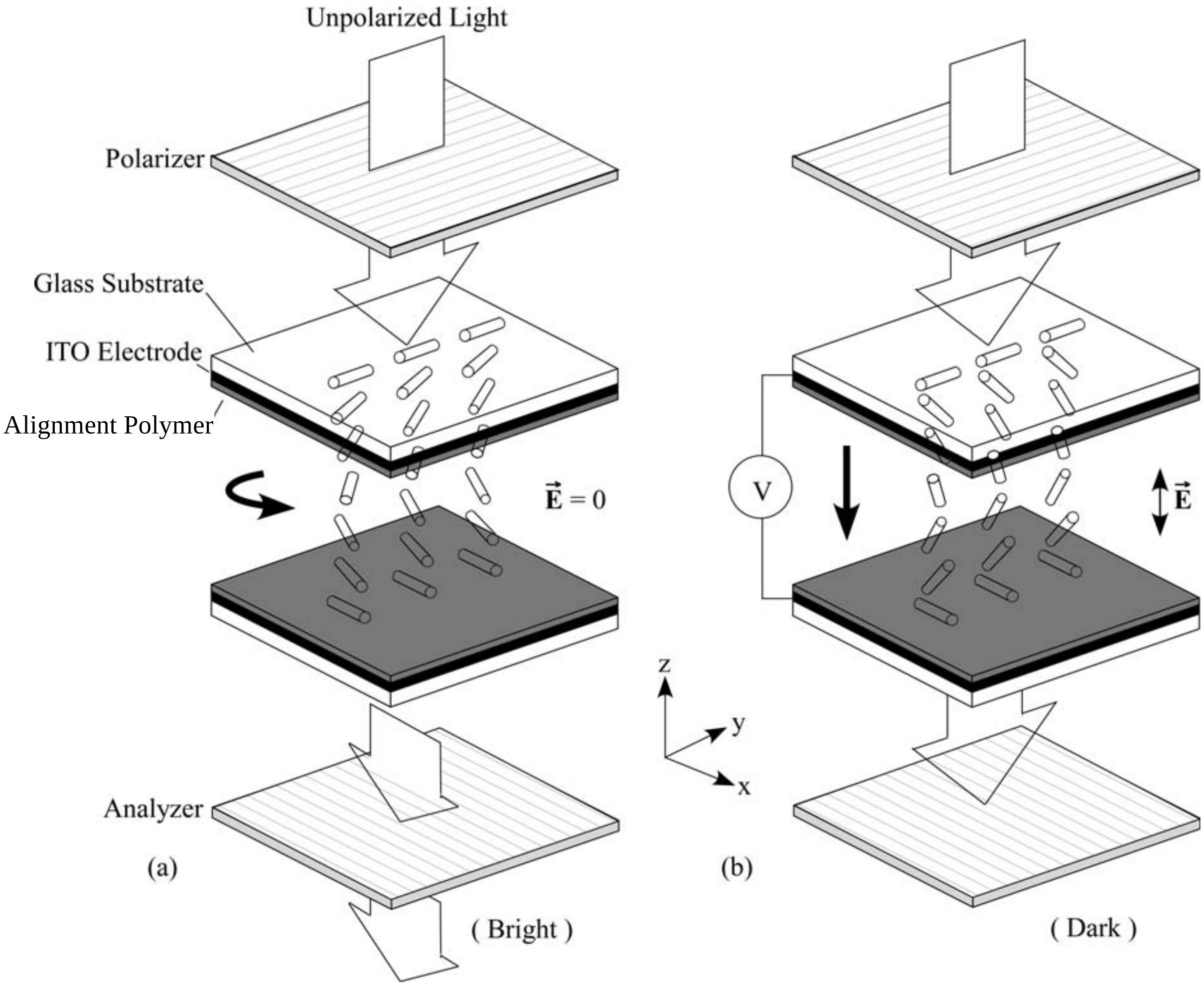


Figure 2. The TN mode in the (a) OFF state, and (b) ON state.

The TN mode uses the principle of polarization rotation to modulate the intensity of light. Consider a beam of unpolarized light incident at the top of the structure in Fig. 2(a). At the output of the polarizer, the electric field is along the y-direction. When no voltage is applied across the two electrodes, a twist is created in the LC layer. With a properly designed cell gap, this twisted LC layer rotates the electric field by 90° so that the field is along the x-direction at the input of the analyzer. Since the optical axis of this second polarizer is parallel to the x-axis, the polarized beam is unaffected and passes through the device. On the other hand, when a voltage is applied, the molecules align parallel to the field, thus preventing rotation and blocking the light, as in Fig. 2(b).

TN Mode: Electro-Optical Properties

To quantify the optical properties of the TN mode, we first begin with light transmission through a single polarizing film [4]. Consider a polarizer with its transmission axis (**p**) parallel to the *x*-axis as shown in Fig. 3. Now consider a plane wave traveling in the -*z*-direction with its electric field polarized at an angle θ to the +x-direction. The electric field of this plane wave field can be expressed as:

$$\mathbf{E}(z,t) = E_0(z,t)\left[\hat{\mathbf{x}}\cos\theta + \hat{\mathbf{y}}\sin\theta\right].$$

Here, $E_0(z,t)$ represents the amplitude. The components of the field along the x- and y-directions, namely $\mathbf{E}_x$ and $\mathbf{E}_y$, are as follows:

$$\mathbf{E}_x(z,t) = \hat{\mathbf{x}}E_0(z,t)\cos\theta$$
$$\mathbf{E}_y(z,t) = \hat{\mathbf{y}}E_0(z,t)\sin\theta.$$

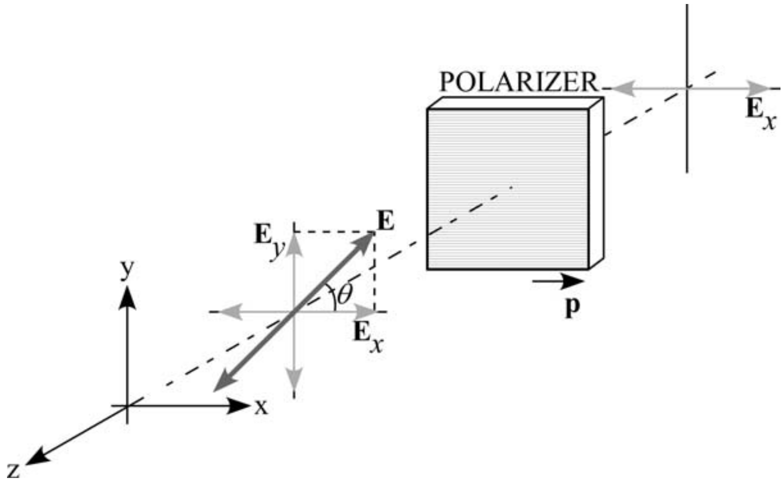


Figure 3. Electric field of a plane wave before and after passing through a polarizer.

Since the transmission axis of the polarizer, $\mathbf{p}$, is along the +x-direction, only the $\mathbf{E}_x$ component is passed while the $\mathbf{E}_y$ component is blocked, resulting in the output field:

$$\mathbf{E}_{out}(z,t) = \mathbf{E}_x(z,t).$$

Now let I_0 be the intensity of the original beam. Since intensity is proportional to the square of the electric field magnitude, we can see that the intensity at the output of the polarizer, I_{out}, takes the form:

$$I_{out} = I_0\cos^2\theta. \qquad \text{(Malus's Law)}$$

If we define Transmittance (T) as the ratio of output to input intensities, then for a polarizer we see that $T(\theta) = \cos^2\theta$. This relation is widely known as Malus's Law. Figure 4(a) displays a plot of T vs. θ. We can verify that maximum (100 %) and minimum (0 %) transmission is achieved when the polarizations are parallel ($\theta = 0^\circ$, 180°) and perpendicular ($\theta = 90^\circ$) to the transmission axis. In the case of unpolarized light, the above expression has to be averaged over $[0, \pi]$ which yields $T = 0.5$. Therefore, a polarizer allows only 50 % of unpolarized light to pass.

Light transmission through the LC layer can be obtained analytically by [3]:

$$T = \frac{1}{2} - \frac{1}{2}\frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+u^2}\right)}{1+u^2}.$$

Here $u = 2\Delta nd/\lambda$, where Δn is the birefringence of the liquid crystal material, d is the cell thickness, and λ is the wavelength of operation. Figure 4(b) displays a trace of this expression for T. One can see that the transmittance reaches a maximum value of 0.5 for values of u satisfying:

$$\sqrt{1+u^2} = 2n\ .$$

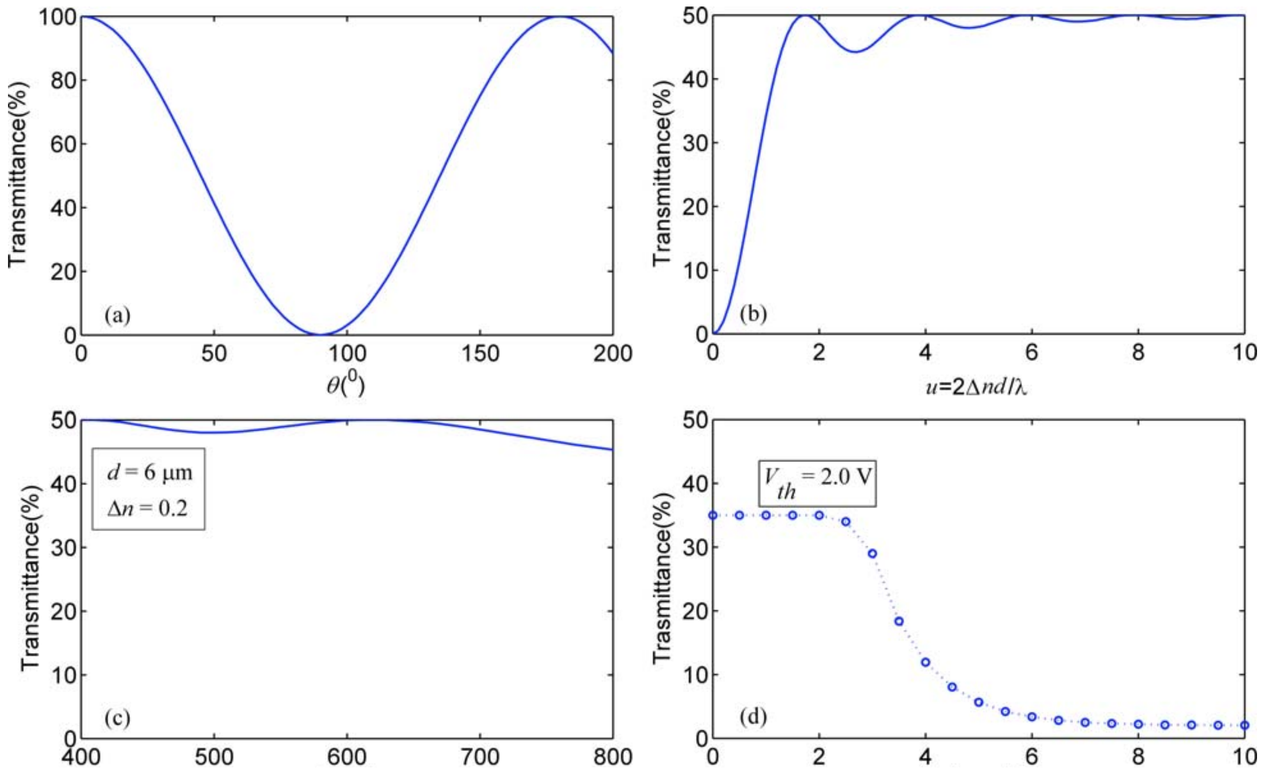


Figure 4. (a) Transmittance of a single polarizer, (b) Transmittance of an LCD pixel as a function of the normalized parameter *u* =2Δ*nd*/λ, (c) Transmittance of an LCD pixel as a function of visible wavelength, and (d) Transmittance of an LCD pixel as a function of applied voltage where threshold voltage is 2.0 V.

Recall the importance of the cell gap thickness in allowing for proper electric field rotation and this relation becomes clear. As an example, for n=2, $\Delta n = 0.2$ and $\lambda = 550$ nm (green light), we find $d = 5.3$ μm. We can then choose 5 or 6 μm spacers (typically polymer spheres of uniform diameter) to design our cell and obtain a reasonable value for the OFF state transmittance. Figure 4(c) is a trace of this transmittance over the entire visible range of wavelengths for $d = 6$ μm. The variation in the transmittance is negligible and, in general, near the maximum value of 50%.

So far, we have looked at the optical properties of the TN mode in the "OFF" state. It is important to understand how these properties change when a voltage is applied across the LC layer. Figure 4(d) is Transmittance (T) vs. Voltage (V) data for a typical LCD pixel. We can see that until the voltage reaches a certain threshold (V_{th}), there is no change in T. Once the voltage exceeds this value, however, T decreases and approaches a minimum. The threshold, V_{th}, is related to the LC material parameters according to the following relation, which can be derived using elastic continuum principles [3],

$$V_{th} = \sqrt{\frac{\pi^2}{\varepsilon_0 \Delta\varepsilon}\left(K_1 + \frac{1}{4}\left(K_3 - 2K_2\right)\right)},$$

where K_1, K_2,and K_3 are the splay, bend, and twist elastic constants. Threshold voltage not only determines the operating voltage but also the switching times of the LCD pixel, dictating the speed at which the device can switch between the "ON" and "OFF" states.

Construction and Characterization

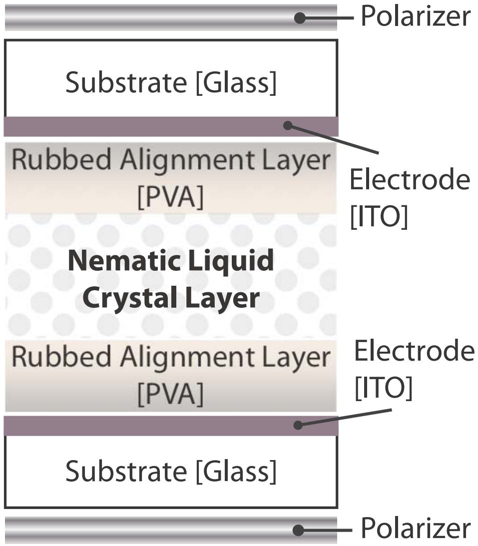


Figure 5. LCD pixel layers.

In this module, we will fabricate a single LCD pixel, with the construction shown in Fig. 5 (see also Fig. 2). We will start with two glass substrates coated with transparent and conductive Indium Tin Oxide (ITO) which will act as electrodes. Various materials can be employed as our alignment polymer, applied to the substrates via spin-casting. To create the alignment condition, we will rub the layers with a velvet cloth in the preferred direction, creating microgrooves into which the liquid crystals align themselves.

Once the two alignment layers have been patterned, spacers and optical adhesive will be applied and the two substrates will be sealed together to create the cell gap. This gap acts like a Fabry-Perot cavity as shown in Fig. 6(a). As such, the transmission from the cavity varies depending on the interference of the multiple reflections of light between the two surfaces. Figure 6(b) plots the transmittance data from one such cavity. Constructive interference occurs if the transmitted beams are in phase, corresponding to a peak in transmittance. Conversely, destructive interference occurs if the transmitted beams are out of phase, corresponding to a minimum in transmittance. A spectrometer will be employed to measure the thickness of the cell gap. A spectrometer operates by measuring the intensity transmitted through the empty gap as a function of wavelength. It is well known that the thickness of the cavity can be determined by noting the wavelengths of two adjacent peaks (Fig. 6(b)), and employing the following relation:

$$d = \frac{1}{2}\frac{\lambda_2\lambda_1}{\lambda_2 - \lambda_1}.$$

After measuring the cell gap thickness, we will fill the pixel with LC material and affix the polarizers on the surfaces to create the LCD pixel.

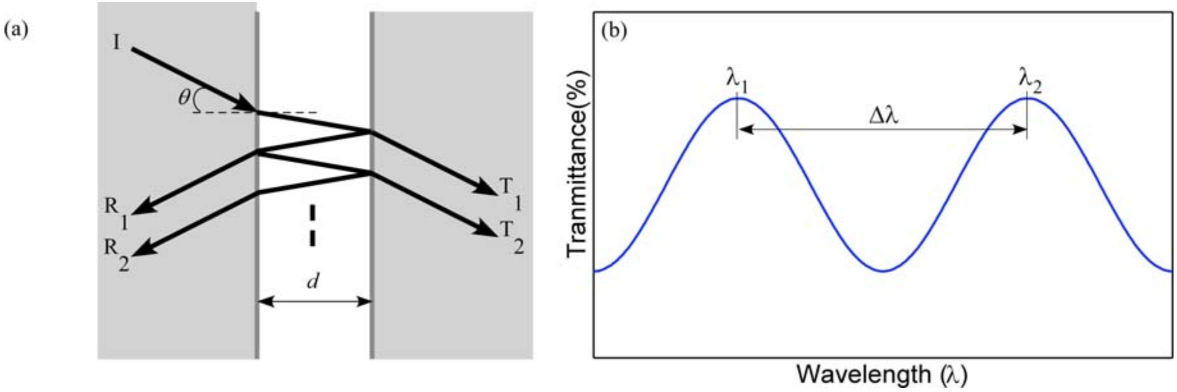


Figure 6. (a) A simple Fabry-Perot cavity, (b) Transmittance data from a typical cavity

An arrangement similar to the one shown in Fig. 7 will be used for characterization. A white LED will be our source of unpolarized light and a photodiode will be used to measure the transmitted intensity. You will be given a mounted polarizer whose optical axis can be rotated. You will first measure its transmittance and then verify Malus's Law by using a second polarizer shown in Fig. 7(a). The second polarizer will then be removed from its holder to be replaced by your LCD Pixel as seen in Fig. 7(b). The voltage across the pixel will be varied using a function generator and the output power will be recorded allowing you to calculate the transmittance of your LCD Pixel.

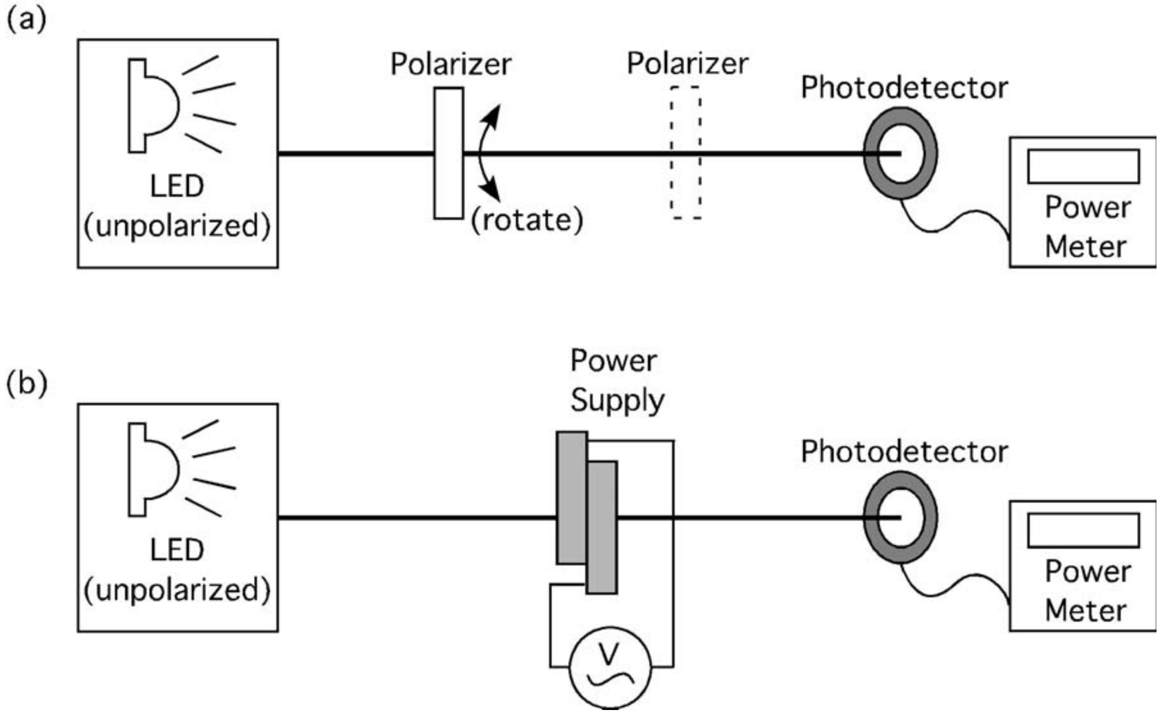


Figure 7. (a) Setup for verifying Malus's Law, (b) Setup for measuring transmittance through the LCD pixel.

Experimental Procedure

Important Notes:

•The option exists to perform this lab within a Glovebox designed to effectively evacuate harmful vapors, to provide a controlled environment in which to construct devices, and to provide a constant flow of nitrogen when necessary. Such is a good alternative to a fume hood or other controlled environment.

•Follow all of the instructions and precautions of your lab director(s) as variations from the procedures below may be in place.

•Always hold your samples along the edges and not by the flat faces.

•Always keep the ITO side of the substrates facing up.

•See Appendix for the alignment layer, spacer solution, and other material recipes.

Part 1 — Alignment Layers

EXPERIMENTAL OBJECTIVE:

To create the alignment layers for TN structure. These are needed to generate the twist in the liquid crystal material.

Procedure

1. Prepare your Lab Notebook:
    a. Fill in your lab notebook headings (Lab #, Station Name, Page #, Name, Date).
    b. Briefly record the objective of this experiment.
    c. Sketch the complete cross-section of the LCD we are creating in this lab.

2. Prepare Two Substrates:
    a. Use a Multimeter (or similar device) in resistance mode to find the conductive side of the ITO-coated glass. The ITO side should measure a resistance of below 1 kΩ.
    b. Clean both substrates using an air gun and **methanol**.
    c. Transfer the substrates to a hotplate set at 180 °C.

3. Spin-Cast the Alignment Layers on Two Substrates:
    a. Secure the substrate in the spin-caster and apply 8-10 drops of **Alignment Polymer** onto the substrate.
    b. Run Program A unless instructed otherwise.
    c. Once spinning is complete, place the substrate on a hotplate at 180 °C to “cure” for ~10 minutes.

Part 2 — Assembling the Cell Gap

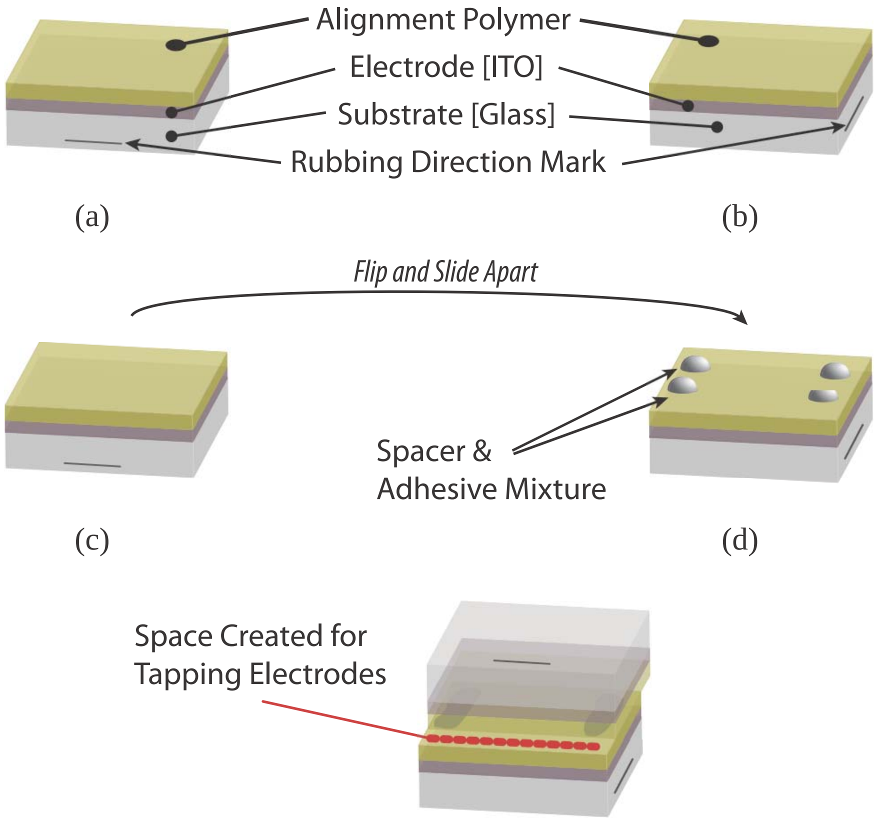
<u>EXPERIMENTAL OBJECTIVE</u>:

To create a cell gap of required thickness between prepared glass substrates using spacers and adhesive.

Procedure

1. Prepare your Lab Notebook as before.

2. Prepare and Rub Both Substrates:
    a. Mark the rubbing direction you desire on the GLASS SIDE as in Figs. 8(a) and (b).
    b. Using medium-strength pressure, rub the Alignment Polymer surface using a felt cloth (OR your pants or clothing) and a straightedge in the marked direction. Rub in the SAME DIRECTION 10-15 times.
    c. Using the air gun *gently* blow on the rubbed surfaces to remove any visible dust or lint sticking to the surface. Surfaces should *not* appear dusty.



(a) (b)

(c) (d)

(e)

Figure 8. (a),(b),(c) Substrates from Part 1 with alignment layers and orthogonal rubbing direction marks, (d) Substrate with spacer & adhesive mixture, (e) Completed cell after removing spacer solution, flipping one substrate onto the other, and offsetting.

3. Apply Spacers and Glue:
    a. Place the substrates on a flat surface such that the rubbing directions are orthogonal to each other as shown in Figs. 8(a) and (b).
    b. On one substrate, apply the mixture of **spacers** and **optical adhesive** in four *small* spots as in Fig. 8(d), leaving the other substrate untouched.

4. Create the Cell Gap:
    a. Carefully flip one substrate onto the other. IMPORTANT: Make sure that your alignment marks are orthogonal, i.e., *crossed*.
    b. Press down on the cell to spread the adhesive. Observe the assembly under diffuse light and “wiggle” the substrates until you see only a few interference fringes.
    c. Offset your substrates as in Fig. 8(e) to provide space for electrical connections.
    d. Cure the adhesive by exposing the substrates to UV light for ~1 minute. *Be sure to have on your safety goggles in order to block the UV light from your eyes!*

Calculations/Questions (Part 2)

These are to be written in your Lab Notebook.

1. Consider the amount of absorption of the completed cell. Roughly speaking, do you think that the glass, ITO, or alignment polymer absorbs much light? If so, which layer do you think absorbs the most? The least?
2. Did you see any visible change on your substrates before/after rubbing of the alignment layers?

Part 3 — Measuring Cell Gap Thickness

Note: *This portion of the lab is intended to be performed with a portable spectrometer and light source, e.g., JAZ by Ocean Optics, Inc. However, any spectrometer or spectrophotometer may be used to perform these same tasks with minimal modification to the procedure.*

EXPERIMENTAL OBJECTIVE:

To measure the thickness of the cell gap using a spectrometer.

Procedure

1. Prepare your Lab Notebook as before, ensuring to sketch the characterization set-up.

2. Prepare the Set-Up:
   a. *If necessary*: Start the spectrometer software, Turn on the spectrometer, Select ‘New Transmission Measurement’, and Perform the required reference measurements.
   b. Set the Zoom Range for the Transmission Measurement to **Wavelength 550 nm – 650 nm** for the x-axis and **Transmission 70% - 100%** for the y-axis.
   c. Ensure that the sample holder is empty and positioned between the input and output optical fibers so that no part of the sample holder is blocking the path of the light.

3. Acquire Transmission Spectra:
   a. Place your cell in the sample holder and turn ON the Light Source.
   b. You should see several peaks and valleys in the Transmission Spectrum as shown in Fig. 6(b). If you do not, try repositioning your cell and ensure that the light is passing through the center of the cell and not the glue spots.
   c. Select any **two adjacent peaks** and record the corresponding wavelengths, λ_1 and λ_2.
   d. Reposition your cell and repeat part (d) twice, tabulating measurements as below.
   e. For the final measurement, save the Transmission Spectrum Data to a file.

Measurement Spot #	Wavelength (λ_1)	Wavelength (λ_1)	Thickness (d)
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Calculations/Questions (Part 3)

These are to be written in your Lab Notebook.

1. Recall that the thickness of the cell, *d*, can be estimated by the Fabry-Perot analogy discussed in the introduction section. Calculate *d* for the three spots measured and complete the table.
2. Comment on the uniformity of the cell gap for your sample. In a few lines, explain how the cell thickness affects the image that can be made in a real LCD (e.g. a television).
3. Using the Transmission Spectrum Data you saved to disk, plot Transmission (%) vs. Wavelength (nm). Adjust the axes of the plot to best show 3-6 transmission peaks. Properly title and label the plot and insert it into your Lab Notebook with glue or tape (no staples!).

Part 4 — Filling the LC Cell

EXPERIMENTAL OBJECTIVE:

To fill the cell gap with liquid crystal and attach the polarizers to complete the LCD pixel.

Procedure

1. Prepare your Lab Notebook as before. Be sure to record the information from the LC bottle.

2. Fill your Cell with LC:
    a. Place your assembly on a black surface.
    b. Pipette a very small amount of LC to one of the unglued sides (the offset shelf) of your cell as shown in Fig. 9. Capillary action will pull the LC into the gap.
    c. After the LC fills the entire gap, gently clean the edges of the cell with a wipe.

3. Apply Polarizers to your Cell:
    a. Remove the blue protective covering (if present) from both sides of two **polarizers**.
    b. Apply double-sided tape to one side of your cell along the glued edges and attach one polarizer as shown in Fig. 9, being careful to not cover up the offset shelf.
    c. Repeat for the other side of the cell, ensuring that the second polarizer is orthogonal to the first.

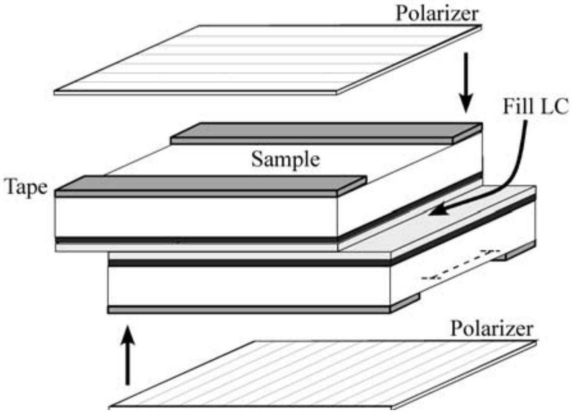

Figure 9. Assembling the LC Cell.

Part 5 — Transmittance Measurements

EXPERIMENTAL OBJECTIVES:

(1) To measure the transmittance of a single polarizer.
(2) To verify Malus's Law.
(3) To acquire the Transmittance (T) vs. Voltage (V) characteristics of the single LCD pixel

Procedure

1. Prepare your Lab Notebook as before. Be sure to include a sketch of the measurement setup.

2. Measure Polarizer Transmittance:
   a. With nothing between the **LED** and the **photodiode**, record the measured power output. This will serve as our baseline reading (I_{IN}).
   b. Place the **rotatable polarizer** between the LED and the photodiode. Record the intensity measured (I_P).
   c. Calculate the **Polarizer Transmittance** using T = I_P / I_{IN}

3. Verify Malus's Law:
   a. Place the **polarizer film** in the sample holder between the rotatable polarizer and the photodiode.
   b. Measure the output intensity within a 90° range at every 10° by rotating the rotatable polarizer to the required angle and recording the intensity measured on the **power meter** (I_{OUT}). Tabulate your measurements in a table like that below.
   c. Calculate the transmittance of the polarizer film at each angle via $T = I_{OUT} / I_P$

Measurement #	Angle (°)	Output Intensity, I_{OUT} (W/cm^2)	Transmittance (T)
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4. Measure the Transmittance of your LCD Pixel:
   a. Remove the polarizer film from the sample holder and insert your LCD pixel.
   b. Remove the rotatable polarizer from the setup and secure it elsewhere on the table.
   c. Attach the **alligator clips** from the **function generator** to your LCD electrodes.
   d. Record the reading on the power meter with the LED OFF as your first reading.
   e. Increase the input voltage in steps of 0.5 V from 0.0 V to 5.0 V, recording values in a table like that above, substituting the heading *Voltage* for *Angle*.
   f. After you complete your measurements, dismount your LCD and switch off the LED.
   g. Calculate the transmittance of your LCD Pixel at each voltage.

5. You are welcome to keep your LCD pixel as a souvenir of a job well done!

Calculations/Questions (Part 5)

These are to be written in your Lab Notebook.

1. Transmittance (T) is given by $T = I_{OUT}/I_{IN}$. Calculate and plot the recorded Transmittance values for the polarizer pair for the different angles. On the same plot, calculate and plot the values expected from Malus's Law. Comment on any differences observed.
2. Plot the Transmittance values for your LCD pixel as a function of the voltage applied to the LCD pixel. Estimate the threshold voltage (V_{th}) for your device (See Fig. 4(c) for reference). For MLC-6080, K_1 = 14.4 pN, K_2 = 7.1 pN, K_3 = 19.1 pN, $\Delta\varepsilon = +7.2$ and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. Use these to calculate V_{th} using the expression given earlier. Compare this estimate with the value measured and identify reasons for discrepancy, if any.
3. The turn-ON and turn-OFF times for an LCD are given by:

$$\tau_{on} = \ln(9)\frac{\gamma_1 d^2}{\varepsilon_0 \Delta\varepsilon\left(V^2 - V_{th}^{\ 2}\right)}$$

$$\tau_{off} = \ln(9)\frac{\gamma_1 d^2}{\varepsilon_0 \Delta\varepsilon\left(V_{th}^{\ 2}\right)}.$$

   Given γ_1= 157 mPa-s, using the cell thickness determined in the previous section, and V_{th}, estimate the above switching times for your device.
4. Assuming that our eye requires at least 30 frames/second to interpret a video clearly and to avoid aliasing, comment on whether the switching times calculated in the previous question are sufficient for this type of application.

Appendix A: Lab Notebook Guidelines

1. **Do** record entries *legibly*, *neatly*, and in *INK*.
2. **Do** sign and date every page.
3. **Do** fill in headings completely (Lab #, Station Name, Page #).
4. **Do** record your experimental objective and describe your experiment.
5. **Do** record your experimental setup, data, and all calculations in such a way that someone else could duplicate/verify your steps.
6. **Do** include extrinsic materials by **tape** or permanent glue (staples are acceptable but not preferred). This includes all raw data from recording instruments (e.g., microscope photos), **computer generated graphs**, drawings, specification sheets, etc.
7. **Do** work in chronological order, i.e., **Do Not** skip parts unless specifically told to do so.
8. **Do Not** erase or remove material. If you mess up, simply cross it out and start again! This is part of the experimental process. We will provide you with as many sheets as you need.

Appendix B: Spin-Caster Parameters

- The following programs were created on a *Laurell Technologies Model WS-40B-6NPP/LITE* Spin-Caster. Other spin-casters can be used but the lab director should ensure the parameters result in quality films.

Program A

Single Stage: Speed 3500 rpm
Acceleration 1500 rpm/second
Time 30 seconds

Appendix C: Alignment Polymer Preparation Instructions

- The following instructions employ *Poly(vinyl alcohol) 98% hydrolyzed (PVA), Item # 348406, Molecular Weight 13,000 – 23,000*, distributed by Sigma-Aldrich, Inc., St. Louis, MO, USA. A single 25 gram bottle of PVA will produce enough polymer solution for ~700 single-pixel LCDs. The instructions below prepare ~20 mL of polymer solution, enough for ~10 single-pixel LCDs (assuming 1 mL of polymer solution per substrate).

- The polymer described is intended to be used in conjunction with the spin-caster parameters in **Appendix B**. The lab director should ensure that alterations to ether the material preparation instructions or to the spin-caster parameters result in quality films and successful device fabrication.

- Other alignment polymers may be used, such as *Sunever Polyimide Varnish, Grade 410, Type 0825*, manufactured by Nissan Chemical Industries, Ltd., distributed by Brewer Science, Rolla, MO, USA. However, the lab director should be aware that preparation and spin-casting parameters would need to be altered.

PVA (2.0% by weight in Deionized H_2O)

1. Clean one 20 mL vial (amber or clear).
2. Add ~340 mg PVA to the vial.
3. Add ~17,000 mg Dionized H_2O to the vial, creating a 2.0 % by weight solution.
4. Secure the cap to the vial and wrap the seam with vinyl tape (aka electrical tape).
5. Place the vial in an ultrasonic bath for 60 minutes or until well-mixed.
6. Total amount of prepared solution will be ~20 mL, adjust as necessary.

Appendix D: Adhesive-Spacer Material Preparation Instructions

- The following instructions employ:
  - 3 mL Syringes with Luer-Lok Tips, *Catalog No. 14-823-41*, distributed by Thermo Fisher Scientific, Inc., Pittsburgh, PA, USA.
  - Precision Dispense Tips, *Part No. 5123-B-45*, distributed by EFD, Inc., East Providence, RI, USA.
  - Ultraviolet-Curable Optical Adhesive, *UVS 91*, distributed by Norland Products, Inc.
  - Dry Spacers, *Silica{Dry} 5 µm Code #SS06N*, distributed by Bangs Laboratories, Inc.

- A single 1 gram bottle of optical adhesive and a single 500 milligram bottle of dry spacers will produce enough adhesive mixture for thousands of single-pixel LCDs. A syringe of the mixture as described below will be adequate for hundreds.

- Other adhesive-spacer combinations may be used with minimal alterations to the lab procedures. However, the lab director should be aware that changes in materials *could* result in variations in the cell gap thickness, thereby yielding unexpected LCD operation.

Adhesive-Spacer Mixture

1. Place ~5 grams of the optical adhesive into a clean petri dish.
2. Sprinkle ~5 milligrams (a very small amount) of the dry spacers over the adhesive.
3. Stir the mixture well (it will become cloudy).
4. Insert the mixture into a 3 mL syringe and remove most of the air with the plunger.
5. Screw a dispensing tip onto the syringe.
6. Wrap syringe with aluminum foil to prevent penetration by ultraviolet light.
7. Mixture will expire on date marked on the original optical adhesive bottle.

Appendix E: Material Recommendations

- **ITO-Coated Glass Substrates**: *Part No. CG – 90IN – 0110*; 25 x 25 x 0.8 mm unpolished float glass, SiO_2 passivated, indium tin oxide coated one surface, R_S = 70 – 100 ohms; distributed by Delta Technologies, Ltd., Stillwater, MN, USA. Two substrates are needed for each single-pixel LCD.

- **Liquid Crystal Material**: *Licristal MLC-6080*; distributed by EMD Chemicals, Inc., affiliate of Merck KGaA, Hawthorne, NY, USA. A single 5 gram bottle contains enough LC for between 175 and 250 single-pixel LCDs (assuming 20 to 30 milligrams per device).

- **Polarizers**: 1 x 1 inch squares cut from larger sheets (17 x 15 inch) *Stock No. NT45-667*; distributed by Edmund Optics, Inc., Barrington, NJ, USA. A single 17 x 15 inch sheet will supply enough polarizers for ~125 single-pixel LCDs (assuming two 1 x 1 inch polarizers per device).

Appendix E: Relevant Sources (Books, Links, Papers, etc.)

1. P.J. Collings, *Liquid Crystals: Nature's Delicate Phase of Matter*, (Princeton University Press, 2001), pp. 1 – 45, 110 – 111.
2. I.-C. Khoo, *Liquid Crystals*, 2nd ed. (John Wiley & Sons, Inc., 2007), pp. 1 – 96.
3. G. Crawford and M.J. Escuti, "Liquid Crystal Display Technology," in *Encyclopedia of Imaging Science and Technology*, edited by J.P. Hornak (John Wiley & Sons, Inc., 2008), pp. 955 – 968.
4. E. Hecht, "Polarization,", in *Optics* 2nd ed., (Addison Wesley, 1985), pp. 325 – 384.
5. A.D. Ryer, *Light Measurement Handbook*, (International Light, Inc., MA, 1997).