DESIGN AND DEVELOPMENT OF LIQUID CRYSTAL LENSES

A thesis submitted by

MUJAHID AL ISLAM ASHRAF

For the degree of

MASTERS OF ENGINEERING

Centre for Micro-Photonics
Faculty of Engineering and Industrial Sciences
Swinburne University of Technology
This thesis is dedicated to my family.
Abstract

The use of optics in the fields of nano-technology, telecommunication and medicine has been growing exponentially in recent years. Application of liquid crystals within optics has been a growing trend from flat screen displays to variable focus lenses in a digital versatile discs.

One area of the recent developments within optics has been the development of two-photon fluorescence microscopy and high-density three-dimensional optical data storage. In such applications, where a light beam has to be focused deep within the volume of bulk media, aberrations are introduced. The most dominant aberration is spherical aberration which results from the mismatch in refractive indices of the immersion and recording media. The aim of this thesis is to design a liquid crystal lens for dynamic tube length compensation of the spherical aberration.

Liquid crystal phase plates are used in everyday liquid crystal displays (LCDs) such as mobile phones and calculators. The technologies required to manufacture a liquid crystal phase plate are well understood. However, an application like three-dimensional data storage requires different properties in the liquid crystal phase plate, which are investigated in this thesis. To fabricate our liquid crystal phase plate we used ZLI-5049-000 from MERCK as the liquid crystal medium, with poly-vinyl alcohol (PVA) and Indium Tin Oxide (ITO) providing the insulating and conducting layers, respectively. It has been demonstrated that vacuum vapour deposition can be used to coat a glass substrate with ITO. However, in order for the ITO coating to be conductive a method is developed where the substrate is heated to 300ºC before, during and after the coating. Similarly, a method has been developed for producing a uniform 10 µm coating of PVA on top of the ITO.
In order to produce a liquid crystal lens with the properties required to compensate for spherical aberration an investigation into the properties of the liquid crystals is first conducted. A liquid crystal phase plate described in chapter 3 is characterised to determine the effect of the rubbing direction of the insulating layer and the effective refractive index change with applied voltage. It has been demonstrated that an effective change in refractive index of 0.11 can be achieved with 30 volts applied across the ITO electrodes.

Based on the characterisation of the liquid crystal phase plate four different liquid crystal lens designs have been proposed and tested. The lens designs are based upon convergent and divergent lenses with different refractive index lens substrates. It is determined that a liquid crystal lens with a divergent lens substrate with a refractive index of 1.785 can be used to effectively compensate for spherical aberration. This has been confirmed experimentally by using the liquid crystal lens in a two-photon confocal microscope and measuring a increase in detected intensity at a depth below the surface of a sample.

The research conducted in this thesis shows the ability to dynamically compensate for spherical aberration introduced by a mismatch in the refractive indices between the immersion and sample mediums. It has also been demonstrated that new methods for fabricating the conductive and insulating layers are suitable for producing a liquid crystal lens. A liquid crystal lens based on the research in this thesis could be used in three-dimensional data storage or microscopy applications.
Acknowledgements

I would firstly like to thank Professor Min Gu for giving me the opportunity to undertake this Masters program under his supervision. This thesis would not have been possible without his support and advice. Professor Gu has been crucial to my success by helping me cross every hurdle. It has been a honour to work with him.

I would like to thank Dr. Daniel Day for his supervision, support and advice not only during this program but also during my undergraduate project. Dr. Day’s advice and training has helped me complete this degree.

Very special thanks go to Dennis McPhail for his help both as a friend and as a mentor. Dennis has been a true friend at times of need throughout my time spent at the Centre for Micro-Photonics. I would also like to thank Dru Morrish, Michael Ventura and Dr. Damian Bird for the numerous helpful discussions.

I would like to thank Dr. Tom Edwards for his help and guidance all through my undergraduate and Master’s program.
Declaration

I, Mujahid Al Islam Ashraf, declare that this thesis entitled

*Design and Development of Liquid Crystal Lenses*

is my own work and has not been submitted previously in whole or in part, in respect of any other academic award.

Mujahid Al Islam Ashraf

Centre for Micro-Photonics
Faculty of Engineering and Industrial Sciences
Swinburne University of Technology
Australia

Dated the 14\textsuperscript{th} of October, 2006.
# Table of contents

Abstract ii  
Acknowledgements iv  
Declaration v  
Table of contents vi  
List of figures viii  
List of tables x

## CHAPTER ONE  
**INTRODUCTION TO OPTICAL IMAGING SYSTEMS**

1.1 Introduction 2  
1.2 Optical imaging systems 2  
1.2.1 Confocal imaging 3  
1.2.2 Fluorescence imaging 4  
1.2.2.1 Single-photon fluorescence 5  
1.2.2.2 Two-photon fluorescence 5  
1.3 Aberration 6  
1.3.1 Spherical aberration 6  
1.3.2 Chromatic aberration 7  
1.3.3 Astigmatic aberration 7  
1.4 Aberration compensation 8  
1.4.1 Wave front correction (adaptive optics) 8  
1.4.2 Tube length compensation 8  
1.5 Objectives of this thesis 9  
1.6 Preview of the thesis 9

## CHAPTER TWO  
**REVIEW OF LIQUID CRYSTAL DEVICES AND LENSES**

2.1 Introduction to liquid crystal devices and lenses 12  
2.2 Liquid crystals 12  
2.2.1 Properties of liquid crystals 13  
2.2.2 Initial alignment of liquid crystals 14  
2.2.3 Alignment of liquid crystals using applied electric fields 16  
2.2.4 Intensity and phase relationship 20  
2.3 Liquid crystal devices 23  
2.4 Liquid crystal lenses 24  
2.5 Summary 24

## CHAPTER THREE  
**FABRICATION OF A LIQUID CRYSTAL PHASE PLATE**

3.1 Introduction 26  
3.2 Structure of a phase plate 26  
3.2.1 Phase modulator 28
3.2.2 Switch  28
3.3 Fabrication of the conducting layer  29
3.4 Fabrication of the insulating layer  30
3.5 Fabrication of the phase plate  31
3.6 Summary  32

CHAPTER FOUR
CHARACTERISATION OF THE LIQUID CRYSTAL PHASE PLATE
4.1 Introduction  35
4.2 Characteristics of conducting layer  35
4.3 Characterisation of the insulating layer  38
   4.3.1 Surface analysis of the PVA layer  37
   4.3.2 Analysis of refractive index of PVA  39
4.4 Characterisation of liquid crystal phase plate  39
   4.4.1 Experimental setup for phase plate characterisation  39
   4.4.2 Characterisation of refractive index  40
4.5 Summary  45

CHAPTER FIVE
DESIGN, FABRICATION AND CHARACTERISATION OF LIQUID CRYSTAL LENSES
5.1 Introduction  47
5.2 Design of liquid crystal lenses  47
5.3 Tube length compensation  48
5.4 Convergent lenses  53
   5.4.1 First option of convergent lens design  53
   5.4.2 Second option of a convergent lens design  59
5.5 Divergent lenses  62
   5.5.1 First option of a divergent lens design  62
   5.5.2 Second option of divergent lens design  64
5.6 Fabrication of the liquid crystal lens  66
   5.6.1 Experimental setup for characterisation of the liquid crystal lens  67
   5.6.2 Characterisation of the liquid crystal lens  68
5.7 Summary  69

CHAPTER SIX
CONCLUSION
6.1 Thesis conclusion  72
6.2 Recommendations for future work.  73
List of figures

Figure 1.1  Schematic diagram of a reflection scanning confocal imaging setup. 4
Figure 1.2  Spherical aberration of a lens. 6
Figure 1.3  Chromatic aberration of a lens. 7
Figure 1.4  Astigmatism of a lens. 7
Figure 2.1  Birefringence in liquid crystals. 14
Figure 2.2  Orientation of liquid crystal molecules between two perpendicularly rubbed surfaces. 16
Figure 2.3  Effect of applied electric field on liquid crystal alignment. 17
Figure 2.4  Cross rubbed cell with voltage applied. 19
Figure 2.5  Parallel rubbed cell with no electric field applied. 19
Figure 2.6  Parallel rubbed cell with electric field applied. 20
Figure 2.7  Polarizer directions for the polarizer analyser and the liquid crystal. 21
Figure 3.1  Exploded structure of liquid crystal phase plate. 27
Figure 4.1  Transmission efficiency of 55 nm ITO coating. 35
Figure 4.2  Transmission efficiency of a 30 μm PVA layer. 36
Figure 4.3  Electron microscope image of the insulating layer before rubbing. 37
Figure 4.4  Electron microscope image of the insulating layer after rubbing. 37
Figure 4.5  Non-pre-aligned layer of Nematic liquid crystals under cross polarised light. 38
Figure 4.6  Pre-aligned layer of Nematic liquid crystal under cross polarized light. 38
Figure 4.7  Experimental setup for phase plate. 40
Figure 4.8  Transmission response to voltage. 40
Figure 4.9  Normalised response to voltage. 41
Figure 4.10  Phase delay in response to voltage. 42
Figure 4.11  Change in refractive index of the liquid crystal phase plate as a function of applied voltage. 43
Figure 4.12  Effective refractive index of liquid crystal phase plate as a function of applied voltage. 44
Figure 5.1  Four combinations of liquid crystal lens design. 48
Figure 5.2  Ray trace through a dielectric slab. 49
Figure 5.3  Schematic diagram of beams being refracted at interface of materials with two refractive indices. 50
Figure 5.4  Ray trace for a simple lens. 51
Figure 5.5  Ray diagram for the first option of a convergent liquid crystal lens. 53
Figure 5.6  Focal length shift as a function of applied voltage for the first option of a convergent lens. 54
Figure 5.7  Liquid crystal lens in combination with 0.75 numerical aperture objective. 55
List of figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8</td>
<td>Change in focal length for first option of convergent liquid crystal lens</td>
<td>56</td>
</tr>
<tr>
<td>5.9</td>
<td>$B$ value for a convergent liquid crystal lens with matching $n_e.$</td>
<td>57</td>
</tr>
<tr>
<td>5.10</td>
<td>Compensation depth as a function of applied voltage for the first option of a convergent liquid crystal lens.</td>
<td>58</td>
</tr>
<tr>
<td>5.11</td>
<td>Ray diagram of the second option for a convergent liquid crystal lens</td>
<td>59</td>
</tr>
<tr>
<td>5.12</td>
<td>Focal length shift as a function of applied voltage for second option of convergent liquid crystal lens.</td>
<td>60</td>
</tr>
<tr>
<td>5.13</td>
<td>Change in focal length for second option of convergent liquid crystal lens.</td>
<td>60</td>
</tr>
<tr>
<td>5.14</td>
<td>$B$ values for the second option of a convergent liquid crystal lens.</td>
<td>61</td>
</tr>
<tr>
<td>5.15</td>
<td>Compensation depth as a function of applied voltage for the second option of a convergent lens.</td>
<td>61</td>
</tr>
<tr>
<td>5.16</td>
<td>Ray diagram for the first option of a divergent liquid crystal lens.</td>
<td>62</td>
</tr>
<tr>
<td>5.17</td>
<td>Focal length shift as a function of applied voltage for first option of divergent liquid crystal lens.</td>
<td>63</td>
</tr>
<tr>
<td>5.18</td>
<td>Change in focal length for first option of convergent liquid crystal lens.</td>
<td>63</td>
</tr>
<tr>
<td>5.19</td>
<td>$B$ values for the first option of a divergent liquid crystal lens.</td>
<td>63</td>
</tr>
<tr>
<td>5.20</td>
<td>Ray diagram for the second option of a divergent liquid crystal lens.</td>
<td>64</td>
</tr>
<tr>
<td>5.21</td>
<td>Focal length shift as a function of applied voltage for second option of divergent liquid crystal lens.</td>
<td>65</td>
</tr>
<tr>
<td>5.22</td>
<td>Change in focal length for second option of divergent liquid crystal lens.</td>
<td>65</td>
</tr>
<tr>
<td>5.23</td>
<td>$B$ value for the second option of a divergent liquid crystal lens.</td>
<td>66</td>
</tr>
<tr>
<td>5.24</td>
<td>Experimental setup for liquid crystal lens characterisation.</td>
<td>67</td>
</tr>
<tr>
<td>5.25</td>
<td>Typical axial response of a confocal setup.</td>
<td>68</td>
</tr>
<tr>
<td>5.26</td>
<td>Change in intensity as a function of voltage at a depth of 20 μm.</td>
<td>69</td>
</tr>
</tbody>
</table>
List of tables

Table 4.1  Resistance of varying ITO coating thicknesses.  36
Chapter One

Introduction to optical imaging systems
1.1 Introduction

Imaging systems play an integral part of today’s society ranging from sophisticated astronomical telescopes to everyday cameras. Optical imaging systems have also been incorporated into mobile phones, computer networks, security systems and medical applications such as endoscopes and cancer cell detection instruments. Many of these applications involve miniaturization of components down to micrometers in size and have been gaining significant technological advances in recent years. Micro-technology demands development and characterization of structures in the micrometer-scale, which would not be possible without adequately developing optical imaging systems. Optical imaging is generally the method of choice due to its non-invasive nature and adaptability to most applications.

1.2 Optical imaging systems

There are numerous optical imaging systems available with new techniques being developed everyday. The developments in these systems are a result of improvements in axial resolution, transverse resolution, detection mechanisms or scanning rates. The commercial availability of high numerical aperture (NA) objectives as well as ultra-short pulsed lasers has further improved existing systems in terms of spatial and temporal resolution.

Imaging using conventional optical microscopes is bound by the NA of the objective and the wavelength of the light used for illumination. The demand for high resolution in images has lead to the development of high NA objectives. However, the finite depth of focus and interference from out-of-plane information hinder three-dimensional imaging.
1.2.1 Confocal imaging

To overcome the issues of imaging three-dimensional objects with conventional microscopy where objects around the focal point get defocused, confocal imaging or confocal scanning microscopy is used.

Confocal imaging is dependent on the fact that the total image intensity is the sum of the intensity distribution of individual points making up a three-dimensional object. The ability to isolate and image individual points gives the confocal imaging system the advantage of reducing noise associated with scattered light from the surrounding medium. The transverse resolution of a confocal microscope is 1.4 times better than that of a conventional microscope (Gu, 1996, Sheppard et al., 1991, Denk et al., 1990).

In a confocal system, only one point on the object is illuminated at any one time. The illumination beam is fed through an objective and focused on to the object. In reflection confocal microscopy, the light reflected from the sample passes back through the objective before a beam-splitter separates the illumination and reflected beams. In transmission mode, the refracted light is collected by another objective behind the object. In transmission imaging the light source for illumination and detection mechanism are placed on either side of the sample as compared to reflection imaging where both the source and detector are on the same side. The choice of the imaging setup depends on factors such as the sample thickness, transparency and surface characteristics. The reflected or refracted light is fed into an electronic detector through a pinhole to filter out ambient light. As the size of the pinhole gets smaller, the transverse resolution of the image improves up to the diffraction limit of the imaging system. To obtain the total image, the object is mounted on a scanning stage and a raster scan is done to collect data pertaining to a layer at a pre-defined depth. The depth is then changed to obtain a three-dimensional image. Figure 1.1 illustrates a simplified example of a reflection confocal microscope.
The uniqueness of the confocal system is the fact that the information from a point in focus is fairly independent of the surrounding volume, which is not illuminated. The volume of illumination is dependent on the spot size of the focus which is dictated by the NA of the objective as well as the wavelength. Any information obtained from the surrounding volume, away from the focus spot, is filtered off by a low pass filter or pinhole. Hence, a plane can be imaged deep in a medium without interference from the medium providing that the effect of scattering is minimal.

1.2.2 Fluorescence imaging

In certain applications, it is critical to isolate and image only part of an object, for example cancer cells in tissue. For such applications, the object is prepared by
adding a fluorescent dye to it. The area of interest within the object is selectively stained by the dye. These dyes are designed to fluoresce at wavelengths different from the illuminating wavelength allowing the fluorescence emitted by the dye to be distinguished from the source. When imaging, the wavelength of the illuminating light is filtered off, highlighting the required section. Fluorescence imaging is also advantageous for imaging bulk material with cavities or voids embedded in it, as space within the material does not have any dye and does not fluoresce. Fluorescence imaging can be further classified depending on the excitation wavelength as compared to the wavelength of the fluorescence.

1.2.2.1 Single-photon fluorescence

In single-photon fluorescence the energy of the illumination is equivalent to the energy required to excite an electron from the ground state to some excited state, of the sample. The subsequent decay of the electron releases energy in the form of light of slightly less energy than the illumination photon. The quality of the image of single-photon systems is superior to conventional systems as the wavelength of excitation is typically shorter, thereby producing a smaller focus spot.

1.2.2.2 Two-photon fluorescence

The confocal system has been further improved by the development of two-photon imaging demonstrated by Denk et al. (1990). In this system, the physical process involves simultaneous absorption of two incident photons, each of which has half the energy required to promote an electron from the ground to an excited state. Again the subsequent decay of electron produces light, this time with slightly more energy than the incident photons. Due to the nonlinear relationship between the incident intensity and excitation, excitation can only occur in a small region of the focal spot where the incident photon density is significantly high. A range of two-photon fluorescent dyes and polymers are commercially available to facilitate this system.
1.3 Aberration

In an ideal imaging system, there would be a unique point in the image for every point on the object i.e., every point on the object would travel the same optical path. Thus, a perfect image would show no loss in quality as compared to the object. Most optical systems are not ideal and therefore result in some loss in quality. The loss of quality may be attributed to a number of factors within the imaging system. These factors contribute by modifying the optical path of some rays introducing aberration.

1.3.1 Spherical aberration

If we consider a simple imaging system comprising of a lens and a col umnated light source, the optical path for a ray, travelling along the optical axis, will differ from a ray travelling at some height away from the axis when refracted through a lens. This difference in optical path increases with the height from the optical axis, resulting in aberration. The height from the optical axis dictates the angle at which the ray is incident on the surface of the lens which can cause a variation in the point of convergence. As can be observed from figure 1.2, the focus shifts from $f$ to $f'$ as the aberration height of the ray changes from $h$ to $h'$. As such there exists a blurring effect resulting from the refraction from the spherical surface of the lens as the height of the object changes. Hence, this kind of aberration is a result of spherical surfaces and is called spherical aberration (Hecht, 1990).

![Figure 1.2 Spherical aberration of a lens.](image-url)
1.3.2 Chromatic aberration

In cases where an imaging system does not use monochromatic light, the optical path differs for different wavelengths of light used. As a result, there is dispersion of images formed for each of the wavelengths. The aberration resulting from different wavelengths is called chromatic aberration. If a beam of white light travels through a convex lens as illustrated in figure 1.3, each component depending on the wavelength would have a different focal spot (Hecht, 1990).

![Figure 1.3 Chromatic aberration of a lens.](image)

1.3.3 Astigmatic aberration

Another contributing factor to aberration is the distance an object is off axis. When an object is a considerable distance from the axis, the rays do not strike the lens symmetrically. As a result, the rays seem to concentrate on to different points on different planes, which is illustrated in figure 1.4 (Smith and King, 2000).

![Figure 1.4 Astigmatism of a lens.](image)
1.4 Aberration compensation

In addition to loss of quality of the image, aberration also causes the focal spot size to increase, dispersing the light to a larger area. This would lead to imaging systems requiring more power to excite a specific region and dispersed light to surrounding area would add noise. Aberration in an imaging system can be reduced by manipulating the optical path of the ray or the wave front before it passes through the imaging objective. Modifying the wave front can be accomplished by introducing negative aberrations that are cancelled out after focusing into the sample.

1.4.1 Wave front correction (adaptive optics)

In many cases, the physical surfaces of the reflective or refractive optics are modified to minimize the aberration. An adaptive optics system consists of a wave front sensor to record the phase of incoming light, a control computer to analyse and calculate the required correction factors and a deformable mirror to correct the wave front (Frazier et. al., 2001). This practice of aberration compensation is called wave front correction. This method is commonly used in astronomical telescopes.

1.4.2 Tube length compensation

Objectives are designed to operate at a fixed tube length, which is defined as the distance between the object and its image. There are two types of commercial objectives, which are designed to operate with a tube length of 160 mm or infinity. Infinity tube length corrected objectives are used in commercial scanning confocal microscopes. As investigated by Sheppard and Gu (1991), spherical aberration generated when altering the effective tube length at which the objective is operated can compensate focusing deep within a bulk medium. Day and Gu (1998) demonstrated that by changing the effective tube length of an objective you can introduce negative spherical aberration. The negative spherical aberration
can then be adjusted to compensate for the spherical aberration introduced by the refractive index mismatch between the immersion and sample media. A more detailed investigation of tube length compensation can be found in section 5.2.1.

1.5 Objectives of this thesis

This thesis aims at designing and characterising a liquid crystal lens for use in applications such as three-dimensional data storage. The advantage of the liquid crystal lens is that a single electronically controlled lens can be used to replace a system of relay lenses. In doing so, the imaging system is modified from a static to a dynamic imaging system capable of compensating for severe aberrations.

The technology for manufacturing liquid crystal devices is well established and understood. However certain processes need to be modified or refined in order to fabricate a liquid crystal lens with the desired properties. Both theoretical and experimental methods will be used to investigate the dynamic control of the effective tube length compensation.

1.6 Preview of the thesis

Chapter 2 is a review of current liquid crystal devices and lenses, which also contains an introduction to liquid crystal properties. The applications of liquid crystal cells as a switch and as a phase plate have been reviewed. The control of the alignment of the liquid crystals and the effect of the rubbing direction of the insulating layer has been discussed in section 2.2.

In order to characterise the electro-optical performance of the liquid crystals, a liquid crystal phase plate is fabricated. The design and the processes involved in fabrication of the phase plate are discussed in chapter 3. An easier and cost effective method of coating indium tin oxide by vacuum deposition is described in section 3.3. This method of fabricating a transparent and conductive coating is more efficient than conventional sputter coating. A method of fabricating a
polyvinyl alcohol insulating layer for the protection of the electrodes has also been developed and is described in section 3.4.

Chapter 4 is an experimental investigation of the properties of the liquid crystal phase plate. In section 4.3 the effect of rubbing on the surface of the insulating layer has been investigated and has exhibited the microscopic scratches. The effect of voltage applied across the liquid crystal phase plate is quantitatively evaluated in section 4.4. From this the relationship between applied voltage across the phase plate and phase delay experienced by the light travelling through it is established.

In chapter 5 the design requirements of a liquid crystal lens for tube length compensation are discussed. Following this four lens designs are postulated and theoretically calculated. A liquid crystal based on one of the four lens designs is then fabricated in section 5.5. The lens is then used in a two-photon confocal setup and the compensation of the detected intensity under the influence of spherical aberration is demonstrated in section 5.7.

A conclusion of the work presented in this thesis as well as a discussion on future research is presented in chapter 6.
Chapter Two

Review of liquid crystal devices and lenses
2.1 Introduction to liquid crystal devices and lenses

Liquid crystals play a very important role in many optical products. In addition to liquid crystal displays, liquid crystals are being used in optical switches, diffraction gratings, phase plates, variable focus lenses and to generate holograms and beam profiles required for future applications such as optical tweezers.

Liquid crystals allow the dynamic control of their optical properties via applied electric fields, making them very suitable for a wide range of electronic as well as optical applications. This unique property of liquid crystals provides a very versatile low voltage solution to many optical systems.

2.2 Liquid crystals

Liquid crystals are materials, which show phase characteristics between solids and liquids. They maintain the crystalline order of solids as well as the mobility of liquids. This dual property of being simultaneously crystalline and liquid makes it ideal for controlled dynamic changes in material properties. Liquid crystal materials are generally composed of large rod shaped molecules with strong dipoles. These dipoles help in aligning the liquid crystal molecules along a preferred direction, namely along the director and maintain a highly ordered arrangement. The degree to which the molecules in a liquid crystal align themselves in terms of the angle between the molecules and the director is known as the order parameter. The order parameter represented by \((3\cos^2\theta-1)/2\) gives a range between 1 and 0 representing an order between a perfect order and a lack of order. The order parameter decreases with increase in temperature as the material enters the liquid phase. The transition temperature at which the order parameter drops to zero is represented by \(T_c\) (Collings, 1990).

Liquid crystals are subdivided into subclasses depending on the nature of the relationship between the molecules and the director. In many cases the director itself rotates periodically giving a helical structure.
Nematic liquid crystals have the director fixed in one direction while chiral nematic crystals exhibit the helical structures. Another phase seen in liquid crystals is Smectic. In this phase the molecules orient themselves in layers perpendicular to the director (Smectic A) or in layers at an angle other than 90 degrees (Smectic C). Liquid crystals generally exhibit one of the phases as the temperature is raised and the compound liquefies. The liquid crystal 4- n-pentylbenzenethio-4’n-decyloxybenzoate—10S5(PAA) shows three phases; smectic C between 60°C and 63°C, smectic A between 63°C and 80°C and chiral nematic between 80°C and 86°C. Other subclasses of liquid crystals include discotic liquid crystals which are composed of molecules which have disk like shapes as compared to the elongated rod like molecules (Collings, 1990).

The characteristic of liquid crystals that allows for most of its applications is that of changing direction of alignment in response to electric fields. The alignment change can be achieved by the application of a strong beam of photons or the application of electric fields. The change in alignment can result in a change of polarisation as well as phase shift of light passing through it. The overall change in refractive index has numerous applications as well.

2.2.1 Properties of liquid crystals

Liquid crystals display a range of optical properties depending on the family of liquid crystals they belong to. For example smectic liquid crystals align perpendicular to the director while nematic liquid crystals align parallel to the direction of the director.

The rod like shape of liquid crystal molecules and their alignment in a general direction give rise to anisotropy in their structure. This results in direction-dependent physical and optical properties. The anisotropy gives liquid crystals their birefringence, whereby a ray of light travelling through it in the z-direction will experience two refractive indices along the x-direction and y-direction, depending on the polarisation of the incident light. This gives us the ordinary ($n_o$)
and the extra-ordinary \((n_e)\) refractive indices associated with nematic liquid crystals (Hecht, 1990). The ordinary ray experiences a refractive index of \(n_o\) and has the electrical-field vector of the incident light normal to the optic axis. The extraordinary ray experiences a refractive index of \(n_e\) and has the electric-field vector of the incident light parallel to the optic axis. This is illustrated in figure 2.1. Most nematic liquid crystals exhibit a large change in refractive index of 0.2 (Collings, 1990). An associated property of the anisotropy of liquid crystals is the response to electric and magnetic fields. The mobility of the liquid crystals and its anisotropy allow for alignment of the molecules along the applied field, thus changing the refractive index. Hence, the birefringence and its controllability make it suitable as an opto-electric switch, gate or control valve. Another key property of liquid crystals is the response to the boundary structure. This very important property allows for initial alignment of liquid crystal molecules.

![Figure 2.1 Birefringence in liquid crystals.](image)

### 2.2.2 Initial alignment of liquid crystals

There are numerous methods of initial alignment or pre-alignment of nematic liquid crystals. The common method of pre-aligning liquid crystals has been rubbing of the insulating surface with felt or velvet (Ito et. al., 2000, Mahajan et. al.,1998, Arafune et. al., 1996, Harrison et. al., 2002, Kim et. al., 2002). The microscopic scratches or grooves produced by the rubbing provide a repetitive order that initiate the beginning of the crystalline phase on the surface. The
surrounding liquid crystals follow by aligning the molecules in the same general direction.

The alignment of liquid crystals can be observed by viewing a thin layer of a liquid crystal solution through a crossed polarised microscope. Light is initially passed through a polariser then on to the thin layer of liquid crystals. As the light passes through the liquid crystal solution, the light undergoes some phase delay depending on both the orientation of the crystals in the solution and the angle of polarisation of the incident light. Placing a crossed analyser after the liquid crystal layer makes the variations visible.

Without initial alignment, a drop of liquid crystals appears to have patches where a group of molecules have the same orientation. At the boundary of the crystals where the orientation does not match fault lines appear breaking up the liquid crystal solution into patches. This is an expected property of nematic liquid crystals whereby the molecules prefer the orientation of the boundary or the surrounding environment.

It is reported by Zhuang et al. (2000), that the alignment of liquid crystals are explained by two models namely, the orientation of polymer chains and the groove model. In addition, Versteeg et al. (2002), investigated alignment dependence on laser etching of the insulating layer, where the anchoring mechanism of liquid crystal molecules to the insulating layer has been studied. The alignment of the liquid crystal is very closely related to the grooves created on the interface between the liquid crystal and the insulating polymer layer.

According to Ito et al. (2000) and Arafune et al. (1996), the molecules of the insulating polymer oriented in the rubbing direction induce an isotropic molecular orientation of the first liquid crystal monolayer via an intermolecular interaction between the insulating layer and the first layer of the liquid crystal. This interaction is propagated through the bulk of the liquid crystals through an elastic interaction between the liquid crystal molecules.
In the case where the rubbing directions are perpendicular to each other, the effect of the initial layers, create a twisted alignment pattern. This results in the liquid crystals on the surfaces to be at 90 degrees to each other and the crystals in the middle of the cell to range from 0 to 90 degrees from either face plate depending on the depth as illustrated in figure 2.2.

Figure 2.2 Orientation of liquid crystal molecules between two perpendicularly rubbed surfaces.

Various surface treatment procedures such as chemical treatment, mechanical abrasion or micro structures can also be used to initially align liquid crystals along the boundary between the liquid crystals and the substrate.

2.2.3 Alignment of liquid crystals using applied electric fields

The most widely used liquid crystal is the nematic type of liquid crystals. This long thread like liquid crystal is generally chosen for its preferred properties of birefringence due to anisotropy and aligning parallel along the applied electric field. The use of light for alignment of liquid crystals has been used as well (Park et. al., 1999, Wang et. al., 1998).
Nematic liquid crystals align themselves along the director which is influenced by a directly applied electric field or electromagnetic wave. This property allows the refractive index to be controlled by varying the amplitude of an electric field across liquid crystals.

The effect of the voltage applied across a cell containing nematic liquid crystals depends on the nature of the liquid crystal used, number and rubbing direction of insulating layers. The gradual application of voltage will not result in a change in alignment until the threshold voltage is reached. Beyond the threshold voltage the crystals start to align introducing a phase delay. The rate of alignment in very high in this transient stage immediately beyond the threshold voltage and slows down to a steady rate before reaching saturation voltage. There is no further alignment beyond the saturation voltage (Wu, 1989).

If a droplet of liquid crystal were placed between two glass slides, the effective refractive index would vary between the ordinary ($n_o$) and the extra-ordinary ($n_e$) refractive indices depending on the alignment or polarisation of the incident ray. Application of an electric field would eventually align all the liquid crystals.

![Diagram](image)

Figure 2.3 Effect of an applied electric field on liquid crystal alignment (a) no applied voltage (b) with voltage applied.
The application of an electric field affects the alignment of the liquid crystal molecules depending on the field strength as well as proximity to the surface. Figure 2.3 shows the effect of an applied electric field. The crystals are aligned along the rubbing direction when no voltage is applied, illustrated in figure 2.3(a) and along the electric field when voltage is applied, illustrated in figure 2.3(b).

Most applications of nematic liquid crystals can be broken down into two main categories, firstly as a switch in displays, where the transmitted light intensity is modulated and secondly as a phase plate where the phase of the transmitted light is modulated.

In switching applications, the rubbing direction on both surfaces for initial alignment is perpendicular to each other. The liquid crystals align along the rubbing directions as discussed in the previous section. The liquid crystals rotate gradually from one pre-alignment layer to the next. This is illustrated in figure 2.2. This type of application requires crossed polarisers to be placed before and after the cell with the angle of rubbing of the polymer layer at 45 degrees to both of the polarisers. Light is transmitted through the initial polariser and is rotated by the birefringence of the liquid crystals. This allows transmission through the crossed polariser. Without the cross-rubbed polymer layers within the liquid crystal cell the two polarisers would block all light appearing black. The rotation of the polarisation allows light to pass through giving a cloudy white appearance. As the voltage is gradually increased across the cell as illustrated in figure 2.2, the liquid crystals gradually align with the electric field up to a certain voltage (saturation voltage) after which the crystals cannot align any further, as illustrated in figure 2.4. The cell at the saturation voltage exhibits a single refractive index in the plane of the initial polariser removing any birefringence. The refractive index is going to be polarisation dependent if the liquid crystals are not completely aligned with the electric field.
In switching applications, the cell is used to toggle in-between on and off, or zero and one. The control of intermediate stages between one and zero as well as the speed of switching is not very significant.

Figure 2.4 Cross-rubbed cell with voltage applied.

The second mode of application is as a phase plate. In this case, the rubbing directions of the pre-alignment layers are kept parallel as shown in figure 2.5. The application of voltage as with switching aligns the liquid crystals as in figure 2.6. The difference is that the liquid crystals rotate in a plane changing the effective refractive index from $n_e$ to $n_o$. This change in refractive index introduces a phase delay. The key element of this application is the control of the degree to which the crystals rotate. The control and the speed at which the liquid crystals rotate have been a challenge to researchers (Wu, 1989).

Figure 2.5 Parallel rubbed cell with no electric field applied.
Figure 2.6 Parallel rubbed cell with an electric field applied.

Modification of electrodes has been the key method of handling these issues of response time and control of orientation. Many groups have studied the use of multiple electrodes. The two main approaches have involved the use of stacked electrodes and concentric electrodes. Nose et. al. (2000) discussed the addition of how controlling electrodes can be used to increase the precision of driving electrode. However, this process would require a more complex design. This technique gives better control over the whole lens. Concentric electrodes provide better control by isolating individual areas of the lens and can be used on the Fourier plane to modulate light (Hain, 2001). Concentric electrodes or electrodes in close proximity require chemical etching.

### 2.2.4 Intensity and phase relationship

A phase plate is the simplest form of a liquid crystal lens. A phase plate allows us to understand the workings of liquid crystals bounded by electrodes. The general set up of phase plate is between a polariser and an analyser. As discussed by Hain et. al. (2001) the variation in intensity for two crossed polarisers with a phase plate in between is given by

\[
I = I_0 \sin^2 \left( \frac{\phi}{2} \right) \sin^2(2\alpha),
\]

(2.1)
where $\phi$ is the variation in phase and $\alpha$ is the angle between the liquid crystal cell director and the first polariser as illustrated in figure 2.7.

If we consider a wave passing through a liquid crystal phase plate sandwiched between a polariser and analyser and assuming that the polariser is at right angles to the analyser as in figure 2.7 and the liquid crystal phase plate is at $\alpha$ degrees to the polariser, we can represent the components of the electric field as follows

\begin{align}
E_{ox} &= E_0 \sin(\alpha), \quad \text{(2.2)} \\
E_{oy} &= E_0 \cos(\alpha) \quad \text{(2.3)}
\end{align}

Equations 2.2 and 2.3 represent the components of the electric field $E_0$ along the x and y axes. Both components are influenced by the liquid crystals in the phase plate and experience phase delays. The effective field at the analyser can be expressed as follows
\[ E_{ox} = E_0 \sin(\alpha) \exp(iP_x), \]  \hspace{1cm} (2.4)

\[ E_{oy} = E_0 \cos(\alpha) \exp(iP_y), \]  \hspace{1cm} (2.5)

where \(\exp(iP_x)\) and \(\exp(iP_y)\) represent the increase in the optical path due to the phase plate. At the analyser, the only effective parts of the components will be along the analyser. As a result, after the analyser the components are \(E_{1A}\) along the positive \(y\)-axis and \(E_{2A}\) along the negative \(y\)-axis giving us the total field along the analyser.

\[ E_{1A} = E_0 \cos(\alpha) \sin(\alpha) \exp(iP_y), \]  \hspace{1cm} (2.6)

and

\[ E_{2A} = -E_0 \sin(\alpha) \cos(\alpha) \exp(iP_y). \]  \hspace{1cm} (2.7)

The total field after the analyser can be represented by

\[ E_{Total} = E_{1A} + E_{2A}, \]  \hspace{1cm} (2.8)

and

\[ E_{Total} = \frac{E_0}{2} \sin(2\alpha) \left[ \exp(iP_y) - \exp(iP_y) \right]. \]  \hspace{1cm} (2.9)

Hence, the intensity of the wave after travelling through the phase plate and analyser can be represented by

\[ I = \frac{E_0^2}{4} \sin^2(2\alpha) \left[ 2 + 2 \cos(P_x - P_y) \right] = \frac{E_0^2}{2} \sin^2(2\alpha) \left[ 1 + \cos(P_x - P_y) \right], \]  \hspace{1cm} (2.10)

with \(\Delta P = P_x - P_y = \phi\), where \(\phi\) represents the phase delay associated with the phase plate, we now have
In terms of intensity, equation 2.11 can be written as

\[ I = I_0 \sin^2(2\alpha) \left[ \sin^2\left(\frac{\varphi}{2}\right) \right]. \]  

(2.12)

To simplify equation (2.12) further the polariser can be placed at 45 degrees to the direction of the director. This reduces equation 2.12 to

\[ I = I_0 \sin^2\left(\frac{\varphi}{2}\right). \]  

(2.13)

We can observe that the intensity change is a function of the phase delay due to increased optical path. The optical path can be changed by changing the effective refractive index by controlling the orientation of the liquid crystals through the application of an electric field. The effective refractive index is a function of the applied voltage and ranges between the ordinary and extra-ordinary refractive index of the liquid crystal. Thus the refractive index experienced by light passing through cell is not the refractive index of the liquid crystal but the effective refractive index due to the alignment of the liquid crystals.

### 2.3 Liquid crystal devices

Liquid crystals have been used in a range of applications, most of which centre around operation as a switch. Most instruments, watches, mobile phones now have alphanumeric liquid crystal displays. The application as a switch has been extended to window tints. The other range of applications include dynamic lenses in optical data readout mechanisms, reading glasses, micro-lenses, optical valves and more recently a overwhelming use as liquid crystal computer colour monitors replacing cathode ray tube (Hong et. al., 2000).
Chapter Two                                         Review of liquid crystal devices and lenses

Liquid crystals have been used in the fabrication of adaptive lenses (Noumov et. al., 1998) and electrically controlled microlenses (Commander et. al., 1995). Hain et. al. (2001) have developed a fast switching liquid crystal lens with dual focus using a convex liquid crystal lens and an adaptive liquid crystal lens. Electrically controlled diffraction gratings have been developed by Zhang et. al. (2000). Liquid crystal polymers have been used in fabrication of waveplates (Morita et. al, 1999 and Yzuel et. al., 2000). In recent years, liquid crystal plates have been used to generate doughnut beams and have the prospect of being used in optical tweezers (Ganic et. al., 2001).

2.4 Liquid crystal lenses

Liquid crystal lenses have been widely used in applications where dynamic focal lengths have been the critical factor. The design of electrodes for the control of the liquid crystals and the speed of response to applied voltage has been the key issues of the research.

The application pertinent to my work is compensation of spherical aberration associated with tube length of an objective. A lot of research has been done in development of multi layered data storage. The necessity of high NA objectives has grown strongly with the increase in data density as the separation between bits of information has reduced drastically.

2.5 Summary

Liquid crystals provide a unique solution for the design of dynamic lenses. The effective refractive index of the liquid crystal can be manipulated with the application of voltage. The control of the refractive index makes liquid crystals suitable for applications as optical switches and phase plates. The design of the electrodes is critical to the control of the liquid crystal molecules and depending on the design of the electrodes, liquid crystal devices such as a switch, a valve, a lens or a display can be developed.
Chapter Three

Fabrication of a liquid crystal phase plate
3.1 Introduction

A phase plate is used to increase the optical path by a fixed length. Phase plates are usually designed for a specific wavelength to provide a delay in the transmitted light by a quarter wavelength or multiples thereof.

A liquid crystal phase plate allows for increasing the optical path by a range rather than a fixed value. The phase delay experienced by the light is dependent on its initial polarization and the birefringent property of liquid crystals. Though the phase can be controlled by adjusting the angle of initial polarisation to that of the director of the liquid crystals, addition of electrodes facilitate dynamic control. This chapter gives the details of the fabrication of a liquid crystal phase plate.

3.2 Structure of a phase plate

The basic structure of the phase plate is that of liquid crystals sandwiched between two electrodes. Application of voltage will align of the liquid crystal molecules along the electric field. The amount of change depends on the nature of the liquid crystal as well as the direction of initial alignment.

The fundamental requirement of the phase plate is for the cell to be optically transmissive at the desired wavelength. The nematic liquid crystals have a translucent appearance. The liquid crystals should be isolated from the electrode to avoid short circuiting the electrodes and not allowing any potential difference to build up between the electrodes. The liquid crystal layer has to be thin enough to allow adequate light to be transmitted. In addition, the electrode and the insulating material should be transparent at the desired wavelength.

The electrical properties of the electrodes will determine the electric field at different regions of the cell and eventually the extent to which the liquid crystals are aligned in a specific direction.
The thickness of the phase plate will dictate the quantity of liquid crystals in the path of the light and after modulation the corresponding change in path length.

![Exploded structure of a liquid crystal phase plate.](image)

**Figure 3.1** Exploded structure of a liquid crystal phase plate.

As with any optical system the level of transmission directly impacts on the efficiency of the system. In order to attain a satisfactory level of transmission, it can be observed from the exploded structure in figure 3.1 that it is required to ascertain that the comprehensive structure is going to be transmissive and that uniformity can be achieved. Having a multi-layered structure raises the issue of the transmission property of each layer making up the structure. This will involve characterization of each layer to ensure that the highest degree of transmission can be achieved.

The area of the cell is a major deciding factor with most liquid crystal displays, modulators or lenses. The deciding factor in terms of size is the area of uniform
region of the aligning layer, which is also the insulating layer. Due to the
dependence of the preliminary orientation on the rubbing or scratches of the
insulating layer, there is limited control. Other factors limiting the size of the
uniform region are properties of the insulating polymer, the thickness of the
electrode, and filling of liquid crystal.

Filling the cell creates another major obstacle in liquid crystal cells, namely air
bubbles within the cell.

This basic phase plate configuration along with polarisers can be used either as a
phase modulator or as a switch depending on the initial orientation of the liquid
crystals controlled by the surface of the insulating layer.

### 3.2.1 Phase modulator

The grooves in the insulating layer induce the liquid crystal molecules to align in
the same orientation. For the purpose of phase modulation, both windows are
rubbed in the same direction causing the director of the molecules to be
perpendicular to the optical transmission path and parallel to the glass windows.
Application of voltage will force the molecules to rotate perpendicular to the glass
windows. To ensure that molecules rotate in a single plane, the rubbing direction
of both windows should be parallel.

### 3.2.2 Switch

To fabricate a switch, the direction of rubbing the two windows is perpendicular
to each other. This configuration forces the molecules to orient in a helical
structure. Having the molecules in this orientation causes the incident light to
rotate and be blocked off by a polariser at the other end, which is placed parallel
to the first polariser. Application of voltage aligns the molecules to align
perpendicular to the window allowing the light to pass through.
3.3 Fabrication of the conducting layer

The most common material for the fabrication of the conducting layer is Indium Tin Oxide (ITO). Once the glass windows are cleaned they are ready to be coated with ITO. The ITO used in this case was procured from CERAC Inc. (Milwaukee, WI, USA). It has to be oxidised to give it its transparent conductive properties required for our phase plate.

Although the common process is the purchase of commercially available ITO coated glass, we have achieved similar results coating ITO onto glass slides using an EMITECH vacuum vapour deposition system. The EMITECH system comprises of a vacuum chamber, substrate heater, thickness monitoring unit and current source for heating the tungsten basket holding the source material. The system allows the substrate to be heated facilitating the oxidation of the coating. Commercially available ITO coated glass is either sputter coated or magnetron sputtering and involves complicated processes making it expensive (Banarjee et al., 1983). Initial vapour deposition showed that the vaporization of the indium tin oxide did not necessarily produce a layer that was oxidized. The colour of the coatings ranged from brown to greyish black. Also, these layers were not found to be conductive. To facilitate oxidation the glass substrate had to be heated. However, heating an un-oxidized sample was tried but had minimal effect on transmission or conductivity. The use of a vacuum deposition system is more cost efficient method of coating indium tin oxide as compared to the conventional method of sputter coating. The use of vacuum coating reduces the time required to fabricate small quantities of glass substrate with conductive and transparent coating.

The substrate holder of the EMITECH was heated to around 300°C. The oxidation visibly occurred when the vacuum was removed keeping the substrate at elevated temperature. For vapour coating purposes the EMITECH K950X vacuum chamber was used with the EMITECH K150X film thickness monitor. For substrate and vacuum chamber heating the EMITECH K75X temperature controller was used.
A clean slide was placed inside the vacuum chamber and a 5g piece of ITO was placed in the heating element (i.e. tungsten basket). After sealing the vacuum chamber the temperature of the substrate heater was elevated to 310ºC for approximately 3 hours to allow uniform heating of the substrate as well as the vacuum chamber. Once a uniform temperature was reached, a 4 amperes current was passed through the heating element to evaporate the ITO pieces. After coating was completed the glass substrate was allowed to remain at the elevated temperature for another hour after the vacuum was removed. Using this method ITO coatings ranging from 35 nm to 70 nm thickness were produced. Conductive ITO coatings have high optical transmission and cannot be identified by the naked eye. Coatings exceeding 50 nm have a brownish tinge.

Most vapor deposited materials have poor adherence to substrates. As a result, they have to be handled very carefully to avoid being rubbed off. To allow for a large area of contact between the voltage supply wire and ITO coating small robust pieces of brass pieces were used. The brass electrodes were attached to the coated glass substrates using two-part epoxy conducting cement. An adhesive saturated with silver has alternatively been used to attach wires to the conducting layer.

3.4 Fabrication of the insulating layer

After the electrodes are attached, the next layer is the insulating layer. Both poly vinyl alcohol (PVA) (Wang et. al., 2002 and Limura et. al., 1993) as well as polyimide have been widely used (Park et. al., 1999 and Versteeg et. al., 2002). The problem with PVA in powder form is that the particles tend to stick together forming aggregates when added to water at room temperature. To avoid aggregates forming, the PVA has to be added to the water in small quantities, while stirring continuously. The dissolved powder solution has a very slight yellowish coloration. The temperature was then increased to around 90 ºC to dissolve any remaining particles. The solution cleared up after the whole solution reached the elevated temperature. It had to be left at that temperature for an hour to allow most of the particles to dissolve completely. Alternatively, an ultrasonic
mixer can be used to create a uniform mixture at around 40 °C and then heated to 90 °C to dissolve the PVA and produce a clear solution.

The degree to which the PVA layer is uniform is dependent on the concentration of the solution. PVA films, which are not adequately concentrated, create concentric rings when dried. After trials with various concentrations, it was decided to use a 60 mg/L solution of PVA. Since the solution is very viscous the spin–coating machine is set to 1600 rpm to spin off the excess PVA to produce a uniform film of PVA. This layer of PVA ranges from a few μm to 10 μm. After spin coating the PVA on to the ITO coated substrate it is allowed to dry for 24 hours before heating it to 80°C to remove any remaining solvents.

Once the PVA layer has dried it is ready to be rubbed for pre-alignment. The velvet or felt material can be attached to a wheel or cylindrical object so as to make a uniformly rubbed surface. It can then be used to glide along the required direction to produce scratches. To create scratches parallel to a required direction it was rubbed 7-10 times in that direction. Alternatively a rubbing wheel can also be used.

### 3.5 Fabrication of the phase plate

The cell fabrication requires a number of steps, which have to be followed to ensure that the cell produced, has a uniform alignment of liquid crystals before and after application of voltage. Any non-uniformity in any of the layers comprising the cell produces either clumping of liquid crystals or random alignment before or after application of voltage. Each of the layers had to be developed by trial and error to ensure the design intent was met.

The glass substrate has to be cleaned with a solvent without leaving any streaks of the solvent. Methylated sprit was used with lens cleaning cloth. After adding a few drops of spirit to the cloth, it was folded carefully using clippers without touching it. Once the spirit was almost evaporated the substrate was wiped once
firmly pressing down on the substrate to avoid streaks. The process was repeated until the window was clean of any dust or particles.

The glass substrate is then coated with ITO and PVA as mentioned above before making the chamber to fill the liquid crystal. The two sides of the cell have to be separately by a uniform spacer in order to have a uniform layer of liquid crystal. 12 mm x 2 mm pieces of poly vinyl chloride (PVC) 20 μm thick were used. They were placed on one of the sides of the cell parallel to the shorter edge of the window to produce multiple cells. Once the spacers were in place the second side was carefully placed creating a tube. The two sides and the spacer were placed in a miniature vice to hold everything in place and were then sealed using a two part epoxy resin. The top and bottom of the cell are left open for filling with liquid crystals.

Once the epoxy resin has dried, 10-15 μl of ZLI-5049-000 liquid crystals from MERCK is placed on the open side and allowed to flow in. The cell fills by capillary action and then epoxy resin is added to the top and bottom of the cell to seal it (Mi et.al., 1984).

### 3.6 Summary

This chapter has investigated the different layers and their associated fabrication processes required to produce a liquid crystal phase plate. The examination of the individual layers involved in a liquid crystal phase plate provides a more comprehensive understanding of the methods in which they interact. This then provides a base from which the properties of the liquid crystal phase plate could be tailored for our design of a liquid crystal lens. The use of vacuum coating indium tin oxide as an alternative method to sputter coating has been developed. This process has been successfully used to produce conductive and transparent electrode used in both the liquid crystal phase plate and the lens. A method of coating PVA solution that has uniform surface required for liquid crystal
applications has been discussed. A method of filling the cell with liquid crystals without air gaps has been stated.
Chapter Four

Characterisation of the liquid crystal phase plate
4.1 Introduction

In this chapter, the functional properties of the phase plate are determined by establishing the relationship between the changes in transmission with that of the voltage applied across the liquid crystals. The polarisation of the incident light as well as the angle between the polariser and the analyser play an important role in determining the response of the phase plate. An investigation of the properties of the insulating and conducting layers was completed.

4.2 Characterisation of the conducting layer

The ITO coating was characterized both for conductivity as well as transmission. From the transmission graph in figure 4.1, it can be observed that the layer of ITO 55 nm in thickness has a transmission of greater than 90% for a wavelength of 633 nm. The transmission data was collected using a UV-VIS spectrum analyser.

![Graph showing transmission efficiency of a 55 nm ITO coating.](image)

Figure 4.1 Transmission efficiency of a 55 nm ITO coating.

Measurements were also made to check the conductivity of different thicknesses of ITO and are presented in table 4.1. The resistance was measured from one edge of the coated slide to the other and recorded.
Table 4.1 Resistance of various ITO coating thicknesses.

<table>
<thead>
<tr>
<th>ITO Coating Thickness (nm)</th>
<th>Resistance (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>35</td>
<td>7</td>
</tr>
<tr>
<td>50</td>
<td>5.5</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>70</td>
<td>4.8</td>
</tr>
</tbody>
</table>

4.3 Characterisation of the insulating layer

The insulating layer serves a dual purpose. Firstly, it is protecting the electrodes from shorting. To ensure that the layer was adequately thin, the layer thickness was measured using a Shimadzu thickness measurement software package with a UV-VIS spectrograph. This software equates the thickness by calculating the gap between the peaks of the thin film interference pattern. The thickness of the layer ranged from 20 to 50 μm. Secondly, the insulating layer serves the important purpose of pre-aligning the liquid crystals in a specific direction. The transmission characteristics of a 30 μm thin PVA layer can be seen in figure 4.2. As with the conducting layer, the transmission efficiency of the insulating layer is greater than 90% at 633 nm.

Figure 4.2 Transmission efficiency of a 30 μm PVA layer.
4.3.1 Surface analysis of the PVA layer

Electron microscope images of the surface of the PVA layer were obtained before and after rubbing with felt as can be seen in figures 4.3 and 4.4 respectively. The images helped determine the extent to which the PVA layer could be rubbed before sections were being removed.

Figure 4.3 Electron microscope image of the insulating layer before rubbing.

Figure 4.4 Electron microscope image of the insulating layer after rubbing.
The effect of rubbing on the alignment of the liquid crystal molecules is only visible once the cell is completed and imaged through crossed polarisers. The rubbing action creates small grooves in the insulating layer as visible in the electron microscope image in figure 4.4. This layer aids in pre-defining the orientation of the liquid crystal directors.

![Image](image1.png)

Figure 4.5 Non-pre-aligned layer of nematic liquid crystals under cross-polarised light.

After a thin layer of the liquid crystals is sandwiched between two coated glass substrates that have not been rubbed, the boundary lines in the liquid crystals become visible under crossed polarisers. These lines as visible in figure 4.5 are at the edge where the orientation of the liquid crystals changes. Without initial uniformity of the liquid crystals it is not possible to ascertain the degree to which the director can be changed with the application of voltage.

![Image](image2.png)

Figure 4.6 Pre-aligned layer of nematic liquid crystals under cross-polarised light.
Primary inspection of the cell in terms of liquid crystal uniformity was assessed by placing the cell between cross-polarised light of an Olympus BX microscope. The uniformity of the liquid crystals as a result of rubbing can be observed in figure 4.6 as compared to figure 4.5.

### 4.3.2 Analysis of refractive index of PVA

The refractive index of the PVA solution was measured using an Abbe refractometer. The refractive index of various concentrations was measured and slides were spin coated to find out the best concentration for our application. The final solution used in our liquid crystal phase plate was 70 g/L, which has a refractive index of 1.46.

### 4.4 Characterisation of the liquid crystal phase plate

The measured change in transmission efficiency reflects the effective change in refractive index of the liquid crystals. The refractive index change is the key factor essential for the design of a liquid crystal lens.

#### 4.4.1 Experimental setup for phase plate characterisation

The transmission characteristics of the phase plate were determined by measuring the transmission power as a function of the applied voltage across the cell. In this experiment a Helium Neon (HeNe) laser at 632.8 nm was used. The setup for this experiment is illustrated in figure 4.7. The intensity of the laser was controlled by the neutral density filter to keep the power to a minimum and to reduce the effect of liquid crystals aligning with the beam. The beam was expanded using a 0.25 NA objective and plano-convex lens of focal length 200 mm. The expanded beam was passed through an iris and polariser and then into the cell. Following the cell was a second polariser (analyser) and finally the power meter. In order to measure the change in transmission of the phase plate, it is necessary to place it between two crossed polarisers. The first polariser was maximized by aligning it with the polarisation of the laser. The analyser was then rotated 90 degrees to block the
laser beam. Next the cell was then placed at 45 degrees to the first polariser, as determined by the angle between the rubbing direction and the polariser. This ensured that the director of the liquid crystal was at 45 degrees to the polariser as the cell was rubbed along its length. The cell was placed at the particular angle of 45 degrees so as to simplify the relationship of transmitted intensity to intensity as per the equation 2.1. The angle of $\alpha = 45$ reduces the relationship to equation 2.13, thus giving us the phase delay information. The change in transmitted intensity as a function of the applied voltage was recorded using an oscilloscope as illustrated in figure 4.8.

Figure 4.7 Experimental setup for characterisation of the liquid crystal phase plate.

**4.4.2 Characterisation of the refractive index**

Figure 4.8 Transmission response to voltage.
Figure 4.8 represents the variation in transmitted power depending on the voltage applied on across the liquid crystal phase plate. For an applied voltage between 30 volts and 0 volt across the liquid crystal phase plate, the intensity of transmitted light was recorded. The voltage source used was a DC supply and was manually driven. The intensity of the transmitted light was recorded as voltage output from a photo-diode. For this experiment the liquid crystal phase plate was placed between two polarisers perpendicular to each other and 45 degrees to the director of the liquid crystals as described in section 2.2.4. This setup reflects equation 2.13.

From the data on transmitted power and applied voltage we are able to identify the sinusoidal relationship as well as any critical points of phase shift by normalising the data. The normalising process involved firstly subtraction of background light. And secondly, every peak was divided by its maximum value to give a transmission range between zero and one.

From figure 4.9, we can observe that a phase shift of over $7\pi$ for voltage applied up to 32 volts. We can extend this information to give us the relationship between the phase shift and applied voltage using equation 2.13, which gives us

$$\varphi = 2\sin^{-1}\left(\sqrt{I(V)}\right), \quad (4.1)$$

where $I(V)$ represents intensity as a function of the applied voltage.

Figure 4.9 Normalised response to voltage.
We can now plot the phase delay using equation 4.1 and figure 4.9 depending on the voltage to give us figure 4.10. Phase unwrapping is achieved by calculating the cumulative phase change for the applied voltage.

![Phase delay in response to voltage.

Figure 4.10 Phase delay in response to voltage.]

From figure 4.10 we can observe that there is an increase in liquid crystal alignment with applied voltage, the phase shift is the highest at 0 volt and decreases at higher voltages. This confirms the effect of the electric field as discussed in section 2.2.3. The resulting phase shift demonstrates the alignment of the liquid crystal molecules along the applied field.

An incident beam experiences the highest refractive index when the voltage is zero. In this state the liquid crystal molecules are perpendicular to the direction of the propagation of light. As a result the effective refractive index is close to the extraordinary refractive index $n_e$. As the voltage is applied across the cell or lens, an electric field is generated in the direction of the propagation of the light. This generated electric field is proportional to the applied voltage and is able to change the alignment direction of liquid crystals along it. As the voltage is increased more and more of the liquid crystal molecules align reducing the effective refractive index close to $n_o$, the ordinary refractive index.
The phase delay $\varphi$ in equation 2.13 is dependent on the wavelength $\lambda$ of the light as well as the thickness $d$ of the cell. The phase delay can be represented by

$$\varphi = \frac{2\pi \Delta n d}{\lambda},$$

(4.2)

which gives us the change in refractive index $\Delta n$. From equation 4.2 we have

$$\Delta n = \frac{\lambda \varphi}{2\pi d}.$$  

(4.3)

Equation 4.3 allows us to calculate the effective refractive index which can represented by the relationship

$$n_{\text{effective}} = \frac{\lambda \Phi}{2\pi d} + n_o.$$  

(4.4)

The data represented in figure 4.10 can be re-calculated to provide us with information about the net change in refractive index.

Figure 4.11 Change in refractive index of the liquid crystal phase plate as a function of an applied voltage.

Figure 4.11 represents the change in refractive index as a function of the applied voltage. It can be observed that we can expect a change of refractive index up to
0.11 from a liquid crystal phase plate with a thickness of 20μm. The overall or absolute change in refractive index would be as in the following figure 4.12.

Figure 4.12 Effective refractive index of the liquid crystal phase plate as a function of an applied voltage.

The figures 4.11 and 4.12 indicate that the refractive index reduces with the increase in voltage. This has a direct impact on whether the focal point for a liquid crystal lens is going to move into or out of the medium with application of voltage. Depending on the design and application of a lens the optical path can be varied according to the change in refractive index from figure 4.12.

The change in transmitted intensity to voltage applied graph shown in figure 4.8 depends on the combination of the liquid crystal, insulating layer and conductivity of the electrode. The nature of the electrode and the insulating layer is unique to our system and cannot be directly compared to published results. Hain et.al. achieved a phase shift of $6\pi$ with a voltage range of 2 to 5 volts and a cell spacing of 7μm. In comparison, we have achieved a similar phase shift of $7\pi$ with a voltage range of 2 to 15 volts and a cell spacing of 20μm. Taking the cell thickness into consideration we can observe that the results are very similar as the liquid crystal response is dependent on the electric field generated across the liquid crystal and not merely the voltage applied.

Any errors in the effective refractive index would be a result of measurement errors of the transmissivity verses voltage of the phase plate. The use of HeNe
laser with wavelength of 632.8nm limits the response accurate to that specific wavelength. The use of any other light source will contribute to the error. For example the use of 900nm source would add 18% error to our calculation. It can be estimated that any errors carried forward would be negligible as the effective refractive index determined here is in good approximation literature for these liquid crystals (Ganic *et. al.*, 2002, Wu *et. al.*, 1988 and Hain *et.al.*, 2001).

### 4.5 Summary

The liquid phase plate used in conjunction with linear polarisers has been used to modulate the intensity of transmitted light. The response of the phase plate has been characterised by the relationship between the transmitted light and the applied voltage. This relationship has been analysed to determine the change in refractive index due to the alignment of liquid crystal molecules as a result of applied electric field. Under the conditions used a maximum change in refractive index of 0.11 was achieved with an electric field of 30 volts across the phase plate.
Chapter Five

Design, fabrication and characterisation of liquid crystal lenses
5.1 Introduction

For the design of a liquid crystal lens, the primary criteria that had to be satisfied was whether the lens would be divergent or convergent. The refractive index of the liquid crystal is predetermined by its optical characteristics. The critical factor was the refractive index of the glass lens making up the lens assembly. This would determine the extent to which the beam would converge or diverge with the change in voltage. The liquid crystal lens was used to modulate the focal point within the bulk medium. To verify the application of the lens in reducing the aberration, the lens was used in a confocal setup.

5.2 Design of liquid crystal lenses

The control of the refractive index as discussed in the previous chapter introduces the possibility of developing a dynamic lens. The effect of the voltage will be dependent on additional factors as compared to a phase plate.

The focal length of the lens will be dependent on the effective refractive index of the liquid crystals as well as the refractive indices between the glass making up the cell. The thickness of the liquid crystal material will vary depending on the distance from the centre of the lens. For the purpose of designing a lens there are four cases as in figure 5.1, with a combination of glasses with a refractive index close to $n_0$ or $n_e$ of the liquid crystals and positive and negative lenses. These combinations can be described as follows:

- First option for a convergent liquid crystal lens: a negative glass lens with refractive index close to $n_e$ as in figure 5.1(a).
- Second option for a convergent liquid crystal lens: a positive glass lens with refractive index close to $n_e$ as in figure 5.1(b).
- First option for a divergent liquid crystal lens: a negative glass lens with refractive index close to $n_e$ as in figure 5.1(c).
- Second option for a divergent liquid crystal lens: a negative glass lens with refractive index close to $n_0$ as in figure 5.1(d).

The details of these four designs are given in sections 5.4 and 5.5.
5.3 Tube length compensation

To gain an overview of the relationship between the aberration function and tube length compensation, we have to relate the phase error generated by a slab of dielectric medium as well as the lens used for imaging.

We can begin with a ray trace of light passing through a dielectric slab. As the light enters the denser medium of the dielectric polymer, it follows Snell’s law of refraction given by

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2. \]  

(5.1)

The same law of refraction applies when the ray of light exits from dielectric into air.
Figure 5.2 Ray trace through a dielectric slab.

If a dielectric slab as in figure 5.2 has thickness $t$ and refractive index $n_d$ were immersed within space with refractive index $n_a$ and a ray approaches at angle $\theta$ then the phase delay or error is the phase associated with extra optical path introduced by the slab and can be represented by (Sheppard and Gu, 1991)

$$\phi = kt (n_d \cos \theta_2 - n_a \cos \theta_1),$$  \hspace{1cm} (5.2)

where $k$ is the wave number and represents a ray with wavelength $\lambda$. Considering that the refractive index of the dielectric is higher than that of air it can be represented as

$$n_d = n_a + \Delta n$$ \hspace{1cm} (5.3)

Changing equation 5.1 to the cosine equivalent of Snell’s Law and solving for $\Delta n$ gives us

$$\cos \theta_2 = n_a \cos \theta_1 (1 + \Delta n / n_a \tan^2 \theta_1).$$ \hspace{1cm} (5.4)

Substituting equations 5.3 and 5.4 into equation 5.2 we get

$$\phi = kt \Delta n \sec \theta.$$ \hspace{1cm} (5.5)
Equation 5.5 can be represented by

\[ \phi = A \sec \theta, \]  

(5.6)

where

\[ A = kt\Delta n. \]  

(5.7)

Equation 5.6 indicates the spherical aberration caused by the mismatching of refractive index between a thick medium \((n_d)\) and its immersion medium \((n_a)\). This aberration is dependent on the incident angle of the ray entering into the dielectric medium. When the light is focussed from a high refractive index medium into a low refractive index medium the incident rays are refracted through a larger angle than for the case of a uniform refractive index medium. As there is a range of incident angles for the focused light, they are focussed progressively closer to the interface as the incident angle is increased, as shown in figure 5.3(a). For the case of focusing from a low refractive index medium into a high refractive index medium, there is refraction of the incident rays away from the interface, as the incident angle increases, as shown in figure 5.3(b).

![Diagram of beams being refracted at interface of materials with two refractive indices](image)

Figure 5.3  Schematic diagram of beams being refracted at interface of materials with two refractive indices. a) with \(n_a > n_d\) and b) with \(n_a < n_d\).
Next, we derive the aberration function when an objective does not operate at the
designed tube length. If we consider figure 5.4, a ray of light from a point source
approaching a lens at height $h$ from optical axis and distance $L$, the phase
introduced by a thick lens can be represented by (Sheppard and Gu, 1991)

$$
\phi = k(l - \sqrt{l^2 + h^2} + nd + n\sqrt{d^2 + h^2}).
$$

(5.8)

Figure 5.4 Ray trace for a simple lens.

Differentiating equation 5.8 gives us the phase error when the tube length is
changed:

$$
\Delta \phi = -k \left[ l^2 \Delta \left( \frac{l}{d} \right) - \frac{l^3}{\sqrt{h^2 + l^2}} \Delta \left( \frac{1}{l} \right) - n\Delta d + \frac{nd\Delta d}{\sqrt{d^2 + h^2}} \right].
$$

(5.9)

With $h = d \tan \theta$ and $l = Md$, where $M$ is the magnification, we get

$$
\phi = -k \left[ M^3 d^2 - \frac{M^3 d^3}{\sqrt{h^2 + M^2 d^2}} \Delta \left( \frac{1}{l} \right) - n\Delta d(1 - \cos \theta) \right].
$$

(5.10)

If the magnification $M$ is large, the square root can be expanded by the binomial
theorem to give
\[
\phi = -\frac{1}{2} k d^2 \Delta \left( \frac{1}{l} \right) \tan^2 \theta + k n d (1 - \cos \theta). \quad (5.11)
\]

Here, the second term \(k n d (1 - \cos \theta)\) represents the defocus and constant phase term. The remaining term represents the aberration and can be represented by (Sheppard and Gu, 1993 and Sheppard and Gu, 1991)

\[
\phi = B \tan^2 \theta, \quad (5.12)
\]

where

\[
B = -\frac{1}{2} k d^2 \Delta \left( \frac{1}{l} \right). \quad (5.13)
\]

Equation 5.12 is the aberration function caused by the tube length for a lens satisfying a tangent condition (Sheppard and Gu, 1993). However, the aberration for a commercial objective satisfying the sine condition is represented by \(\phi_t\) and can be represented by (Sheppard and Gu, 1993, Sheppard and Gu, 1991).

\[
\phi_t = B \sin^4 (\theta_i/2), \quad (5.14)
\]

where \(B\) is the aberration co-efficient parameter chosen for maximum compensation of the first order spherical aberration and \(\theta_i\) is the angle of the incident light (Day and Gu, 1998).

The combination of equations 5.6 and 5.14 can be used for compensating for the spherical aberration caused by a refractive index mismatch.

For an objective with an NA of 0.75 the balanced condition is achieved for

\[
B = -1.35 k d \quad (5.15)
\]
where $d$ is the focus depth within the medium for an air-polymer interface and $k$ is the wave number $k = 2\pi/\lambda$ (Day and Gu, 1998).

To reduce aberrations a negative phase term is introduced through an addition of a lens with a negative $B$ value. The process of incorporating an additional lens to modulate the tube length and compensate for aberration is called tube length compensation.

### 5.4 Convergent lenses

#### 5.4.1 First option of a convergent lens design

In this section we investigate the possibility of constructing a convergent liquid crystal lens. The first section of the lens is a plano-concave (negative) lens. The glass lens used in this case has the following properties: BK7 ($n_g = 1.517$) plano-concave lens with a radius of -9.3 mm and effective focal length of -18 mm. From a ray diagram we can expect the combined lens to act as a converging or positive lens depending on the voltage applied.

![Ray diagram for the first option of a convergent liquid crystal lens.](image)

Figure 5.5 Ray diagram for the first option of a convergent liquid crystal lens.  
(a) for liquid crystals with $n = n_e = 1.617$. (b) for liquid crystal with $n = n_o = 1.507$. 

53
It can be observed from the figure 5.5 that the focal point is going to move away from the interface within the medium with the application of voltage. When no voltage is applied, the effective refractive index of the liquid crystals 1.617 causing the focal spot to be closest to the lens following path $a$ in figure 5.4. As the voltage is applied across the cell, the liquid crystals are going to gradually align along the field reducing the effective refractive index to 1.507, moving the ray from path $a$ to path $b$. As a result the focal spot is going to move away and then start to diverge. Hence, this option is suitable for applications where an object within a medium has to be imaged or data written deep within a medium has to be read. From a construction point of view, this configuration is easier to seal than if the first lens were plano-convex.

From the relationship between the voltage and the refractive index in figure 4.12, we can calculate the focal length of the liquid crystal lens according to the radius of the curvature and the effective refractive index of the liquid crystals.

The lens makers’ formula can be extended to give the focal length $f_{LC}$ where

$$f_{LC} = \frac{R}{\left(n_{\text{effective}}(V) - n_{\text{glass}}\right)}, \quad (5.16)$$

where $R$ is the radius of curvature of the glass lens.

![Figure 5.6](image)  
Figure 5.6 Focal length as a function of the applied voltage for the first option of a convergent lens.
In this case, the focal length described by equation 5.16 can be estimated from the phase plate data and is illustrated in figure 5.6. It can be seen in figure 5.6 that for the voltage range displayed the focal length increases exponentially. At larger voltages the focal spot tends towards infinity, and the fast change in focal length above 15 volts makes it difficult to obtain an accurate measurement.

This combination of the liquid crystal lens and an objective is suitable for moving the focal point of a lens into the sample medium. This combination will be ideal for cases where the scanning or imaging depth has to be dynamically modified.

For our application of tube length compensation we have to calculate the combined focal length of the lens along with an objective as illustrated in figure 5.7.

For the combination of the liquid crystal lens with an objective we have

\[
\frac{1}{f_c} = \frac{1}{f_{LC}} + \frac{1}{f_o},
\]

(5.17)

where \(f_c\) is the combined focal length and \(f_o\) is the focal length of an objective of numerical aperture 0.75.

Figure 5.7 Liquid crystal lens in combination with a 0.75 numerical aperture objective.
From equation 5.17 we can obtain the difference between the focal length of the objective and the combined system. This difference in can be described by equation 5.18

$$\Delta f = f'_c - f'_0.$$  \hspace{1cm} (5.18)

The change in focal lengths can be observed in figure 5.8.

Before using this combination for spherical aberration compensation by changing the effective tube length, we have to calculate the $B$ value for this case. Spherical aberration introduced by refractive index mismatching can be compensated by altering the effective tube length of the objective through the introduction of a lens as discussed in section 1.4 and given by equation 5.14 (Sheppard and Gu, 1993 and Day and Gu, 1998).

![Figure 5.8 Change in focal lengths for the first option of a convergent liquid crystal lens.](image)

According to equation 5.14, $B$, the aberration coefficient, can be represented by (Sheppard and Gu, 1993)

$$B = \frac{-2k_0 \Delta l}{D^2}.$$  \hspace{1cm} (5.19)
In equation 5.19, \( D \) is the demagnification factor and \( \Delta l \) is the change in tube length. From the ratio of the image and object positions or the magnification factor we can infer

\[
\Delta l = -\Delta f D^2 . \tag{5.20}
\]

Substituting equation 5.20 into equation 5.19 we have

\[
B = 2k_0 \Delta f (V) , \tag{5.21}
\]

where

\[
k_0 = \frac{2\pi}{\lambda} . \tag{5.22}
\]

From our lens combination, we can calculate the expected values of \( B \), illustrated in figure 5.9.

![Graph of B values for the first option of a convergent liquid crystal lens.](image)

Figure 5.9 \( B \) values for the first option of a convergent liquid crystal lens.

From equation 5.19 and 5.20, it can be observed that the aberration can be controlled for varying voltages. The \( B \) value required for balancing a 0.75 NA objective focused in a thick medium is represented by equation 5.15 (Day and Gu, 1998).
Equations 5.21 and 5.15 give us a measure of the depth for which we should be able to compensate for the aberration

\[ B = 2k_0 \Delta f(V) = -1.34k_0d, \quad (5.23) \]

thus

\[ d = -1.5\Delta f(V). \quad (5.24) \]

Using the values for the shift in focal length from figure 5.8, an estimate of the depth of a focus in a medium to which the aberration can be compensated as illustrated in figure 5.10.

![Figure 5.10 Compensation depth as a function of the applied voltage for the first option of a convergent lens.](image)

From figure 5.10, it can be observed that the lens of this design can be used to compensate for the spherical aberration caused by a thick medium at a depth of almost 170 μm within a medium. An important characteristic with this design is the compensation depth is maximum at the lowest applied voltage. As such, a lens of this design will be more suitable for imaging within a bulk medium where the surface information is not crucial. The most significant factor that would affect the depth of compensation for this case and the other cases is the uniformity of the liquid crystal alignment in the lens configuration. Any non-uniformity in the
initial (0 voltage) and the final alignment is likely to introduce more aberrations into the imaging system.

### 5.4.2 Second option of a convergent lens design

In this option we investigate the possibility of constructing a liquid crystal lens with the following characteristics. The first section of the lens is a plano-convex (positive) lens. From the ray diagram we can expect that the combined lens acts as a converging or positive lens. The glass lens used in this case has the following properties: SF11 ($n_g = 1.785$) plano-convex lens with a radius of 7.06 mm and a focal length of 9.0 mm. From figure 5.10 we can expect the focus to move deeper into the medium as the voltage is decreased. This combination will be suitable for spherical aberration compensation.

Without voltage applied the light travels from the glass lens of refractive index 1.785 through the liquid crystals aligned along the surface of the glass lens exhibiting an effective refractive index of 1.617. As a result, the refraction of the light is going to be small, following path $a$ as indicated in figure 5.11. As the voltage is applied across the lens the effective refractive index of the liquid crystals is gradually going to reduce from 1.617 down to 1.507. There is going to be further refraction of the light and the ray path is going to shift from $a$ to $b$.

Figure 5.11 Ray diagram of the second option for a convergent liquid crystal lens. a) for liquid crystals with $n = n_e = 1.617$. b) for liquid crystals with $n = n_o = 1.507$. 
As discussed earlier in section 5.4.1 the focal length of the liquid crystal lens can be calculated using equation 5.15. It can be observed from figure 5.12 that the focal length changes from 43 mm to 25 mm as the voltage changes from 0 V to 30 V. The values of the focal length change again give us the change in focal length when the liquid crystal lens is used in combination with an objective, illustrated in figure 5.13.

Figure 5.12 Focal length as a function of the applied voltage for the second option of a convergent lens.

Figure 5.13 Change in focal lengths for the second option of a convergent liquid crystal lens.
Figure 5.14 $B$ values for the second option of a convergent liquid crystal lens.

The corresponding $B$ values for the focus shift in a thick sample in figure 5.13 are illustrated in figure 5.14. As discussed in section 5.4.1, the $B$ value is negative making the liquid crystal lens a viable option for tube length compensation. The depth to which the combined lens system can be used to compensate is illustrated in figure 5.15. It can be observed from figure 5.14 that this design is suitable for tube length compensation between the depths of 0.37 mm and 0.6 mm.

Figure 5.15 Compensation depth as a function of the applied voltage for the second option of a convergent lens.
5.5 Divergent lenses

5.5.1 First option of a divergent lens design

In this option we investigate the possibility of constructing a liquid crystal lens with the following characteristics. The first section of the lens is a plano-concave (negative) lens. From a ray diagram we can expect that the combined lens acts as a diverging or negative lens regardless of the voltage applied as illustrated in figure 5.16. The glass lens used in this case has the following properties: SF11 ($n_g = 1.785$) plano concave lens with a radius of -21.19 mm and a focal length of -27 mm.

The focal length of the liquid crystal lens will always be negative as may be observed from figure 5.17. This option may have applications in laser trapping as a trapped particle is within a medium which has a refractive index lower than that of the cover glass.

![Figure 5.16 Ray diagram for the first option of a divergent liquid crystal lens.](image)

a) for liquid crystals with $n = n_e = 1.617$. b) for liquid crystals with $n = n_o = 1.507$. 


Figure 5.17 Focal length as a function of the applied voltage for the first option of a divergent lens.

Figure 5.18 Change in focal length for the first option of a divergent liquid crystal lens.

Figure 5.19 $B$ values for the first option of a divergent liquid crystal lens.
The combined focal length change when used in combination with an objective is illustrated in figure 5.18. The corresponding $B$ values as per equation 5.20 gives us the following figure 5.19.

It can be observed from figure 5.19, that the corresponding $B$ values are positive. As a result, this design is not suitable for tube length compensation in optical data storage in which case the refractive index of the sample is larger than that of the immersion medium. It may however, have applications in laser trapping where controlled divergence of the trapping beam is required.

### 5.5.2 Second option of a divergent lens design

In this option we investigate the possibility of constructing a liquid crystal lens with the following characteristics. The first section of the lens is a plano-convex (positive) lens. From the ray diagram in figure 5.20 we can expect the combined lens to act mainly as a negative lens or diverging lens. The glass lens used in this case has the following properties: BK7 ($n_g = 1.517$) plano-convex lens with a radius of 10.85 mm and a focal length of 21 mm.

![Figure 5.20 Ray diagram for the second option of a divergent liquid crystal lens.](image)

- a) for liquid crystals with $n = n_o = 1.507$.
- b) for liquid crystals with $n = n_e = 1.617$. 
It can be observed from the calculations of the effective focal length of the liquid crystal lens that it is going to be divergent for up to 20 volts. This again would be an option for aberration compensation in laser trapping.

The focal length shift when a liquid crystal lens is used in combination with an objective is illustrated in figure 5.21. This option is similar to the design described in 5.5.1 where the $B$ value is positive as illustrated in figure 5.20. As a result this design is not suitable for tube length compensation in optical data storage.

![Figure 5.21 Focal length as a function of the applied voltage for the second option for a divergent liquid crystal lens.](image)

![Figure 5.22 Change in focal lengths for the second option of a divergent liquid crystal lens.](image)
5.6 Fabrication of the liquid crystal lens

A convergent liquid crystal lens based on the details in section 5.4.1 can be manufactured using the same processes as that used for the phase plate (Section 3.3 - 3.5). Having thin spacers makes filling the cavity with liquid crystals in the phase plate easier than that for the lens. It is not possible to use capillary action to fill the cavity produced by the lens as with the phase plate. As a result, the glass lens has to be over filled with liquid crystals. Then the glass substrate has to be carefully placed over the lens starting from one edge. The excess liquid crystals have to be gradually pushed out only when the whole of the glass substrate is in position. The glass substrate has to be kept pushed against the lens until the two parts can be sealed using the two part epoxy.

In an ideal case, a liquid crystal lens would be made up of a glass lens with refractive index matching that of the extra-ordinary refractive index of the liquid crystal. Such a design would allow for moving the focal point deeper into the medium with the increase in voltage. However, fabrication of such a lens would require greater control over the sealing mechanism of the lens as well a thickness control of the spacer.
Fabricating a liquid crystal lens with the plano-concave glass lens allowed us to validate the principle of moving the focal point in a medium like that previously demonstrated in optical data storage (Day and Gu, 1998).

### 5.6.1 Experimental setup for characterisation of the liquid crystal lens

The liquid crystal lens was characterised by obtaining an axial scan from a two-photon (2-p) fluorescent polymer (Day and Gu, 1998). The 2-p polymer was illuminated with 800 nm light from a Spectra Physics Titanium Saphire Tsunami tuneable pulsed laser. The pulse width and repetition rate of the laser were 80 fs and 82 MHz, respectively. The diameter of the pinhole used in the set up was 100μm. A photo-multiplier tube (PMT) was used for the fluorescence signal detection. The objective used was an Olympus ultra long working distance with numerical aperture of 0.75. The set up of the experiment is illustrated in figure 5.24. Such a system is similar to that used in optical data storage (Day and Gu, 1998).

![Experimental setup for liquid crystal lens characterisation.](image)

The 2-p polymer was mounted on a computer controlled x-y-z translation stage. The fluorescence signal from the polymer was passed through a beam splitter and
focused through a pinhole into the PMT. A band pass filter was used in front of the detector to filter out the excitation light. The axial response at different voltages was recorded using a computer.

The beam path was blocked and the voltage returned to zero before a new voltage was applied across the lens. This allowed the liquid crystals to return to the original alignment.

### 5.6.2 Characterisation of the liquid crystal lens

The axial response to the polymer block is usually aberrated because of the mismatch of the refractive indices (Day and Gu, 1998). To demonstrate the effect of the liquid crystal lens compensation for the aberration in this case, a series of axial responses were obtained for different voltages using the liquid crystal lens fabricated with the design discussed in section 5.4.1. When there is no voltage applied across the liquid crystals, there is a sharp drop in the axial response inside the medium. This drop in intensity is a result of the spherical aberration caused by the refractive index mismatching. From figure 5.24, it can be observed that the surface of the medium is approximately at the 50 μm mark of travel of the scanning stage.

![Figure 5.25 A typical axial response of a 2-p confocal setup without the voltage applied to the liquid crystal lens.](image)

Figure 5.25 A typical axial response of a 2-p confocal setup without the voltage applied to the liquid crystal lens.
This type of aberration can be compensated for if the voltage is applied to the liquid crystal lens. The measured intensity at a depth of 20 μm within the medium is shown in figure 5.26.

It can be observed from figure 5.26 that regulation of the voltage between 8 volts and 10 volts allow us to adjust the intensity of the axial response. The amount of variation in intensity depends on the depth and the applied voltage.

Figure 5.26 Change in intensity as a function of voltage at a depth of 20 μm.

It can be observed from figure 5.26 that the intensity of the light traveling to a point 20 μm within the bulk media can be maximised. This method can be used to reduce aberration losses which make writing and reading data deep within a medium difficult.

### 5.7 Summary

Four types of liquid crystal lenses were designed as either divergent or convergent lenses by choosing a glass lens with a refractive index matching either the ordinary or extra-ordinary refractive index of the liquid crystals. Fabrication of the liquid crystal lens was similar to that of the phase plate with the exception that the liquid crystals cannot be filled by capillary action.

The liquid crystal lens with a positive focal length was used in a 2-p confocal setup to improve the quality of the 2-p fluorescence response from a fluorescent
polymer substrate. A significant improvement in the detected intensity at a depth of 20 μm was observed when the voltage applied to the liquid crystal lens was increased to 10V. This result indicates that a liquid crystal lens can be used to improve the quality of imaging inside a bulk medium by reducing the amount of the combined aberration.
Chapter Six

Conclusion
6.1 Thesis conclusion

This thesis provides a detailed study in the fabrication of liquid crystal lenses. Liquid crystal devices include phase plates, lenses and displays. A liquid crystal phase plate using Merck liquid crystal ZLI-5049-000 has been fabricated. The structure, design and application of a phase plate depend on the rubbing direction of the insulating layer.

The insulating layer of the liquid crystal phase plate was fabricated by spin coating polyvinyl alcohol solution on to a glass substrate coated with ITO from CERAC. The transparent ITO electrodes were coated using vacuum vapor deposition rather than traditional sputter deposition techniques. This provides an alternative low cost and easier alternative to sputter coating. The transmittance of the various layers has been measured and transmissions efficiency above 90% have been recorded.

The phase plate was characterised using a HeNe laser measuring the transmission dependence on the applied voltage. The relationship between the change in transmission and the applied voltage exhibited a phase change of up to $\pi$. An effective refractive index change of $0.11$ was achieved with an applied voltage of $30\text{ V}$.

The phase plate data has been used to design and calculate parameters for lenses that are convergent or divergent. A convergent lens has been developed and used in a 2-p confocal system for imaging through bulk media at different depths and an increase in the detected intensity has been observed. This lens was dynamically controlled to improve the axial response within the medium. Improvement in transmission at a depth of $20\mu\text{m}$ has been recorded.

This lens has the potential to be developed into a dynamic control system using the same principle exhibited for tube length compensation without physical
movement of addition lenses conventionally used. This mechanism can be used in a wide range of applications including data storage and trapping.

6.2 Recommendations for future work

In order to develop a dynamic system for tube length aberration compensation, a number of additional aspects would have to be developed. Firstly, a more appropriate glass with a refractive index matching the refractive index of the liquid crystal could be used to reduce the effect of the lens on the beam path. Secondly the structure of the insulating layer should be modulated to control the thickness of the lens as well as the initial orientation. Thirdly, the electrode should be designed to allow application of different voltages to different regions of the lens.
References


