Investigating the Optical Shaping Properties of a Liquid Crystal Display

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science with Honors in Physics from The College of William and Mary in Virginia

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Abstract

A pulse-shaper is a device that can alter the shape of an optical packet, such as the output of a modern femtosecond laser system. Having greater control over the shape of the pulse means control over its properties and broadening the laser system's capabilities. However, in order for a device to be a good pulse-shaper, it must not alter the desired properties of the optical packet. This research is interested in examining the suitability of a Liquid Crystal Display to act as a pulse-shaper, and examines its effects on specific qualities such as intensity, phase, and polarization of the light it interacts with, in addition to its ability to control the shape of the light packet.

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Acknowledgements

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1.0 Introduction

Modern ultrafast lasers can produce a pulse of light with a peak pulse power of around 10^{15} W and duration on the order of 10^{-15} s (one femtosecond), and thus are also known as femtosecond lasers. The advent of ultrafast laser technology has allowed the re-creation of physical conditions that were previously impossible to find on Earth, including gigagauss magnetic fields, terabar light pressures, and electron accelerations on the order of $10^{22}\ \mathrm{m/s}^2$, physical conditions which only occur in nature in the cores of stars or at the regions bordering a black hole [3].

Ultrafast optical systems are often geared towards one of two goals: using light pulses to explain fast-evolving events in materials or the use of these pulses to focus an extremely high energy density into a small volume. In either case, a greater degree of control over the shape of the light pulse can increase its utility, and that is why research into the pulse-shaping properties of a Liquid Crystal Display (LCD) is an interesting topic to explore. The LCD in this case is an LCD monitor with everything (including the polarization layers) but the liquid crystal plate stripped away. It is still connected to video input cables and attempts to display whatever image is sent to it, which means it will shape light passing through it. What are the advantages and disadvantages of using the LCD to shape a laser pulse? For this thesis, we have used a Helium Neon (HeNe) laser, the LCD, and various optical configurations to determine how the LCD affects the intensity, polarization, and phase of coherent light passing through it. An ideal phase-only pulse shaper (changes the shape of the optical packet by adding or subtracting phase) would not change the polarization or reduce the average intensity of the pulse.

2.0 Background Theory

Before an in-depth discussion of the methods and results taken for this research, it is useful to step back and review the theory behind the research.

2.1 Basic Laser Theory

The word “laser” is an acronym for Light Amplification through Stimulated Emission of Radiation. A laser uses a source of pure energy (light source, voltage source, etc.) and amplification techniques to generate a *coherent* beam of light. Coherent light is light in which each light particle (or wave, depending on how one wants to view it) shares the same properties. Perfectly coherent light has the same direction, wavelength, phase, and polarization for each light particle. Put simply, stimulated emission is the process by which the light from the light source is turned into laser light and optical feedback is the process which laser amplifies light. The simplest laser (shown below) would consist of three parts: a light source, a gain or amplifying medium (where stimulated emission occurs), and mirrors to trap light in the laser cavity and reflect it back through the amplifying medium to achieve beam growth.

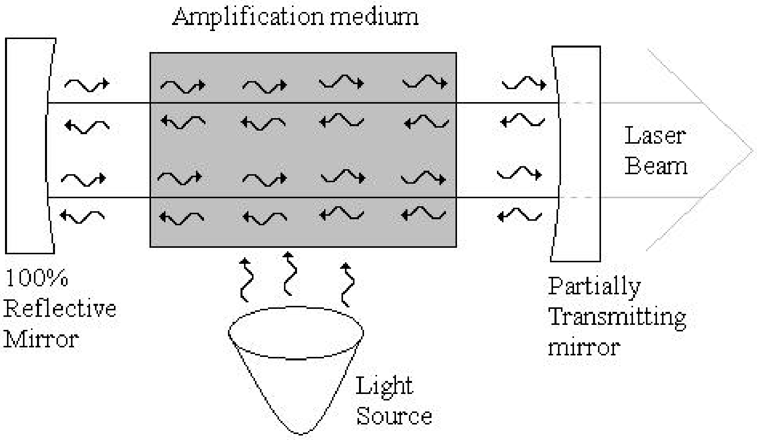


Figure 1: A simple laser cavity.

In the example, light emitted from a light source travels into the amplification medium and excites atoms in the medium from their ground states into their excited states. In a real laser, the excitation source need not be a light source, but could be any thermal or electrical energy source so long as it is able to excite the atoms in the amplification medium and create a *population inversion* in the medium. Population inversion is the state in which the number of excited atoms exceeds the number of ground state atoms in the amplification medium. To see how population inversion occurs, imagine a medium in which there are three possible energy states for atoms to exist in: 1 (ground state), 2 (metastable excited state), and 3 (unstable excited state), as depicted below:

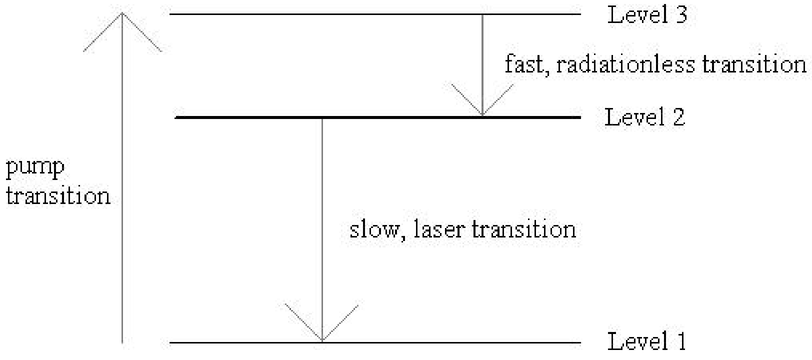


Figure 2: Energy states of amplification medium

Unless something is exciting the amplification medium, its atoms are in the ground state (Level 1). When the excitation source is *pumping* the atoms, or exciting them to a higher energy level, a certain number of the atoms transition to that state (Level 3 in the picture). The atoms then spontaneously decay to a more stable excited state (Level 2). This decay is often very fast, and usually doesn't involve any sort of radiative emissions (normally atoms emit photons as light energy when they drop in energy level). Instead, what little energy is lost in the transition often goes to vibrational motion of the medium (heat). If the lifetime of the transition τ_{21} is much larger than the lifetime of the transition τ_{32} (atoms are much more stable in level 2 than 3), then atoms will begin to accumulate in level 2 and the number of atoms, or *population*, of level 3 will be negligible ($N_3 \approx 0$). If after sufficient pumping over half the atoms in the medium are in level 2, population inversion ($N_2 > N_1$) has been achieved.

To understand the importance of population inversion, let us look at the general equation for the intensity of light at a distance *z* into a medium:

$$I = I_0 e^{\sigma_{ul}[N_u - (g_u/g_l)N_l]z} \tag{1}$$

This refers to a beam of initial intensity I_0, in a medium whose atoms can be in upper energy level *u* (level 2 in the previous example) or lower energy level *l* (level 1 in the previous example). Here, σ_{ul} is a constant that is based on the average decay rate from *u* to *l*, the wavelength of the emitted light, and the temperature of the medium. The constants g_u and g_l are statistical weights of the likelihood for an atom being in a particular energy state, and N_u and N_l refer to the populations of those energy levels. Clearly by looking at equation (1), *I* will only increase beyond I_0 if the exponent of *e* is positive, and since σ_{ul} and *z* must be positive, we can deduce that $N_u > \frac{g_u}{g_l} N_l$ in order for there to be any gain in the medium. Thus, population inversion is a requirement to have the amplification necessary for a laser to operate.

Once an excitation source has excited a number of atoms in the amplification medium, those atoms will eventually decay to the lower energy level and emit a photon. The frequency of the photon emitted is related to the energy difference between the two levels by the equation:

$$E = E_u - E_l = h\upsilon \tag{2}$$

where E_u is the energy of the atom's excited state, E_l is the energy of the atom's lower state, h is Planck's constant and υ is the frequency of the photon emitted. The frequency, and therefore wavelength (which is just $\lambda = \frac{c}{\upsilon}$), of light emitted can be predicted. This natural decay process is known as *spontaneous emission*. What differentiates lasers from more mundane light sources, however, is their utilization of *stimulated emission* of light. Stimulated emission occurs when an incoming photon strikes an atom in an excited state. If that atom is capable of dropping to a lower energy state by emitting a photon of equal energy (and hence, frequency) to the incoming photon, there is a probability (which can be calculated using quantum mechanics) that it will do so. Thus, an incoming photon interacting with an excited atom can result in two outgoing photons and a ground-state atom. The remarkable (and useful) property of this process is that the two outgoing photons will not only be identical in frequency, but also in direction, phase, and polarization.

Thus far, an excitation source has created a population inversion in the gain medium, and that population inversion along with spontaneous emission of light has led to the stimulated emission of light. The light is made coherent by coupling it to a laser cavity. Only light that is capable of forming a standing wave in the laser cavity is able to continue propagation, and so only photons of the wavelength $\lambda_n = 2L/n$ are allowed to propagate within the laser cavity (in Figure 1, L is the distance between the two mirrors that make up the simple laser cavity). The frequency of the light in the laser cavity is therefore constrained by the type of light allowed by the energy transitions available and the type of light allowed to propagate by the laser cavity.

This means that only light of a certain wavelength, phase, and direction is allowed to propagate. Through stimulated emission in the gain medium, this light is amplified and creates more photons of the same wavelength, phase, polarization, and direction, and thus coherent light is created in the laser. As depicted in Figure 1, one of the mirrors of the laser cavity is only semi-reflective and transmits some of the light in the cavity, and this is how light is extracted from the cavity to be used. The rate at which photons are lost from the laser cavity, whether due to absorption by the medium or due to photons simply exiting the cavity through the partially silvered mirror, is known as *loss*. The number of photons created through stimulated emission is known as *gain*. Of course in order for a laser to function the gain must be greater than the loss.

2.2 Ultrafast Chirped-Pulse Amplification Systems

As mentioned before, ultrafast optical systems are often geared towards one of two goals: using light pulses to illuminate fast-evolving events in materials or the use of these pulses to focus an extremely high energy density into a small volume (Backus et al). Our laser system is designed with the latter in mind. Ultrafast lasers are built on the same principles as ordinary *continuous wave* (CW) lasers. The laser must be pumped, spontaneous emission will produce only certain wavelengths of light, and of those wavelengths only a few will be allowed to propagate in the laser oscillator cavity. The difference between an ultrafast laser and a CW laser is that an ultrafast laser can *mode-lock* in the oscillator cavity. The laser in the cavity is made up of a small spectrum of Wavelengths. When these wavelengths interfere constructively at only certain points along the laser cavity axis and interfere destructively elsewhere, the laser is considered mode-locked. The modes interfere with each other in the cavity of a mode-locked laser, producing a single point of constructive interference that travels around the cavity and is used as the output signal. This is shown below.

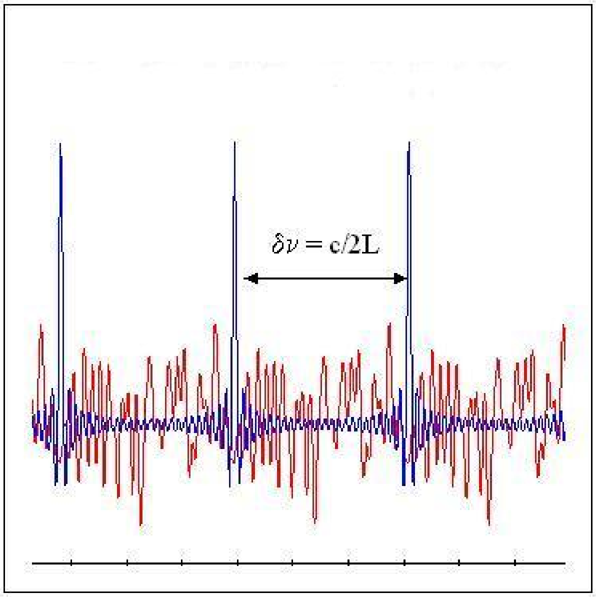


Figure 3: Mode-locked (blue) intensity compared to CW (red) intensity[5].

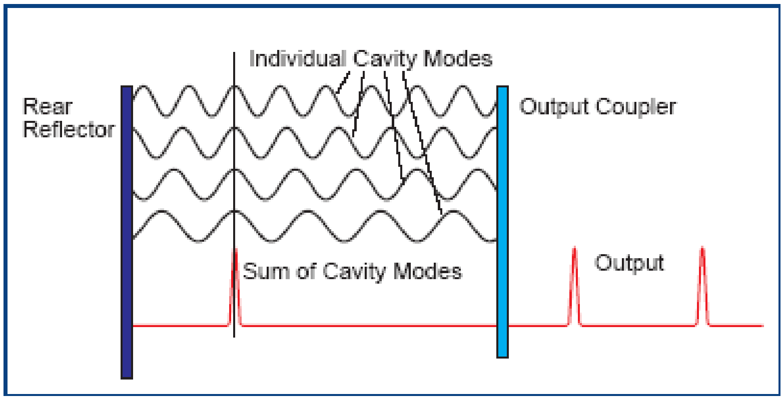


Figure 4: A mode-locked oscillator[5].

Clearly, the output signal would not look as clean as shown in Figure 4 through interference alone, as the different modes would not interfere completely destructively in all places but the selected pulse. In order to remove the unwanted signal, one can place a *saturable absorber* into the laser cavity. A saturable absorber is a substance that absorbs all light below a certain intensity threshold. Each time the light passes through the saturable absorber, the most intense part of the signal is reduced less than the rest, until eventually there is just one peak oscillating back and forth in the cavity (our lab does not use a saturable absorber).

Another important aspect of ultrafast lasers is that they often employ a process known as Chirped-Pulse Amplification (CPA). The goal of CPA is to increase the energy of the light pulse while avoiding very high peak powers in the amplification process itself (which could lead to non-linear optical effects and even damage to the amplifier). Refer to Figure 5 for a diagram of the CPA process. First the light pulse is directed to a stretcher, which consists of a prism or diffraction grating pair that stretches the pulse out

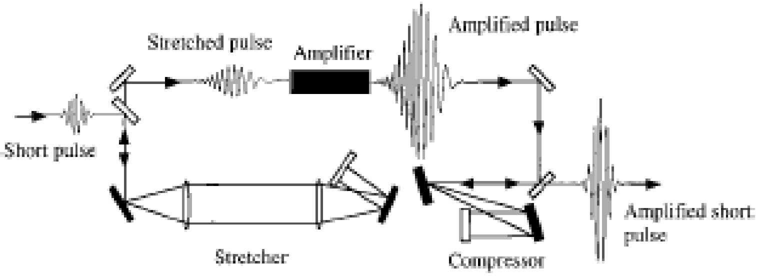


Figure 5: Diagram of a CPA system
Courtesy of [7]

in duration (making a longer pulse). In Figure 5 the stretcher consists of a grating pair with a lens pair in between. Here, a pulse travels to the stretcher, and is diffracted by the first grating. Different wavelengths will be diffracted at different angles, so the grating serves to spread the wavelengths out. The beam is then refocused using a pair of lenses and reflected off a second grating and mirror to go back the way it came. The stretched pulse is then sent to the amplifier where amplification increases the energy of the pulse. After amplification, the pulse is recompressed using another grating or prism pair, so that the final output signal is as short as the input signal, but much more energetic.

2.3 Theory Behind LCDs

Along with lasers, Liquid Crystal Display (LCD) technology is one of the recent fields that has attracted much scientific as well as public interest. Their applications range from devices as diverse as microwave ovens, televisions, computer monitors, CD players, and digital clocks and watches. They offer many advantages over other display technologies since they are light and relatively power efficient when compared to their competitors. The key materials in LCDs are, as the name implies, liquid crystals. But how can something be both a crystal (which most people think of as a solid) and a liquid? Well, they possess some of the qualities of each. Like a solid, liquid crystals maintain their orientation with respect to one another. Like a liquid, they can change their position with respect to one another. Liquid crystals are closer to their liquid phase than to their solid phase, as it takes a tremendous amount of heat to turn something from a solid to a liquid crystal, but only a relatively minor amount of heat to turn a liquid crystal into a liquid (thus LCDs are very temperature sensitive). There are many types of liquid crystals, and they can be in different phases, but the types used in LCDs are in the *nematic phase*. When in the nematic phase, the molecules of the liquid crystal are parallel and able to travel past each other on their longitudinal axis. The optical axis of a crystal in this phase orients itself in the direction of a *director*, which can be anything from an applied magnetic field to a surface with microscopic grooves cut in it. Most LCDs use a particular type of crystal in the nematic phase called *twisted nematics* (TN). TN crystals are naturally twisted, and applying current to them untwists them to a degree dependent on the applied voltage.

Most LCDs are no more than a variation on a fairly simple arrangement. They are essentially composed of a sheet of TN crystals sandwiched between two sheets of polarized glass. The glass has its polarizing coating on the side that does not touch the TN crystals, and the side that does touch the TN crystal has rows of grooves etched into it in the same direction as the polarization. The outgoing polarized glass plate is oriented with its polarization and etchings perpendicular to the incoming one, and the TN crystals in between twist their orientation 90 degrees in spanning the two plates so that they line up with the grooves where they touch the plates. Light traveling through the TN crystals will have its polarization shifted by the same amount as the twist in the TN crystal. Incoming light, therefore, will go through the first polarized plate and become linearly polarized. If the TN crystal is in its normal, twisted state the light then travels through it and rotates its polarization 90 degrees to exit through the perpendicularly polarized plate. When a charge is applied to the TN crystals, they untwist and incoming light maintains the polarization imparted to it by the first plate. Because this polarization is perpendicular to that of the second plate, the second plate blocks the light. This is clearly illustrated in Figure 6.

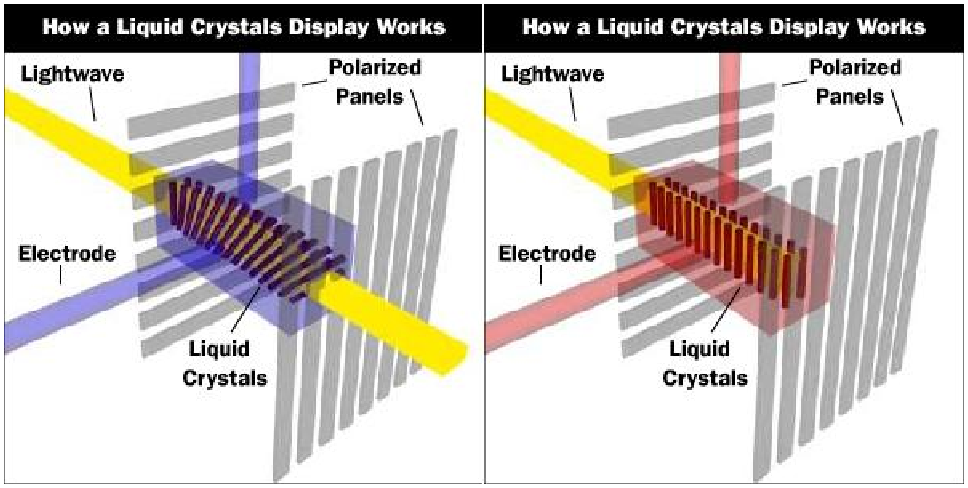


Figure 6: Light passing through an LCD without voltage applied to the TN crystals (left) compared to when charge is applied (right) and the crystals straighten out[4].

More advanced forms of LCDs (like those used in computer monitors) are composed of a matrix of TN pixels that react as described above. There are two common types of monitors: passive matrix and active matrix. In a passive matrix monitor, one of the plates of glass is etched with a substrate of transparent, conductive rows (often of indium-tin oxide) and the other is etched with columns. Each of the substrates is controlled by integrated circuits that determine which columns and which rows deliver charge, and the circuits need only determine the row and column that correspond to a specific pixel and deliver current down it in order to activate that pixel. The disadvantage of passive matrix monitors is that it is difficult to control the flow of current precisely, so often when one pixel untwists the pixels around it slightly untwist too from voltage leaks, resulting in a fuzzy picture.

Another form of LCD monitor is the active matrix monitor. These depend on *thin film transistors* (TFTs). TFTs are essentially small transistors and capacitors that can control how much, if any, charge is allowed onto a pathway. The setup is essentially the same as the passive matrix, the difference being that though the columns are still connected to voltage sources, the rows are instead connected to TFTs. When a pixel is to be activated, the appropriate TFT activates the corresponding row, allowing the voltage source to send its charge down the corresponding column. Since the adjacent rows were not activated, they cannot pick up any of the charge, which makes for sharper image quality. Also, since the TFTs can control to a great degree of precision how much charge a pixel accepts, they can control how much the TN crystal untwists, allowing more or less light to come through the pixel.

The kind of LCD being examined in this research is a View Frame Spectra C by the NView Corporation. It is a transmissive LCD to be used with an overhead projector and designed to display the output of another electronic device (like a computer). We have stripped away everything (including the polarizing layers) from the device, so that it is just a layer of liquid crystals sandwiched between two layers of etched glass and capable of attempting to display input as an image on its display. We do our work using it by connecting it to a computer and feeding it the same output as the monitor. Thus, when activated, the LCD attempts to display anything on the computer monitor, which is how we can control its signal.

3.0 Experimental Setup and Results

3.1 Stretching HeNe Beam in Space and Passing it through the LCD

This first experiment is intended to measure how well the LCD transmits light and to determine whether or not the color displayed on the screen imparts any relative phase onto the light passing through it. As shown in Figure 7 below, the laser is first blown up by a spherical lens (L1), and then it is collimated by a lens (L2) one focal length away. Once the beam has been blown up and collimated, it is sent through the LCD and refocused by another lens (L3) two focal lengths away from L2. The beam then is allowed to focus down and expand is re-focused loosely, and the resulting signal is sent through a filter to the Charged Coupled Device (CCD) camera, which reads the intensity of the beam.

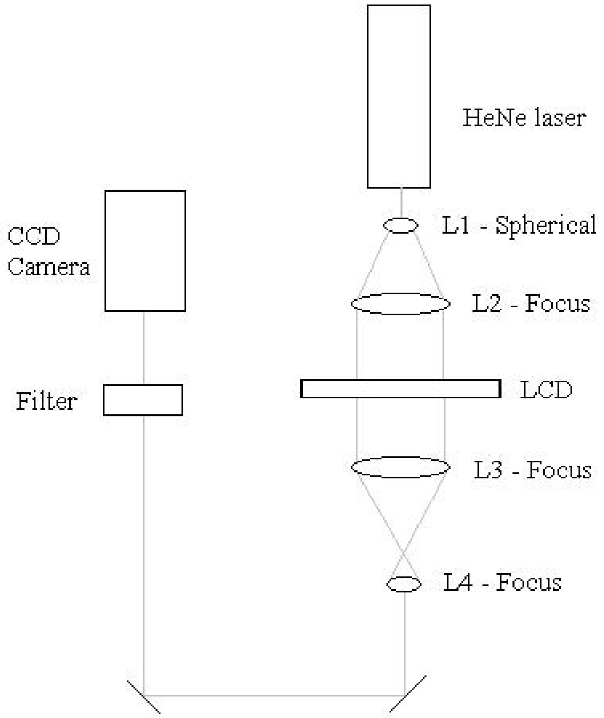


Figure 7: Stretching HeNe setup

The first measurement, that of intensity, is fairly straightforward. The following measurements of intensity were taken using the CCD camera. It should be noted that the intensity is not in any real units; it is simply a measurement of relative intensity that the CCD can do. The reason for an adjusted column is that I had to use a filter 100 times more powerful for the readings with no LCD, so I multiplied this value by 100 to give it the correct intensity relative to the other readings.

	Measured Intensity	Adjusted Intensity
No LCD	62	6200
With LCD	95	95

As is obvious, the LCD did a terrible job of transmitting the light. Only about 1.5% of the signal got through ($^{95}\!/_{6200} = 0.01532258$). Already, that is a strike against its efficacy as a pulse-shaper.

The next thing to do was see if putting an image on the LCD affected the relative phase of the light. The way we chose to do this was by sending an image to the LCD that was half black and half white, and comparing this to a monochromatic image. The results are illustrated in Figure 8 below. Changing the color of half the region from white to black clearly had an effect. The maximum that was in the center (caused by all parts of the beam interfering constructively) split into two separate maxima, so there was destructive interference in the middle. In all likelihood, the LCD added relative phase to one of the parts of the beam, thus causing the interference.

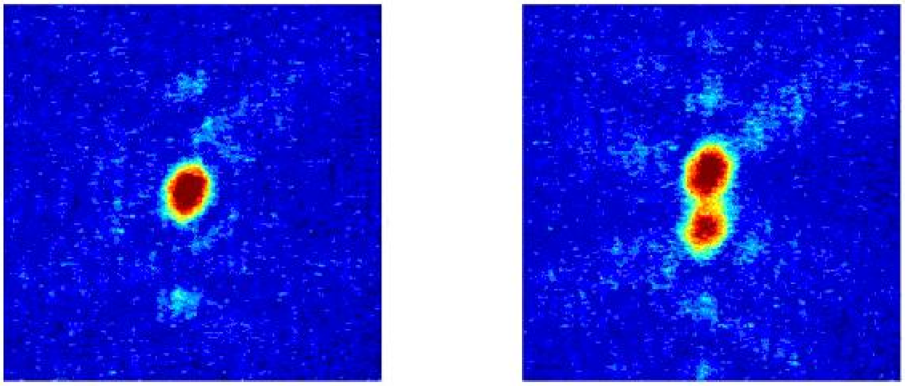


Figure 8: The laser image on the CCD is changed from a single maximum to two once half of the image on the LCD it passes through is changed from white to black

3.2 Proof of Principle: Building an Interferometer

The goal of this experiment is to build an interferometer that utilizes the tilting of a microscope slide to change the phase between two otherwise identical, coherent beams of light and make sure it behaves as expected. Building this rather standard interferometer is important not only because it will serve as a simple model to build upon for the next experiment, but also because it will allow us to ensure that all the parts in our arrangement are working as intended. The materials for this experiment are the HeNe laser, two mounted mirrors, two 50/50 beamsplitters, two irises, a pin diode, and a normal glass microscope slide fastened with double sided tape to an adjustable kinematic optical mount. A diagram of the setup is shown below in Figure 9.

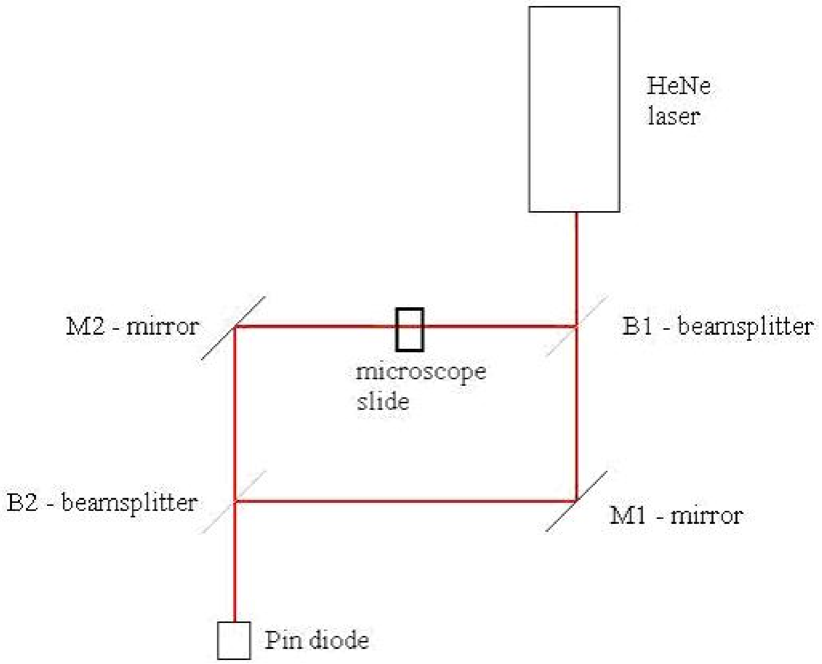


Figure 9: Microscope slide interferometer setup

The first stage in construction was turning on the laser and adjusting the laser until it hit a point on the opposite wall that roughly corresponded to its position (to ensure the beam was level). Next, I adjusted all of the mounts to be the same height as the laser, and clamped the first beamsplitter (B1) into place in front of the laser such that the laser hit the optic in the center at a roughly 45 degree angle as diagrammed. I then secured the rest of the optics into place following the diagram and similar logic. To align the optics properly, I then put the two irises in a straight line to catch the output beams, one (I1) just after B2 (where the pin diode will go) and the other (I2) in a straight line behind it, as far back as the table would allow. I then adjusted B1 until the beam that intersected the microscope slide (beam 1) lay dead in the center of I1. After that, I adjusted M2 until beam 1 intersected I2 in the center. With beam 1 aligned, I turned my attention to the other beam (beam 2), adjusting M1 until the beam lined up perfectly with I1, and then adjusting B2 until the beam lined up perfectly with I2. In this way I was able to ensure as close to perfect overlap of the beams as possible when they hit the sensor, intersecting not at just one point, but rather all along the end of the beams. Now that the interferometer is set up, I started the microscope slide at a 90 degree angle (perpendicular to the table) which happened to be an area of complete destructive interference and very gradually turned the vertical adjusting screw. As I turned the screw, the pin diode's signal went from a flat line at zero volts to an flat line of increasing signal strength, then eventually swept back down until it reached its minimum again. This took a total of a little more than 4.75 turns.

How many turns should be expected? This can be solved by a little geometry and application of Fresnel's Law. Keep in mind that what is causing the phase change between beam 1 and beam 2 is the fact that as the microscope slide is tilted, beam 1 is traveling through more glass, making beam 1 travel a longer distance and thus changing the phase. The laser is known to operate at a wavelength of 632nm; the adjustable screw in the kinematic mount has 80 threads/in; and the microscope slide has a thickness of 0.0475in. Beam 1 will thus have to travel 632nm more distance in order to go from minimum to minimum.

$$632nm = 632nm \times \frac{1m}{10^9 nm} \times \frac{39.37in}{1m} = 2.488 \times 10^{-5} in$$

d_f is the final distance that beam 1 will travel through the slide once it has been adjusted

$$\Delta d = 2.488 \times 10^{-5} = d_f - d_i = d_f - 0.0475$$

$$d_f = 0.04752488$$

We know that the slide will end up at an angle Θ_f, and according to Fresnell's Law:

$$k_i \sin\Theta_i = k_f \sin\Theta_f$$

where k is the index of refraction of light's medium, and Θ is the angle of light with respect to the normal before and after changing mediums.

To simplify, we also make the approximation $d_i \approx d_f \cos\Theta_f = d_f\sqrt{1-\sin^2\Theta_f}$

So: $d_f = 0.04752488 \approx \dfrac{d_i}{\sqrt{1-\sin^2\Theta_f}} = \dfrac{d_i}{\sqrt{1-\dfrac{k_i^2}{k_f^2}\sin^2\Theta_i}} = \dfrac{0.0475}{\sqrt{1-\dfrac{1.00029}{1.52}\sin^2\Theta_i}}$

Solving for Θ_i (the end angle of tilt of the slide), we get $\Theta_i = 2.2857014°$ = 2.2857014°

It is thus simple geometry to realize that the x-displacement at the top of the slide is:

$$\Delta x = 1.5 \times \tan(2.2857014°) = 0.05987$$

and since there are 80 turns per inch on the screw that causes the x displacement:

$0.05987 \times 80 = 4.7897$ turns × 80 = 4.7897 turns

which matches up quite nicely with our experimental measure of a little more than 4.75 turns.

Building this simple interferometer proved beneficial to understanding the physics behind what would be going on in more complex interferometer setups and for perfecting the design. For example, when the interferometer was first set up, there was no discernable interference pattern, and this was because the beam paths ended up much longer than the *coherence length* of the HeNe laser. Coherence length is the distance beyond which a laser loses the coherence of its signal. This was important because the beams could not interfere if they were not coherent.

3.3 Measuring Relative Phase Change Due to the LCD

The interferometer setup having been proven sound, we may now apply it to the LCD. In 3.1 there was evidence that the LCD changed the relative phase of light passing through it if there was an image on the screen. In this experiment we will explore the phase contributions of the LCD more fully. The setup is the exact same as in 3.2, the only difference being the position of the LCD across both beams and there is no need for the microscope slide any more. Also, because the LCD transmits so little of the beam, the CCD camera must once again be used instead of the pin diode as the CCD is a much more sensitive instrument. The construction of this experiment likewise is the same as earlier. A depiction of the experimental arrangement is shown in Figure 10.

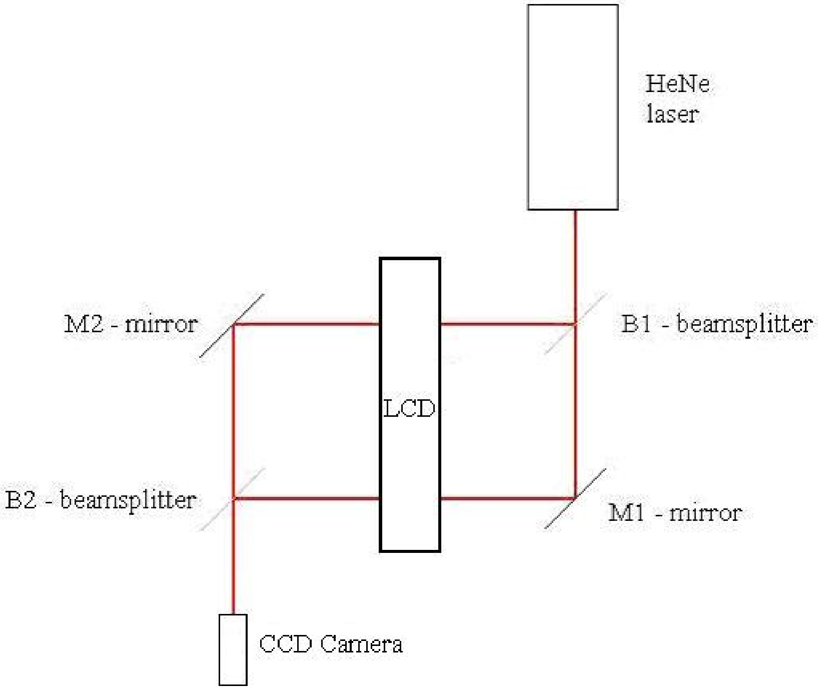
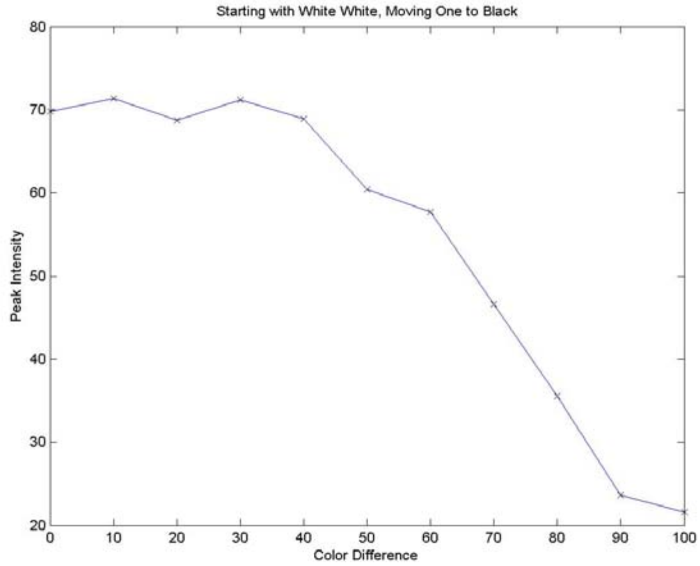


Figure 10: An LCD interferometer

As the laser beam goes through the LCD, the beam's phase is shifted. Furthermore, a different amount of phase gets added to the light depending on what shades are being displayed on the part of the screen the laser is passing through. It is impossible to know the absolute phase addition or subtraction of passing through the LCD with this setup, but it possible to find the relative phase, or phase addition when compared to another image. For this reason, we are letting both beams pass through the LCD, each at a different point. We are then holding a constant black or white image on one of the beams intersection points, while varying the other by 10% shading either from white to black or black to white. The important variable in this experiment (other than intensity of course) is the shade difference between the two images, as this will be tied to relative phase difference if it is indeed the shades that add phase. I have labeled this as being from 0-100, with 0 meaning that both points are at the same color (white or black) and 100 meaning that they are at complete opposite ends of the spectrum (one of the points is black and one of them is white). Anything in between means the variable color is some shade of gray, with the range in value signifying the difference between the variable color and the base color (0-50 meaning they lie on a similar end of the spectrum, 50-100 meaning they are on opposite ends). This was done using Adobe Photoshop 4.0, in which I could change the shade on the screen in 10% increments by controlling how much of the standard red, green, and blue scale was displayed (essentially determining how many of these color pixels are allowed to activate). Below are the results.



Color Difference	Peak Interference Intensity
0	69.8
10	71.4
20	68.8
30	71.2
40	68.9
50	60.4
60	57.7
70	46.6
80	35.6
90	23.6
100	21.6

Figure 11: White-white to white-black interference.

Color Difference	Peak Interference Intensity
90	43.3
80	39
70	43.7
60	50.1
50	62.8
40	62.2
30	66.1
20	65.2
10	67.4

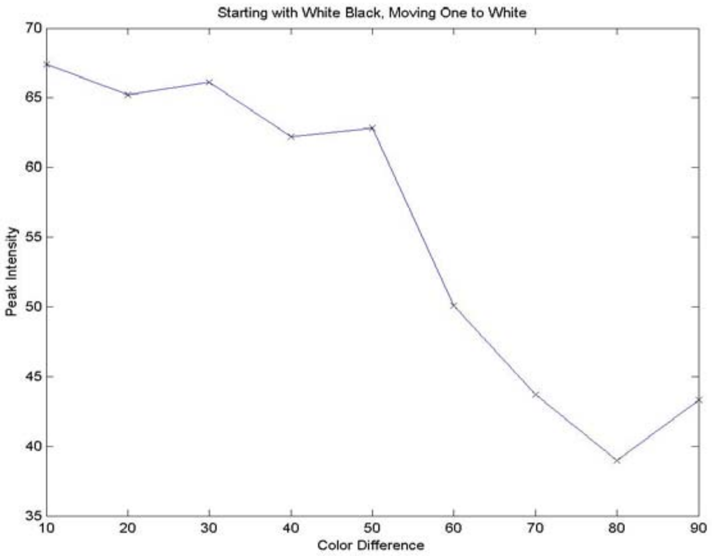
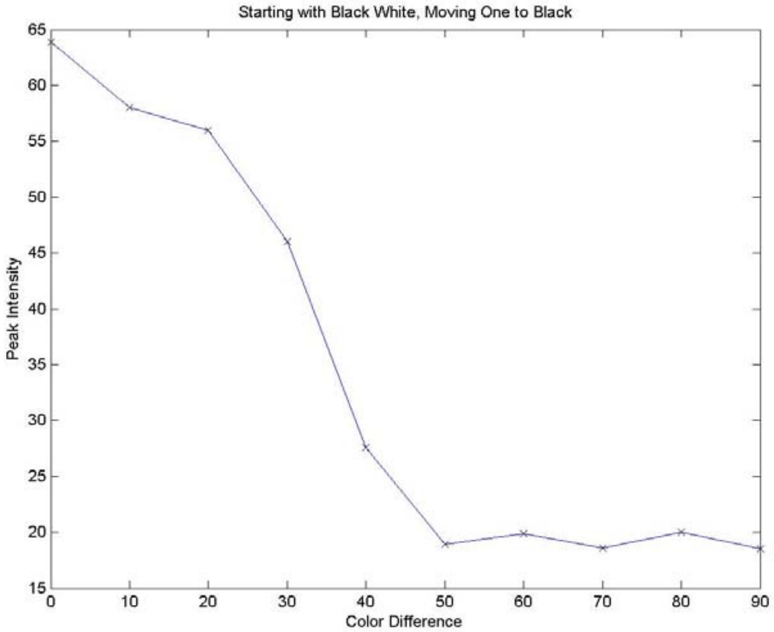


Figure 12: White-black to white-white interference.



Color Difference	Peak Interference Intensity
90	18.5
80	20
70	18.6
60	19.9
50	18.9
40	27.6
30	46
20	56
10	58
0	63.9

Figure 13: Black-white to black-black interference.

Color Difference	Peak Interference Intensity
10	67.8
20	66
30	55.4
40	48.5
50	48
60	44.5
70	43.9
80	41.8
90	43.9
100	40.5

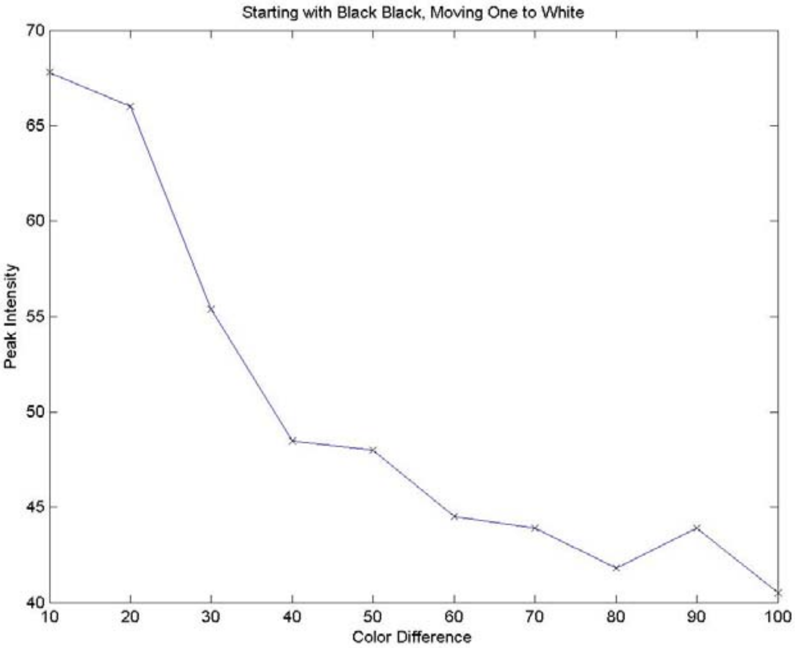


Figure 14: Black-black to white-black interference.

These data sets are consistent with one another and suggest a relationship between color difference and relative phase. Notice that the first two graphs are very similar, and this reinforces the validity of the findings as they are graphs of the same transitions but going in different directions (WW to WB, and WB to WW). This also holds true for the second two graphs (BW to BB and BB to BW). Thus it is depicting various shades that adds phase to the light going through an LCD. This makes sense because of the way LCDs work, twisting and untwisting nematic crystals to create certain colors. It stands to reason that this adds phase to the crystals, either by lengthening the nematic along the axis of the light or something similar. The shape of the graphs suggests something further. The best interference occurs with white on white or black on black interference, and it makes sense that if white on white interference creates high intensity peaks then so should black on black, as they will have the same phase relative to each other.

3.4 Measuring Polarization change due to LCD

Well, we would expect from what we know about the way LCDs work that this LCD would rotate the polarization of incoming light 90° unless a voltage is being used to untwist the nematics. To test this hypothesis, we used the HeNe laser, the LCD, an adjustable polarizer, a neutral-density filter (transmiting only 1% of incoming light) and the CCD camera. We set them up as shown in Figure 11 below (the only variation being that for the measurements with no LCD, we did not use the LCD at all).

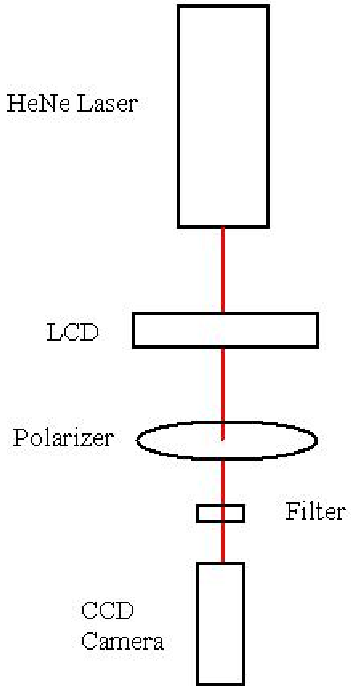


Figure 15: Polarizer setup

The HeNe laser is, itself, linearly polarized, so to get an accurate understanding of what the LCD does to light's polarization, we needed to take measurements from different orientations of the HeNe. Therefore, for each set of measurements, we took readings for the HeNe positioned at 0° (vertical polarization), 45°, and 90° (horizontal polarization). For each of those positions, we took data in the case of no LCD (to characterize the HeNe), the LCD switched off, and the LCD switched on with a White, Grey, or Black image, and we swept the polarizer over a from 90° to -90° in ten degree increments. The following is what we observed:

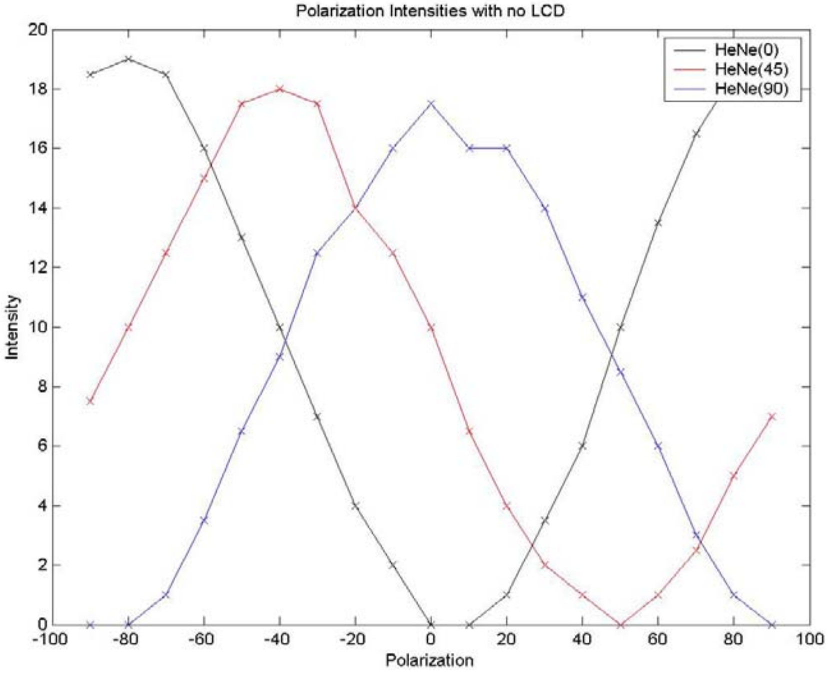


Figure 16: Polarization intensity with no LCD.

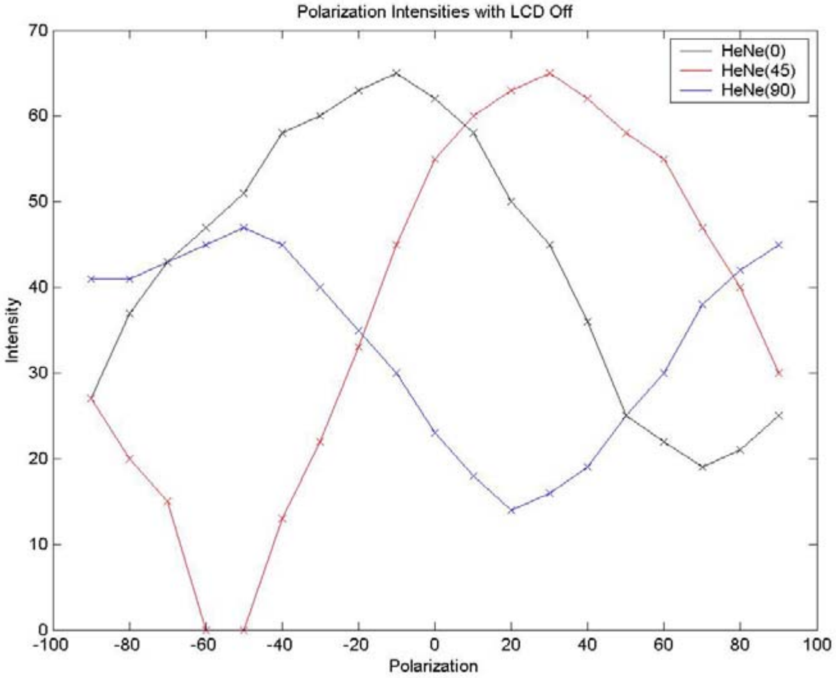


Figure 17: Polarization intensity with LCD off.

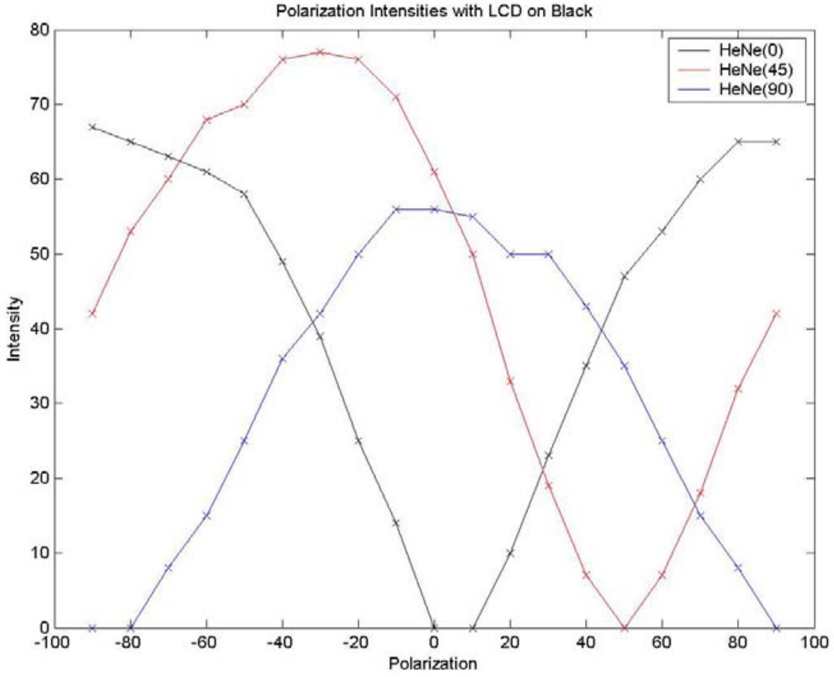


Figure 18: Polarization intensity with LCD on black.

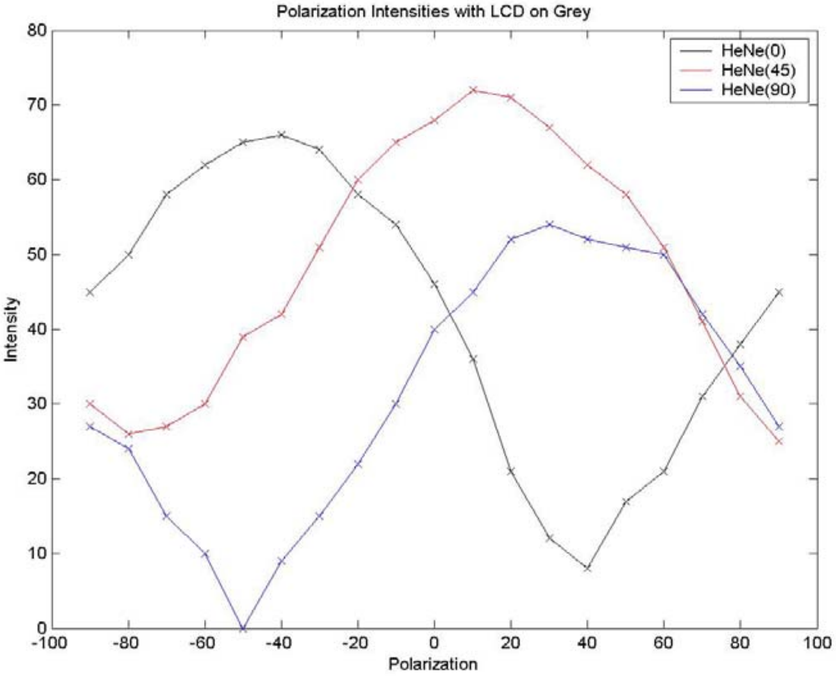


Figure 19: Polarization intensity with LCD on grey.

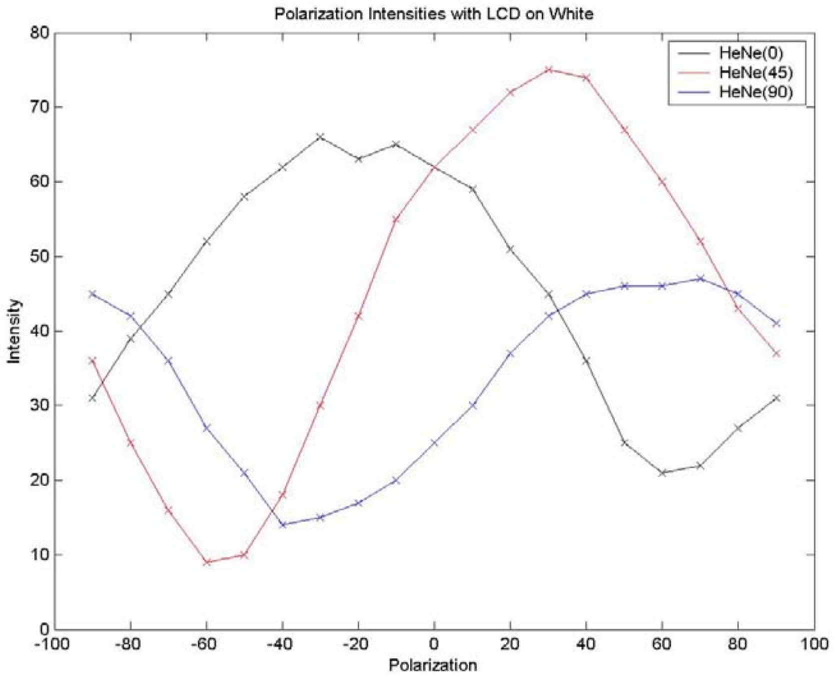


Figure 19: Polarization intensity with LCD on white.

These graphs of intensity with respect to the polarization angle tell quite a bit about the effect LCDs have on polarization, and confirm what I suspected based on the earlier information regarding LCD theory. Comparing the graphs, notice that the graphs of Polarization Intensities with no LCD (in other words, based on the polarization of the laser source itself) have the same peaks and general shape as the graphs of Polarization Intensities with the LCD on Black. As mentioned in section 2.3 of this thesis, when an LCD attempts to make a black image, it really just supplies sufficient charge to completely untwist the TN crystals over the image area, meaning light passing through those crystals will maintain it's original polarization. Thus, our findings show our LCD to be in line with general LCD theory so far. Now, compare to the graphs of peaks for the LCD turned off or with a white image. These graphs have peaks and profiles that appear about 90° shifted from those of the LCD showing black or of the laser itself. Once again this follows the theory, which predicts the TN crystals will rotate light's polarization 90° unless untwisted by charge. However, that theory doesn't account for the fact that the graphs for white image and LCD off don't seem to be entirely filtered by the polarizer at any polarizer angle (notice that the origin for the y-axis is not at 0). This seems to indicate that the LCD is somehow imparting an *elliptical polarization* to photons, which is unexpected and strange. Elliptical polarization occurs when a photon has polarization in both the x- and y-direction (if it is an equal amount of polarization in those directions, the photon is circularly polarized).

4.0 **Conclusion**

Liquid Crystal Displays have a lot of potential for use in many fields; unfortunately the field of pulse shaping for ultrafast lasers is not one of them. The largest strike against using this LCD for anything optical is that it only transmits anywhere from one to ten percent of the light which is shone at it. It simply wouldn’t be worth the energy loss in most cases to go through the LCD, and techniques such as auto-correlation (a way of measuring ultrafast output and characterizing it using the beam itself) that rely on high intensities would be unfeasible. In addition, it is the ability of LCDs to add or subtract phase which makes them so interesting as signal shapers, but as has been demonstrated here in this thesis, that ability likely comes from twisting or untwisting nematic crystals which also has the unfortunate side effect of changing the polarization of light traveling through them. If the polarization stayed linear this wouldn’t be a problem, but the LCD imparts an elliptical polarization to the light that is not as useful to work with. One would use the LCD as a pulse shaper and change the phase of a portion of a packet of light, only to find that this also changes the type of polarization on that light and takes away a lot of the qualities that made it interesting in the first place (coherence, ability to form bands of constructive or destructive interference, etc)!

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