TUNABLE LIQUID CRYSTAL POLARIZATION GRATINGS

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Chapter 1

Introduction

1.1 Introduction to beam steering technology

Laser beams with high accuracy, high efficiency, agile pointing, fast speed, and controllable direction to a desired target is an important topic in such fields as free space communications, projection displays, fiber-optical switches or connectors, optical data storage, and other general industrial applications. As shown in Fig. 1.1, beam steering is one of the key techniques to direct the laser beam (data carrier) from one node in the communication links to another remote node, or deliver the light from the transmitter to the receiver precisely and efficiently in the free space communication. Beam steering device also plays an important role in military applications such as laser guided weapons, laser radar, range determination, and directed-energy weapons, etc.

In terms of beam steering, the direction of the main lobe of a radiation pattern is changed by switching antenna elements or by varying the refractive index of the medium through which the beam is transmitted or by the use of mirrors or lenses.

The most traditional and common method of implementing beam steering is the using of macroscopic mechanically controlled pivoting planar mirrors that have already
been a mature technology for many years. The steering speed of the approach is severely limited by the mechanical movements of driven mirrors. The resulting devices are also excessively expensive, heavy, bulky and high power consumption. Other beam steering methods such as acousto-optic modulator, has such problems as a very limited angular range, slow switching speed. It is very critical for such applications as aerospace systems to both keep costs down and have wide angular range and high steering efficiency. To resolve these limitations, several beam steering technologies have been proposed and developed, such as DMD/DLP by Texas Instruments technology,\textsuperscript{9-11} grating light valve,\textsuperscript{12} inorganic digital light deflector.\textsuperscript{13-16}

The micro beam steering technologies are attracting more and more researchers’ interests and attentions because of the nature of fast tuning, agile, light weight, changes adaptive, etc. There are currently several implementations of beam steering, such as deformable micro-electrical mirrors (MEMS),\textsuperscript{17-20} liquid crystal optical phased array (OPA),\textsuperscript{21-23} and lenslet arrays.\textsuperscript{24} The MEMS technology is fast and reflective. However, it has issues with fill factors and pitch, and only suitable for fine angle steering that is less than 1 degree. The liquid crystal OPA technology has been considered for small angle beam steering because of the small pitch, low driving voltages, large birefringence, flexibility, and electrical control. Nevertheless, the large area resets of the phase profile caused by the fringe fields degrade the achievable device efficiency.\textsuperscript{25} Lenslet arrays (Decentered micro-Lens Arrays, DLAs) are excellent candidate for moderate angle beam steering, while it also has the limitations with mechanical motion that downgrade the performance of steering speed. When the micro-lens arrays are transformed and encoded
into liquid crystal devices, we can replace the mechanical motion of lenslet with electrical control of the voltage profile precisely. In the recent work, we develop a liquid crystal tunable polarization grating device characterized with continuous angular tuning capability and high efficiency.

### 1.2 Liquid crystal beam steering devices

Liquid crystal (LC) technology has become a promising and excellent candidate for non-mechanical optical beam steering components because of low driving voltage, large birefringence, and low cost fabrication techniques.\(^{21}\)

In general, the concept of the common LC beam steering devices can be regarded as a blazed phase gratings (in Fig. 1.2). The LC device with controlled applied voltage profile or cell thickness profile led to the linear phase profile of the transmitted or reflected light exiting from the device. This repeated periodically phase across the entire cell forms a saw-tooth periodic phase characteristic of a blazed grating.

Liquid crystal based beam steering devices usually follow the basic idea of generating a linear change of optical path difference (OPD) across the aperture, which tilts the incident phase front and thereby steers the optical beam.\(^{26}\) The steering angle is determined by the magnitude of phase gradient caused by the spatially varying retardation \(\Delta n d\) (\(\Delta n\) is the effective birefringence, and \(d\) is the LC cell thickness). Either the variation of \(\Delta n\) or linear changing of gap \(d\) will result in the spatially varying optical phase retardation. This phase profile is imposed on the incident optical beam will steer the light to the designed direction.
Three major approaches are typically considered to implement the liquid crystal beam steering capability. They are liquid crystal digital beam deflector, liquid crystal optical phase arrays, and liquid crystal decentered micro-lens arrays. Furthermore, we have developed a tunable liquid crystal polarization gratings device with angular tunability and high diffraction efficiency starting from the concept of Pancharatnam QHQ plate.27

1.3 Liquid crystal prisms

One approach, first pursued by several research groups like W. Thust, Chuck Titus, et al., is prismatic liquid crystal digital beam deflector as shown in Fig. 1.3, which consists of cascaded binary light switches.28-31 In each switch, it is consisted with a polarization rotation switch and a passive birefringent deflecting element. The incident light with linear polarization with e-mode or o-mode is first guided into the polarization rotation switch. The o-mode light unalter the polarization state after propagating through the switch, while the e-mode will be rotated the plane of polarization by 90 degrees. The resulting light is then transmitted into the passive birefringent deflecting prism. The prism consists of a birefringent medium (e.g. liquid crystal) and a means of supporting glass substrates. The optic axis of the birefringent medium is oriented parallel to the vertex of the prism. When light of polarization parallel to the optic axis is received by the prism, its path is deflected. The angular separation between these two deflections is the characteristic angular deflection of that prism. Stacking N such binary switches together can create a device that is capable of deflecting light of $2^N$ angles. However, the
efficiency of this kind of device is limited by the losses caused by the prism array. And no efficient treatment has been found to resolve this problem till now.

1.4 Liquid crystal optical phased arrays

In 1970s, a lot of LC beam steering concepts were developed based on the liquid crystal materials sandwiched between two substrates, having a common electrode on one side, and multi parallel stripe electrodes on the other side. Individual voltages can be applied on the stripes electrodes and common electrodes. Then the spatial variation of the refractive index can be formed. In this approach, $\Delta n$ is varied to achieve a gradient, however to achieve a large gradient over a large aperture with a continuous phase profile requires a large value of $d$. The large value of $d$ leads to slow response, absorption and scattering of light by the device. In 1990s, OPA technology was first introduced into beam steering by Paul F. McManamon et al. As shown in Fig. 1.4, the OPA approach fixes the problem of large $d$, found in the simple approach by introducing “resets” into the phase profile whose OPD step is an integer number of wavelengths of the light being considered. These resets, if mathematically ideal, would not be a large problem for a single frequency wavefront, however in real devices it is well known that they degrade the achievable device efficiency. The first OPA devices were described by McManamon et al. with an efficiency of 85% for steering $1\mu m$ radiation to $1.5^\circ$. Higher efficiencies have been reported by Raytheon for $10.6\ \mu m$ radiation. Raytheon Company firstly fabricated the OPA device in 1988. However, the resets lead to severe wavelength dependence and difficulty to obtain high efficiency ($>95\%$).
1.5 Liquid crystal decentered micro-lens arrays

Another type of liquid crystal beam steering device is called liquid crystal decentered micro-lens array proposed by E. Watson. The basic concepts of beam steering using all positive or mixed three-layer decentered micro-lens arrays are shown in Fig. 1.5(a, b). By shifting the position of the second and third layers, the input beam will be redirected to the steered angle. Some preliminary researches at the AFRL (air force research laboratory) have already described this type of system. With the micro-lens arrays encoded into liquid crystal devices, we can substitute the mechanical motion of lenslet with electrical control of the voltage profile. That could be preferable to the LC-OPA device since no resets are existed in the LC lenslet cascades. With appropriate phase compensations on each layer of the cascades, it is possible to obtain very high diffraction efficiency above 95%.

1.6 Tunable liquid crystal polarization gratings

Another approach to obtaining high efficiency beam steering is to apply the concept of Pancharatnam QHQ phase plate in Fig. 1.6. Several research groups have reported work based on this idea. For example, Honma et al. have shown a lens fabricated through a micro-rubbing technique. Crawford and co-workers have demonstrated a LC diffraction grating through a polarization holography exposure on a linear photo-polymerizable polymer alignment layer. Escuti et al. report their LC polarization grating to modulate unpolarized or polarized light with a grating
period as small as 6.3\(\mu\)m.\(^{34}\) These results have demonstrated the validity of this basic idea of what is called a polarization grating.

In this type of device, circular polarized light is normally incident on a half wave optical retarder with its optic axis spiraling in the plane of the retarder as shown in Fig. 1.7. The half-wave retarder is here considered to be a liquid crystal whose director axis corresponds to the slow retarder axis that has an in-plane spiral configuration where the azimuthal angle \(\beta\) linearly continuously rotate from 0 to \(\pi\), \(2\pi\), \(3\pi\), etc. As a result of Jones calculus, when the optical path delay (OPD) across the LC cell normal (along \(z\) axis) is half wave, the spatial phase profile (along \(x\) axis) of the transmitted circularly polarized light will have a common factor \(\exp(i \cdot 2\beta(x))\), which means the output phase will linearly transform from 0 to \(2\pi\), \(4\pi\), and \(6\pi\), etc. If the gradient of the azimuthal angle of liquid crystal director is a constant with the rotation angle increasing along a particular direction (\(x\) or \(-x\) axis in Fig. 1.7), we will obtain a device with increasing phase without any “reset” or discontinuity.

In consideration of a tunable device, we developed a vertically surface aligned, continuous optical phase array (V-COPA) that uses a negative dielectric anisotropy LC material.\(^{35}\) The period of the spiral grating was shown to be varied by adjusting an applied voltage profile, which allows for continuous angular control of the steering angle. In addition, only thickness with half-wave retardation is required for the LC polarization gratings, Throughput of the transmittance light without considerable absorption, scattering etc can be reach to 100% steering efficiency.
1.7 Overview of the dissertation

The dissertation is organized as follows. In the first chapter, we will review the background and previous work of liquid crystal beam steering technology. In chapter two, we will investigate the causes of low efficiency for optical beam steering devices based on liquid crystal Decentered micro-Lens Arrays (DLAs). We show that the efficiency is effected by: the relative phase of light exiting the individual lenses; the imperfect focusing of small lenses due to diffraction; the aberrations related to off-axis light going through a lens; and the diffraction spreading of light beams going through the DLA structure. High steering efficiency of over 94.4% is demonstrated by modeling the transmitted light through the DLA with scalar diffraction theory. We also propose modified phase profiles for the lenses that are a function of angle that substantially improve the performance of these types of devices over the unmodified profiles.

In the following chapter three, we will focused on basic design and concepts of tunable liquid crystal polarization gratings with a nematic liquid crystal (LC) optical phase plate, with a large continuous in-plane gradient that is variable, and its application to a beam steering device with high efficiency. The device is a vertically aligned, continuous phase, optical phased array (V-COPA), that uses a negative dielectric anisotropy liquid crystal material. High steering efficiency of over 95% is demonstrated by modeling of the liquid crystal director field, and its effect on transmitted light. The period of the V-COPA grating can be varied by adjusting an applied voltage profile, which allows for continuous angular control of the diffraction angle. This continuous steering combined with such high efficiency is unprecedented.
To improve the important issue of tuning speed, in chapter four, we consider the dynamics of the LC polarization gratings. In this chapter we study the dynamics of discrete changes in the phase profile, and also continuous changes in the phase profile through acquired data and numerical modeling. We show that a design based on liquid crystals whose dielectric anisotropy can change sign (as a function of frequency) allows continuous tuning with reasonable response times.

In addition, the liquid crystal based electronically controlled lens will be briefly described in Chapter five. With this technique, we are able to replace the conventional eye glass with non-mechanical electrically controlled LC lens, also with the capability of different focal length.

Finally, we will present our conclusions and outline the potential future research subjects of the tunable liquid crystal polarization gratings for LC beam steering device.
Fig. 1.1 Beam steering component used in free space communication
Fig. 1.2 A blazed grating used to deflect the beam
Fig. 1.3 Liquid crystal digital beam deflector with LC prisms
Fig. 1.4 Director configuration of one period of liquid crystal optical phased array device
Fig. 1.5 Liquid crystal decentered micro-lens array

(a) all positive three-layer LC decentered micro-lens array

(b) mixed three-layer LC decentered micro-lens array
Fig. 1.6 A basic setup of Pancharatnam QHQ stack

(a) & (e): Polarizer; (b) & (d): Quarter-wave Plate; (c): Half-wave plate
Fig. 1.7 In-plane spiral director configuration (x-y plane) of the polarization grating (named as V-COPA in our design)
Chapter 2

Liquid crystal decentered micro-lens array

2.1 Introduction to liquid crystal decentered micro-lens array

As we have introduced in Chapter 1, the liquid crystal based lenslet (liquid crystal decentered micro-lens array, LC-DLAs) offers an option to realize high efficiency non-mechanical beam steering. The researchers from Wright Patterson Air Force Research Lab, such as Dr. Edward A. Watson, proposed some different configurations of decentered micro-lens array system, for instance, all positive decentered lens array where all the lens are designed with equal positive focal length, and mixed decentered lens array system where a center lens with negative focal length is sandwiched between two layers of positive lens cascades. They concluded that the wavefront exiting from a micro-lens array can be treated as a blazed grating, with the angle dependent on the amount of the decenter. Moreover, the periodic nature of the wavefront limits the final diffraction efficiency to the desired direction.

The advanced liquid crystal technology also provided the opportunity to replace the mechanic glass micro-lens with non-mechanical LC materials. When encoding the micro-lens array system into the LC cell, in principal the encoded process is similar to the traditional liquid crystal optical phase array (LC-OPA) system which has been studied for
more than ten years. In the typical LC-OPA system, the issue of resetting problem (usually referred as fringe field effect) seriously downgraded the steering efficiency as shown in Fig 2.1. However no such effect will exist in the liquid crystal decentered micro-lens array system that the LC material is used to reproduce the phase profile of lens arrays that have no abruptly phase resets internally. Another advantage of DLAs with liquid crystal material is that the LC micro-lens cascade can be electronically controlled solely and can be packed more densely in practice. It can offer the capability of phase correction by tuning the liquid crystal phase profile to the objective compensated lens profile which will minimize the loss from the edge diffraction and obtain high diffraction efficiency.

Dr. Jianru Shi from Liquid crystal Institute of Kent State University has developed the numerical modeling program of DLAs in analyzing the limits and considerations of Liquid crystal decentered micro-lens array. In his work, Dr. Shi implemented the detailed calculation and optimized simulation results of the expected efficiency of this LC-DLAs cascade system by scalar integration approach and the FDTD (Finite Difference Time Domain) modeling method. Some unexpected issues in the all positive lens system are raised in his work, such as the “flipping” effect and ill-focusing problem of positive lens with incident light of Gaussian beam. To avoid these issues, as an alternative design, we will introduce the mixed LC-DLAs cascade system where the center liquid crystal lens has a negative focal length. Both of these LC-DLAs systems will suffer from the edge diffraction loss and low efficiency caused by several factors without any phase correction and compensation. In this chapter, we will investigate
several important factors related to the final loss of the diffraction efficiency and thereafter show the optimized phase compensation procedures which can lead to a very high steering efficiency of over 94%.

The general algorithms of beam steering with all positive or mixed three-layer decentered micro-lens array system have already been shown in Fig. 1.5(a, b) of Chapter 1. In this chapter, we will denote the lens with positive focal length as positive lens, and the lens with negative focal length as negative lens. To illustrate the steering algorithm, the configurations of three-layer macroscopic lenses are shown in Fig 2.2(a, b). Note that the subscript numbers (1, 2, and 3) are defined as the layer number. In the all positive micro-lens system (Fig. 2.2(a)), the focal lengths of all the lenses are identical, \( f_1 = f_2 = f_3 \). The inter-layer spacing is equal to the focal length. The beam after exiting the third lens is steered by shifting the second and the third lens towards the same direction. The decentered amount \( \Delta_2 \) of the second lens is also same as the one of the third lens. In the mixed lens system (Fig. 2.2(b)), the second negative lens and the third positive lens are translated with respect to the first positive lens in the opposite direction, with the amount \( \Delta_2 \) and \( \Delta_3 \) respectively, where \( \Delta_3 \) is two times of \( \Delta_2 \). The focal length of negative lens \( f_2 \) is one fourth of the positive lens \( f_1 \), where \( f_1 \) is equal to \( f_3 \). The inter-layer spacing is half of the focal length \( f_1 \).

To characterize the optical performance of the LC cascades, firstly we develop the simulation programs and tools to simulate the light propagation through the three-layer LC lens cascade. By the means of our LC3D routine, we are able to simulate and optimize the phase profile of the liquid crystal micro-lens required in the system.
2.2 Numerical modeling methods

2.2.1 Kirchhoff’s scalar integral method

To describe the propagation of the incident beam through the LC-DLAs cascade system and calculate the final diffraction efficiency in the far field, we develop a scalar integral method according to the Huygens-Fresnel diffraction theory. In Fig. 2.3, three micro-lens layers are assumed to be thin layers with the optical path delay (OPD) profile of \( \text{OPD}_1(x_1) \), \( \text{OPD}_2(x_2) \), and \( \text{OPD}_3(x_3) \). Denote the radius of lens as \( r \), and the off axis distance as \( x \), the OPD function of an ideal positive ideal lens is given by:

\[
\text{OPD}_1(x_1) = \sqrt{r^2 + f_1^2} - \sqrt{x_1^2 + f_1^2}
\]  

Similarly, the OPD function of an ideal negative lens is defined as follows:

\[
\text{OPD}_2(x_2) = \sqrt{x_2^2 + f_2^2} - f_2
\]

In addition, three different phase compensations (phase-up correction, aberration correction and mirror symmetry correction) will be applied to the phase profile of LC micro-lens to obtain high efficiency respectively (details in section 2.4). Therefore the final objective OPD profile for each layer can be written as:

\[
\text{OPD}_1'(x_1) = \text{OPD}_1(x_1)
\]

\[
\text{OPD}_2'(x_2) = \text{OPD}_2(x_2) + \text{OPD}_{\Delta 2}(x_2) + \text{OPD}_{\Delta \text{mirror} 2}(x_1)
\]

\[
\text{OPD}_3'(x_3) = \text{OPD}_3(x_3) + \text{OPD}_{\Delta 3}(x_3) + \text{OPD}_{\Delta \text{phase} \_ \text{up} 3}(x_3)
\]

A Gaussian beam \( E_0 \) is normal incident through the first positive lens layer:

\[
E_1(x_1) = E_0(x_1) \cdot e^{ik \text{OPD}_1'(x_1)}
\]

By the Kirchhoff’s scalar integral, we may calculate the field from the first layer to the second layer by Eq. (2.5):
The wave traversed through the second negative lens layer is:

\[ E_{2a}(x_2) = \int E_1(x_1) \left( \frac{1 + \cos \theta_1(x_1)}{2} \right) \cdot \frac{e^{ikr_1}}{\sqrt{r_1}} dx_1 \]  

(2.5)

The wave traversed through the second negative lens layer is:

\[ E_{2b}(x_2) = E_{2a}(x_2) \cdot e^{i(\text{OPD}_2(x_2))} \]  

(2.6)

From the second layer to the third layer, the transmitted wave can be given by:

\[ E_{3a}(x_3) = \int E_{2b}(x_2) \left( \frac{1 + \cos \theta_2(x_2)}{2} \right) \cdot \frac{e^{ikr_2}}{\sqrt{r_2}} dx_2 \]  

(2.7)

At the third positive lens layer:

\[ E_{3b}(x_3) = E_{3a}(x_3) \cdot e^{i(\text{OPD}_3(x_3))} \]  

(2.8)

The wave \( E_{3b} \) is equivalent to the near field \( E_{\text{near}} \), which can be transformed to the far field \( E_{\text{far}} \). The diffraction pattern of exiting beam in the far field can be obtained by Kirchhoff’s scalar integral too. To be consistent with the general mechanism of light detection, we can define the diffraction efficiency as the ratio of the peak intensity of the main lobe over the peak intensity of the reference beam.

### 2.2.2 Liquid crystal director modeling method

The DLAs cascade system can be programmed into liquid crystal based devices. Liquid crystal director modeling is employed to find the correct voltage that needs to be applied on each pixel region of the lens to obtain the desired phase profile. Fig. 2.4 shows the structure of a typical LC cell configuration of a positive liquid crystal micro-lens unit. It has a liquid crystal layer sandwiched between two glass plates coated with a common indium tin oxide (ITO) transparent electrode on one substrate, and striped electrodes on
the other. By applying different individual voltage on the electrodes, the orientation of LC director over all the pixels in the bulk can be controlled precisely. Variable optical path delay (OPD) along x axis can be obtained to form a phase profile of either the positive or negative micro-lens as described in Eq. (2.1–2.3).

To encode the micro-lens phase profile into the liquid crystal cell, the first step is to characterize the LC cell’s OPD curve with respect to the ramped voltage by a simple one dimensional (1D) LC director simulation (along z axis) as shown in Fig. 2.5. Since for each point on the OPD profile of a LC micro-lens can be found a corresponding voltage value on the OPD vs. Voltage curve, the first entry voltage profile of a positive or negative micro-lens can be thereby derived. In principle, the OPD depth of the target lens profile must less than the maximum OPD of LC cell as shown in Fig. 2.5. In order to avoid the two plateau regions I and III, where one is applied with 0V or small voltage (approximately keep with the initial director configuration along the surface alignment direction), and another is involved with high voltage (vertical director configuration, not stable and hard to convergent and reach equilibrium state), we usually select the linear region II as shown in the Fig. 2.5 to map the objective ideal positive or negative lens phase profile as shown in Fig. 2.6 into the individual voltage on each pixel of LC cell.

By applying the initial voltage on the system, the equilibrium state of the LC director configuration will be simulated by a two dimensional LC model with vector field method. The liquid crystal director orientation is considered to be a function of x and z. Note that we define x axis is along the cell surface and perpendicular to the stripe electrodes, y is
along the electrodes direction, and \( z \) is along the cell normal. The generalized force on
the director components \((n_x, n_y, \text{ and } n_z)\) is given by:

\[
[f_G]_{ni} = -\frac{\partial f_G}{\partial n_i} + \sum_{j=x,y,z} \frac{d}{dj} \left[ \frac{\partial f_G}{\partial (dn_j/dj)} \right] \quad i = x, y, z. \tag{2.9}
\]

Where \( f_G \) is the Gibbs free energy density, formed from the elastic free energy
density and the electric free energy density, and \( -\frac{\partial f_G}{\partial n_i} \) is the functional Euler-
Lagrange derivative of it.

The general update formula for each grid is the balance between the viscous torque
and that from Eq. (2.9):

\[
\gamma \frac{dn_i}{dt} = -\frac{\partial f_G}{\partial n_i} + \lambda n_i \quad i = x, y, z. \tag{2.10}
\]

Here \( \gamma \) is the viscosity coefficient and \( \lambda \) is a Lagrange multiplier used to maintain the
unit length of the director \( |n| = 1 \). Since the \( n \) will be renormalized in each iteration, the
Lagrange multiplier \( \lambda \) can be dropped.

The derivatives can be replaced by finite difference to discretize the Eq. (2.10) in our
2D modeling:

\[
\gamma \frac{\Delta n_i}{\Delta t} = -[f_G]_{ni}
\]

\[
\Delta n_i = -\frac{\Delta t}{\gamma} [f_G]_{ni} \tag{2.11}
\]

\[
n^\text{new}_i = n^\text{old}_i - \frac{\Delta t}{\gamma} [f_G]_{ni}.
\]
Here vector method is employed to obtain the liquid crystal director configuration with applied electric field. The derivative of elastic free energy density can be derived by the typical Frank-Oseen equation including splay, twist and bend free energy density as shown in Eq.(2.12):

$$f_{\text{elastic}} = \frac{1}{2} K_{11} \left( \nabla \cdot \vec{n} \right)^2 + \frac{1}{2} K_{22} \left( \vec{n} \cdot \nabla \times \vec{n} + q_0 \right)^2 + \frac{1}{2} K_{33} \left( \nabla \times \nabla \times \vec{n} \right)^2$$  \hspace{1cm} (2.12)

Where $K_{11}$, $K_{22}$, and $K_{33}$ are the elastic constants named as splay, twist and bend constants of deformation of the liquid crystal directors, $q_0$ is the chiral number to specify the twist of LC material.

The electric free energy with respect to $n_x$, $n_y$ and $n_z$ can be defined by the Eq.(2.13), that is, the product of the electric field and electric displacement, which is for constant voltage case:

$$f_e = \frac{1}{2} E \cdot D =$$

$$\frac{1}{2} (\nabla V) \cdot (\varepsilon_0 \varepsilon \nabla V) =$$

$$\frac{1}{2} \left( \frac{\partial}{\partial x} V(x, y, z) \right) \left( \varepsilon_0 \left( \frac{\partial}{\partial x} V(x, y, z) \right) \right) \varepsilon + \varepsilon_0 \left( \frac{\partial}{\partial y} V(x, y, z) \right) \Delta \varepsilon \cdot n_z^2(x, y, z)$$

$$+ \varepsilon_0 \Delta \varepsilon_n, (x, y, z) \cdot n_x, (x, y, z) \cdot \left( \frac{\partial}{\partial y} V(x, y, z) \right) +$$

$$\varepsilon_0 \Delta \varepsilon_n, (x, y, z) \cdot n_z, (x, y, z) \cdot \left( \frac{\partial}{\partial z} V(x, y, z) \right)$$

$$\frac{1}{2} \left( \frac{\partial}{\partial y} V(x, y, z) \right) \left( \varepsilon_0 \Delta \varepsilon n_z (x, y, z) \cdot n_z, (x, y, z) \left( \frac{\partial}{\partial x} V(x, y, z) \right) + \varepsilon_0 \left( \frac{\partial}{\partial z} V(x, y, z) \right) \varepsilon \right)$$

$$+ \varepsilon_0 \left( \frac{\partial}{\partial y} V(x, y, z) \right) \Delta \varepsilon \cdot n_z, (x, y, z) \cdot \left( \frac{\partial}{\partial z} V(x, y, z) \right) +$$

$$\frac{1}{2} \left( \frac{\partial}{\partial z} V(x, y, z) \right) \left( \varepsilon_0 \Delta \varepsilon n_x (x, y, z) \cdot n_z, (x, y, z) \left( \frac{\partial}{\partial y} V(x, y, z) \right) + \varepsilon_0 \left( \frac{\partial}{\partial z} V(x, y, z) \right) \varepsilon \right)$$

$$+ \varepsilon_0 \left( \frac{\partial}{\partial z} V(x, y, z) \right) \Delta \varepsilon \cdot n_z, (x, y, z) \cdot \left( \frac{\partial}{\partial x} V(x, y, z) \right)$$

$$+ \varepsilon_0 \left( \frac{\partial}{\partial x} V(x, y, z) \right) \Delta \varepsilon \cdot n_z^2(x, y, z)$$  \hspace{1cm} (2.13)
Then we can derive the functional derivative of the electric free energy with respect to $n_x$, $n_y$ and $n_z$, which are the director components at discrete points on a two dimensional spatial grid. During each update of the director components on each grid point, the time derivatives are only taken in the forward direction and the spatial derivatives are centered around the grid locations by only considering the nearest neighbors. The electric field can be also discretized into grids represented by the $V(x,y,z)$. The grids of electric field will be updated in each loop once the dielectric tensor is regenerated by the contemporary liquid crystal director configuration. The approaches for updating the LC director are known as “successive displacement” and “simultaneous displacement”. In each loop, the relaxation process will cover all of the grid points, and for each grid, a new value of each director component ($n_x$, $n_y$ and $n_z$) will be calculated. In the successive displacement, each component at a particular grid point will be updated immediately, while the simultaneous displacement will calculate the new values of all the grid points and update them at the same time. To study the equilibrium relaxation process, the successive approach is employed since it tends to reach the equilibrium state quickly and efficiently. As for the simultaneous approach, it is typically used in the dynamics study (details in Chapter 4).

To ensure all the grids can be updated by calculating the new voltages and new director configuration from the adjacent grid points, we need consider the appropriate boundary condition for the LC grids system. There are two common boundary condition used in the liquid crystal modeling: periodical boundary condition and mirror symmetry boundary condition. In the current DLAs system, periodical boundary condition is used.
Since we cut the first electrode into half and place them in the first and last pixel (along x) of the system to be consistent with the periodical boundary condition, the LC director configurations in the last pixel are identical to these LC directors in the first pixel.

In this DLA model, the grid size used in our calculation was 2230×50 and the grid spacing was 1.0×0.5 \( \mu \)m for x and z respectively. In our descretized numerical model, we enforced the unit length of the director by normalization, rather than using the Lagrange multiplier method. The equilibrium state was assumed to be reached when the tolerance (which is the absolute value of the difference between the current iteration’s average \( |f_{G}^{\text{new}}| \) and previous iteration’s average \( |f_{G}^{\text{old}}| \) was less than \( 10^{-6} \) N/m².

When the equilibrium state of director configuration is reached, the OPD profile of the simulated LC configuration can be given by:

\[
OPD(x) = \int_{0}^{d} (n_{\text{eff}}(x, z) - n_o) \cdot dz
\]

(2.14)

where \( n_{\text{eff}}(x, z) = \frac{n_v n_e}{\sqrt{n_v^2 \cos^2 \theta(x, z) + n_e^2 \sin^2 \theta(x, z)}} \), while \( \theta \) is angle between the director and z axis in LC cell.

However, the first entry of the voltage profile may not result in the desired OPD profile of the ideal positive lens or negative lens or the profile combined with phase correction. This is because the fringe field effect which is yielding from the small electrode width (much smaller than the cell thickness) and because of the elastic coupling in the x direction. To minimize the errors between the desired OPD profile and the simulated one, the OPD difference can be calculated and thereby transformed into a voltage difference. Adding the voltage modification to the initial voltage profile (note as
the optimization loop #1), we can calculate the LC director configuration again (note as the optimization loop #2). We will repeat the optimization loops until the simulated OPD profile is closed enough to the desired one. This optimization procedure can be illustrated by Fig. 2.7.

Typically, five or six optimization loops are good enough to meet the tolerance requirement and obtain the final optimized phase profile of the LC micro-lens, either the positive lens array or the negative one.

2.3 All positive decentered micro-lens array

2.3.1 Description of all positive micro-lens array

To illustrate the all positive decentered micro-lens array system in Fig. 2.2(a), we trace the light propagation through the micro-lens cascades from the geometric point of view, in which diffraction effects are ignored. A collimated input beam is split into separate cones at the first layer. The wavefront is supposed to focus at the plane of the second layer and then recover to the parallel transmitted beam with the third lens array, and redirected to some certain angle by the decentered displacement of the second and third layer. In the all positive LC-DLAs, the layer spacing is equal to the focal length of the positive lens. The decentered amounts are also equal for the 2nd and 3rd lens array. Since the individual micro-lens is only in the dimension of hundreds of microns, the output beams are characterized with diffraction properties that the macroscopic lenses did not appear obviously. The final output wavefront is actually similar to the blazed grating.
2.3.2 “Flipping effect”

Obviously, in this all positive system, a “flipping effect” will be occurred as shown in Fig. 2.8. The reconstructed deflected beam will have certain loss inevitably because of the inversion of the individual wavefront of each lens.

2.3.3 Robust lens condition for a positive lens

To understand the throughout loss of the all positive DLAs, an analysis of the robust lens condition for a positive lens will be helpful. A lens does not meet this condition when the Gaussian beam divergence related to the lens aperture is significant compared to its focusing power as shown in Fig. 2.9. In this case it is not possible for the lens to provide a sharp focus point when illuminated with collimated light.

Guenther describe the robust lens condition \( \Gamma \) as:

\[
\Gamma = \left( \frac{\pi \cdot w^2}{\lambda \cdot R} \right) \gg 1
\]  

(2.15)

where \( w \) is the beam waist of a Gaussian incident light, set it as \( D/2 \), where \( D \) is lens diameter, \( R \) is equal to the focal length \( f \) here, then we can rewrite \( \Gamma \) as:

\[
\Gamma = \left( \frac{\pi \cdot w^2}{\lambda \cdot R} \right) = \left( \frac{\pi \cdot D^2}{4\lambda \cdot f} \right) = \frac{D^2}{\lambda \cdot f} \gg 1
\]  

(2.16)

For a positive lens, the OPD profile can be written as \( x^2/2f \) approximately. Note that the variable \( x \) is off axis distance, range from \( -r \) to \( r \), and \( r \) is the radius of the lens. The OPD depth (maximum available OPD of a lens) of a positive lens is about \( D^2/8f \). The robust lens condition \( \Gamma \) can be given by:
From Eq. (2.17), to make a robust positive lens, the OPD depth should be much larger than the designed wavelength. Otherwise, the Gaussian beam waist will locate far away from the spherical center of lens. The micro-lens is not able to focus the incident beam and is actually an ill lens.

For the case of an all positive DLAs this condition is a limiting one, however in the case of a mixed lens system, we will shown in the next section that a modification to the lens phase profile of the center lens can correct for this problem.

2.4 Mixed decentered micro-lens array

2.4.1 Description of mixed micro-lens array

As for the mixed decentered micro-lens array system in Fig. 2.2 (b), similarly, from the geometric point of view, a collimated input beam is also split into separate cones at the first layer same as the all positive system. However, the wavefront is reconstructed at the second layer without focusing to the back focal point. Compared with the all positive system, the negative lens will avoid such issues as ill-focusing of a Gaussian beam and “flipping” effect. The beam is recollimated and deflected to a non-zero field angle exiting from the third layer. A paraxial ray trace shows that the tangent of the field angle $\phi_3$ is equivalent to the amount of decentered $\Delta_3$ divided by half of the focal length $f_3$. By shifting the position of the second and third layers, the input beam will be redirected to the steered angle. When the micro-lens arrays are encoded into liquid crystal devices, we

$$\Gamma = \frac{D^2}{\lambda \cdot f} = \frac{8 \cdot OPD_{\text{max}}}{\lambda} \gg 1$$ (2.17)
can substitute the mechanical motion of lenslet with electrical control of the voltage profile in all the electrode pixels.

2.4.2 Design considerations

The properties of the exiting wavefront of micro-lenses are different with the output from the macroscopic lenses that can be simply analyzed by the paraxial ray tracing. In fact, it is necessary to consider DLAs (all positive DLAs or mixed DLAs) as being diffractive devices.

When we consider DLAs as diffractive devices, the diffraction efficiency (DE) of a decentered lens arrays is affected by:

- Phase up of the outgoing wavefronts from the individual lenses
- The off-axis aberration of the lenses
- Robust lens condition limitation
- Diffractive scattering from the aperture of the first lens layer

The first two can be corrected by modifying the lens profile vs. steering angle. The robust lens condition limitation can be corrected in the “mixed lens” system by modifying the lens profile of the center negative lens. Therefore, in a mixed DLAs system these three issues can be corrected by the phase compensation of the conventional lens profile. However the last factor cannot be corrected and sets the DE limit of a micro-lens array as determined by the lens diameter.

2.4.3 Three phase compensations of mixed micro-lens arrays
To understand the efficiency losses of the micro-lens cascades, we studied three
different aspects of the phase compensations. We studied three sources of the efficiency
loss occurred in mixed micro-lens arrays and their correction approaches. The off-axis
aberration correction can be applied on either positive or negative micro-lens layers. The
phase-up corrections are usually applied on the third positive micro-lens array. The
mirror symmetry correction is designed specifically for the mixed micro-lens system to
correct for the non-robust nature of the micro-lenses.

a. Off-axis aberration correction

The algorithm of off-axis aberration correction of the DLAs can be understood by
first considering an ideal single positive lens, as shown in Fig. 2.10. A collimated input
plane wave, denoted as ray $AB$ and ray $A'B'$, is oblique incident on the positive lens with
a tilted angle $\varphi_3$ from right to left. Note that BD is perpendicular to A’B’, point B and D
are in the same wavefront before the beam passes through the lens. The exiting beam is
focused to the back focal plane $OO'$ at point $O$ with ray $BO$ and ray $B'O$, where the
distance $BO$ is denoted as $R$. Draw a circle of radius $R$ centered at $O$. Note that point C in
ray $A'B'$ is also on the circle with radius R. Then point B will have the same wavefront as
point C after the beam transmits through the lens. Compare the two wavefronts, the
optical path difference of this positive lens can be written as:

$$\text{OPD}_{A} = -DC = OD - OC = OB' + B'D - OC = OB' + B'D - OB$$

(2.18)

Note that $O'B'$ is equal to $f_3$, $BB'$ is the distance x from point $B$ to the center of lens
$B'$, $OO'$ is denoted as $d$.

From Eq. (2.18), the phase difference in Fig. 2.10 can be described by:
Fig. 2.11 shows the case of a single negative lens. The collimated beam incidents at the negative lens with a tilted angle $\phi_2$ from left to right, defined as ray AB and ray A’B’.

Similarly, point B and D are in the same wavefront before pass through the lens, while point B and C have the same phase after pass through the lens. It yields the following optical path difference of the negative lens:

$$\text{OPD}_{\Delta_\text{negative}} = DC = A'C - A'D = A'B - A'B'-B'$$

(2.20)

As illustrated in Fig. 2.11, it can be rewritten as:

$$\text{OPD}_{\Delta_\text{negative}} (x) = \sqrt{f_2^2 + (x + d)^2} - \sqrt{f_2^2 + x_2^2} - x \sin \phi_2$$

(2.21)

In Fig. 2.2(a, b), consider a non-steered system where the decentered amount $\Delta_2$ and $\Delta_3$ are both equal to 0, and $\phi_2$ and $\phi_3$ are thereafter equal to 0. The phase differences of non-steered system can be given by:

$$\text{OPD}_{0+} (x) = f_3 - \sqrt{f_3^2 + x^2}$$

(2.22)

$$\text{OPD}_{0-} (x) = \sqrt{f_2^2 + x^2} - f_2$$

(2.23)

The final aberration of the third positive lens for a non-zero steered angle can be described as Eq. (2.19) minus Eq. (2.22):

$$\text{OPD}_{\Delta_3}(x_3) = \sqrt{f_3^2 + (x_3 + f_3 \tan \phi_3)^2} - f_3 + x_3 \sin \phi_3 - \left( \sqrt{f_3^2 + (x_3 + f_3 \tan \phi_3)^2} - \sqrt{f_3^2 + x_3^2} \right)$$

where the term $\sqrt{f_3^2 + (f_3 \tan \phi_3)^2} - f_3$ is a constant, and can be neglected. The off-axis aberration correction for the third positive lens is given by:

$$\text{OPD}_{\Delta_3}(x_3) = x_3 \sin \phi_3 - \left( \sqrt{f_3^2 + (x_3 + f_3 \tan \phi_3)^2} - \sqrt{f_3^2 + x_3^2} \right)$$

(2.24)
In the same way, the off-axis aberration correction for the second negative lens can be given by:

\[
OPD_{\Delta 2}(x_2) = \sqrt{f_2^2 + (x_2 + f_2 \tan \varphi_2)^2} - \sqrt{f_2^2 + x_2^2} - x_2 \sin \varphi_2
\]  \hspace{1cm} (2.25)


b. Phase up correction

The discontinuous phase profile of the wavefront (E_{3b}) exiting from the third positive micro-lens layer is the same as that exiting a blazed grating. The OPD introduced by each lens of third layer is analogous to each prism in a micro-prism array of a blazed grating as shown in Fig. 2.12. The discontinuous phase profile shows some deviations from a straight line that represents the ideal phase without reset for designed wavelength. These discontinuities will cause dispersion and loss of efficiency if they are not a multiple of the transmitted light’s wavelength. However an addition term, \(\text{OPD}_{\text{Phase_up3}}\) can be added to each micro-lens in the third layer to cause this condition to be met.

c. Mirror symmetry correction

In Fig. 2.2(b), given the decentered amount of the second and third lenses equal to 0, the wavefront is symmetric on both sides of the second negative micro-lens from the geometric point of view. However, due to the diffractive effects of the first positive micro-lens array, this mirror symmetry about the second layer will be destroyed. The idea of this correction is to modify the phase profile of the second LC micro-lens by adjusting the voltage profile, so that the ideal mirror symmetry is restored.
In Fig. 2.13, as for a case of non-steering, the phase entering the second layer is shown as \( P_{2a}(x) \). The phase of the second lens is given as \( P_2(x) \). The exiting phase, \( P_{2b}(x) \), from the second layer can be given by:

\[
P_{2b}(x) = P_{2a}(x) + P_2(x)
\]

(2.26)

As required by the mirror symmetry, the input wavefront is defined as:

\[
P_{2a}(x) = -P_{2b}(x) + 2 \cdot h
\]
\[
P_{2a}(x) = -(P_{2a}(x) + P_2(x)) + 2 \cdot h
\]

(2.27)

where \( h \) is the peak height of \( P_{2a} \). The modified phase \( P_2(x) \) for non-steered case can be rewritten as:

\[
P_2(x) = -2 \cdot P_{2a}(x) + 2 \cdot h
\]

(2.28)

Then the mirror symmetry correction term required for the ideal negative lens with phase profile \( OPD_2(x) \) of the non-steered case will be given by:

\[
OPD_{\Delta mirror_2}(x) = P_2(x) - OPD_2(x)
\]

(2.29)

Note that \( P_2(x) \) is actually determined by the inputting wavefront of the first lenslet, that is always in the fixed location. Even the second micro-lens layer is translated by the decentered amount \( \Delta_2 \), the mirror symmetry correction term \( OPD_{\Delta mirror_2} \) will keep with the same profile and location of the initial non-steered one. The new phase profile of the negative LC micro-lens will be the fixed \( OPD_{\Delta mirror_2}(x) \) superimposed on the shifted ideal negative lens profile \( OPD_2(x) \).

### 2.5 Simulation Results of LC-DLAs
2.5.1 Limitations of all positive DLAs

The Fig. 2.14(a-e) below show the near field phase profile from a non-steered positive lens array as a function of the OPD of the micro-lens and their diameter.

It can be seen that there is a strong correlation with the smoothness of the near field profile with the OPD of the lenses. This smoothness is reflected in the far field DE as is also shown. The figures also show the “flipping” effect of the input Gaussian beam profile by an all positive DLA (that can be understood by considering the dashed lines that represent light rays in Fig. 1.5(a)) (in Chapter 1) further affects the far-field DE.

It is interesting to study the efficiency dependency with respect to the OPD depth of the all positive micro-lens array. In Fig. 2.15, it turns out that the all positive micro-lens system with single lens will be very hard to achieve high efficiency unless the OPD depth of the lens is larger than about 5\(\mu\m) at the wavelength of 1.5\(\mu\m). This result is actually expected from the “robust lens” condition in Eq. (2.17). Moreover, in a five-lens array, the maximum efficiency decreases to 95% because of the “flipping” effect of positive lenses. Considering a liquid crystal cell with the relatively high birefringence of 0.3, to satisfy the “robust lens” condition, the thickness of the cell should be around 15\(\mu\m) at least. Such a thick LC cell will make high speed switching difficult, and can lead to extra scattering and absorptive losses.

Looking at the far-field results, both on axis and as a function of the steering angle, we can consider an all positive micro-lens array in Fig. 1.5(a) with lens radius as 552 \(\mu\m), focal length as 57.498 mm, OPD depth as 2.6496 \(\mu\m), and totally 5 lenses in each layer, the final diffraction efficiency is only about 89.05\% for no steering at the wavelength of
1.5µm with a Gaussian incident beam, as shown in Fig. 2.16(a). Without any phase compensations, the efficiency for steering light in Fig. 2.16(b) will even lower to 55.4% at the steering angle of 0.50 °.

For the small lenses with long focal length, the beam divergence can compete with the focusing power of the lens, and therefore prohibit the positive lens from focusing as it does for larger diameter or shorter focal length lenses (with an OPD > 5). This major drawback is hard to resolve in the all positive lens system without going to thick liquid crystal cells. However in the mixed micro-lens system, since no focus at the position of the second layer is required as described in the proceedings, the issues with the “robust lens” condition can be solved by modifying the phase profile the middle lens so that the phase fronts on either side of it are mirror symmetric. And also the flipping effect is eliminated.

2.5.2 Out-of-lens leakage of mixed micro-lens array

In the next section, the results of phase compensation to the lens profiles of a mixed lens system will be shown to be capable of solving the issues with off-axis lens aberration, the phase up of the outgoing wavefronts from the individual lens, and the “robust lens” issue by applying the “mirror symmetry” condition to the middle lens. However there is another issue, related to the diffractive loss, that cannot be corrected, given a particular lens diameter, that we will discuss first.

To understand the diffraction loss of the mixed system, a very simple model is designed to illustrate the efficiency loss with respect to the micro-lens diameter size.
Consider a square phase profile that traverses through the first positive layer of a mixed system with 5 micro-lenses in each layer. The square phase profile is located in the center of the array, and has a diameter exactly equal to the lens size, as shown in Fig. 2.17(a). The beam profile after the first positive layer and right before the second negative layer can be derived from Eq. (20). By comparing the integral of light intensity within the diameter of the lens in the 2\textsuperscript{nd} layer, with the overall intensity, the out-of-lens leakage for each single micro-lens unit can be calculated. As shown in Fig. 2.17(b), the out-of-lens leakage for a micro-lens array with 1104 µm diameter is the regions outside of the two markers, which is about 0.358% in the case of non-decentered array. The leakage implies that the maximum efficiency available for the system is about 99.642% even with all potential compensations applied. In Fig. 2.18, the out-of-lens leakage will keep increasing to 4.38% when decreasing the lens size to about 86µm because the diffraction effect will become more and more dominant, especially for smaller diameter of micro-lens. In the case of a decentered array, for example 0.20 decentered ratio in Fig. 2.18, this leakage will increase a little, to 0.419% for a 1104 µm diameter lens, and to 4.99% for a 86 µm diameter lens because more light will diffract and leak out of the shifted second lens. The out-of-lens leakage determines the maximum efficiency available for the mixed system. To construct a mixed micro-lens system with requirement of 98% efficiency, the diameter of each micro-lens should be at least larger than 250 µm.

2.5.3 Simulation results of mixed decentered micro-lens array
In the modeling, the liquid crystal used for a positive LC lens is MLC-10000-000, where $n_e = 1.6528$, $n_o = 1.4971$, $\Delta n = 0.1557$ (at $\lambda = 589\text{ nm}$, $20^\circ\text{C}$) and $\varepsilon_{||} = 37.2$, $\varepsilon_{\perp} = 8.0$ (at 1 kHz, $20^\circ\text{C}$). The LC cell gap is $25\ \mu\text{m}$. Since the desired OPD depth of a negative LC lens is four times of the positive one, it means the cell gap of a negative lens will be also approximately four times of the positive lens if the same liquid crystal material is used. However, a thicker cell will lead to more extra light energy loss by scattering, and absorption, etc. Licrilite-18349 with a larger birefringence is used as the negative LC lens in our model, where $n_e = 1.8025$, $n_o = 1.5321$, $\Delta n = 0.2704$ (at $\lambda = 589\text{ nm}$, $20^\circ\text{C}$) and $\varepsilon_{||} = 21.9$, $\varepsilon_{\perp} = 6.1$ (at 1 kHz, $20^\circ\text{C}$). The cell gap of the negative LC lens is $50\ \mu\text{m}$. There are 5 LC micro-lens units in each layer.

The electrode width in Fig. 2.4 is $20\ \mu\text{m}$, which is a little thinner than the thickness of LC cell. The gap between each electrode is $3\ \mu\text{m}$. A single LC micro-lens radius covers 24 electrodes. The radius of each micro-lens is $552\ \mu\text{m}$. The focal length $f_1$ and $f_3$ of the positive layers are designed to be $57.498\ \text{mm}$, while the focal length $f_2$ of the negative layer is designed as $14.374\ \text{mm}$.

After six optimization loops described in section 2.2, an equilibrium director configuration of a positive LC lens can be obtained with small errors of OPD profile compared with the ideal one at the wavelength of $1.5\mu\text{m}$ as shown in Fig. 2.19(a). The director configuration of LC cell is illustrated in Fig. 2.19(b). To implement the aberration correction for the third positive lens, we can add the OPD compensation to the ideal positive lens profile together. Since the amount of the aberration correction for a
positive lens is relatively very small compared with the OPD depth, it can be easily encoded into the OPD optimization procedures.

The situation for modeling the negative LC lens will be more complicated, which is caused by the mirror symmetry correction. As we mentioned above, the amount and location of mirror symmetry will be in the fixed position according to the location of the first positive layer, while the OPD profile of the second negative lens will be translated by a decenter amount $\Delta_2$. Hence for each steering angle, the final sum of the ideal OPD profile and the mirror symmetry correction will be different. So the director configuration will be different for each steering angle. In Fig. 2.20(a), a negative LC lens OPD profile incorporated with mirror symmetry correction for a non-dencentered array is shown. For a steered angle of 0.64°, the simulated OPD profile is shown in Fig. 2.20(b).

The phase-up correction to achieve a 0 or $2\pi$ discontinuity in the exiting OPD profile of the third positive lens, is implemented by placing a series of phase retarder plate at each micro-lens.

Without any phase correction described above for the mixed micro-lens array, the diffraction efficiency for no steering is only about 84.2% in Fig. 2.21. The lowest one is 44.4% at the steering angle of 0.275°. It also shows the different contribution of the efficiency improvement by the different phase corrections. Obviously, the aberration correction plays the least important role to improve the efficiency and may be neglected for the case of small deflection angles. The phase up correction is especially critical to some steering angles where the phase discontinuity is about $\pi$. The most important factor for micro-lens with small diameter is the mirror symmetry correction. It will enhance the
overall performance of the final diffraction efficiency for all of the steering angles. With all these three phase corrections integrated in the mixed LC micro-lens array, the average diffraction of all available steering angles is 96.8%, while the minimum one is 94.4% at the steering angle of 1.008°.

2.6 Fabrication and characterization of LC-DLAs

In order to demonstrate the modeling results, we fabricated the individual layer of LC-DLAs as shown in Fig. 2.22. Four micro-lens cells in each LC layer are designed to make one layer. Each individual lens is controlled by 48 electrodes. The electrodes on the ITO substrate were coated with accurate width by the photo-lithography technique. The general electrode pattern is shown in Fig. 2.23. There are totally 192 inter-digital electrodes etched in the active area of LC cell on one substrate, while another substrate is simply coated with a common electrode. With the fan-out regions of electrodes, the electrodes in microns can be bonded to the external cables. The mixed liquid crystal micro-lens arrays are filled with the LC materials introduced in section 2.5.3. The positive LC-DLAs is filled with MLC-10000-000. To reduce the large thickness of the negative LC micro-lens, we choose the liquid crystal Licrilite-18349 that has relatively large birefringence $\Delta n$ as 0.2704.

To verify the algorithm of scalar integral method that is used to characterize the light propagation through the system, the beam profile of each layer is first measured by the schematic diagram of set up in Fig. 2.24. The LC micro-lens layer is illuminated by a collimated beam at 632.8 nm with normal incident angle. The beam expander is used to
collimate the incident beam, and also zoom in the diameter of the beam to cover the whole active area of LC micro-lens, which is about 5 × 10 mm. Before the collimated light meets the LC micro-lens layer, the polarization state of the beam will be changed into linear polarization along the rubbing direction by the first polarizer. The LC micro-lens layer is driven by 48 × 4 electrodes connected with cables to the voltage amplifier controlled by computer. Since the driven voltage profiles are identical for all the four LC lens units, only 48 electrodes input that controlled by the Labview program is necessary. When the driven voltage profile is applied, the collimated beam is then focused by the LC micro-lens at the focal point, which is 57.49 mm theoretically. The second polarizer is used to attenuate the light intensity to avoid the saturation of light that collected by the PULNiX camera system. The camera system is moved back and forward to locate the focal plane of the positive micro-lens layer, where the focused light beam should have the sharpest profile and highest peak. The measured focal distance is about 51.3 mm. The image of beam profile is shown in Fig. 2.25(a). To compare with the simulation results with exactly same parameters and set up, the image profile can be converted into intensity profile in Fig. 2.25(b). Note that the measured beam profile needs to be calibrated with the peak-to-peak distance and the height of the maximum lobe to compare with the simulation intensity profile at the focal point. With these calibrations, the FWHM of main lobe and the side lobes are very consistent with the predicted results. Fig. 2.25(b) is consistent with the expected Fraunhofer diffraction pattern as for the example shown in Chapter 10 of “Optics” by Hecht where the amplitude variations are related to the single slit diffraction caused by the finite size of the lens.37
As for the negative micro-lens, the beam profile is not as good as the positive LC micro-lens because it is related to the 50µm cell thickness in Fig. 2.26(a-b). The cell thickness of the second negative micro-lens can seriously result poor performance of the final assembled mixed micro-lens arrays. To revolve this, two 25µm negative LC layers that attached together but driven separately might help to reduce the error. In addition, in the final assembled system, the multi-reflection effect between each layer will affect the final light throughput seriously. The coating layers or some index match medium for the whole LC-DLAs system should be considered to reduce the reflection problem of inner layer.

2.7 Summary

We used a two dimensional liquid crystal director modeling method and three-layer scalar integral optical calculation method to study the liquid crystal mixed micro-lens array. The properties of three different phase correction methods were investigated detailed to optimize the diffraction efficiency. In general, the mirror symmetry correction and the phase-up correction can resolve the low efficiency problem. By mapping all the phase corrections into the phase profile of LC cells, the minimum efficiency of the system can be improved from 84.2% to 94.4% at the steering angle of 1.008 ° and with the lens radius of 552 µm. We also studied several other important factors that lead to the efficiency loss in the micro-lens system, such as robust lens condition for all positive system, and the out-of-lens leakage due to diffraction.
Another aspect of the LC-DLAs work is that it makes clear that a mechanically DLA may have low efficiency because it does not offer the possibility of providing the steering angle dependent corrections considered here. So this work points to the possibility of considering a larger angle beam steering device that uses mechanically decentered short focal length fixed lens, that are dynamically corrected by integrated LC layers. We also fabricate the positive/negative micro-lens layer of LC-DLAs. The measured beam profile at the focal plane of the positive LC micro-lens demonstrated the feasibility of the above modeling results. However, the very thick negative LC micro-lens resulted in some beam profile error. We may divide the single thicker negative LC cell into two separate units with the opposite rubbing direction (in general, the LC director in one cell will tilt along +x axis, while the other one will tilt along –x axis) to minimize the view angle problem. In addition, to assemble the three layers together, we need to take account into the inner reflection loss between different layers. Specific index match coating technique or medium selection may be considered in the future work.
Fig. 2.1 Resetting issues (red circled regions, also refer as fringe field effect) in liquid crystal optical phase array

Green line: ideal grating profile with strictly reset of each period

Blue curve: LC phase profile with resetting regions
Fig. 2.2 Geometric illustration of beam steering with (a) all positive decentered macroscopic lenses; (b) mixed decentered macroscopic lenses
Fig. 2.3 Scalar integral approach of three-layer decentered micro-lens array
Fig. 2.4  Structure diagram of a single positive liquid crystal micro-lens with director configuration and top and bottom substrates’ electrode pattern
Fig. 2.5 Calculated OPD of a LC cell (designed for positive lens) with respect to the applied voltage (region I and III are two plateaus with low and high applied voltage, region II are linear region with medium voltage)
Fig. 2.6 Optical path delay (OPD) profile of ideal objective positive (blue curve) and negative (green curve) lens with 552 μm radius, no reset issue exists in the lens design.
Fig. 2.7 Optimization loops to implement optimized LC micro-lens phase profile with applied voltage profile modification
Fig. 2.8 “Flipping effect” in the all positive LC decenter lens cascade
Fig. 2.9 “Ill lens” in the case of a positive lens incident with Gaussian of large R where the spherical center is far from the beam waist
Fig. 2.10 Off-axis aberration of a single positive lens
Fig. 2.11 Off-axis aberration of a single negative lens
Fig. 2.12  Phase up correction for third positive micro-lens layer

(a) Ideal Phase for designed wavelength; (b) Phase of $E_{3b}$ with $2\pi$ phase up; (c) Unfolded phase of $E_{3b}$; (d) Phase profile of $E_{3b}$; (e) Third layer lens
Fig. 2.13  Algorithm of mirror symmetry correction of the second lens phase profile
Fig. 2.14 Near field intensity profile for a non-steered positive DLA (5 lenses in each layer) as a function of OPD and diameter
Fig. 2.15  OPD range of a robust all positive micro-lens array
Fig. 2.16  All positive micro-lens array with 552 µm radius

(a) Far field Intensity for non steering

(b) Diffraction efficiency with respect to Deflection angle
Fig. 2.17  (a) Incident square wave and first layer phase profile of mixed micro-lens array; (b) out-of-lens leakage right before the second layer
Fig. 2.18 Out-of-lens leakage with respect to the diameter of micro-lens
Fig. 2.19  (a) OPD profile of a positive LC layer; (b) director configuration of a positive LC layer
Fig. 2.20  (a) OPD profile for a negative LC lens with steering angle = 0 °

(b) OPD profile for a negative LC lens with steering angle = 0.64 °
Fig. 2.21 Contributions to the final diffraction efficiency by the three different correction approaches
Fig. 2.22 A positive LC-DLA layer connected with interface board
Fig. 2.23  Inter-digital electrode pattern with fan-out region (part) in one substrate of LC-DLAs
Fig. 2.24 Schematic diagram of beam profile measurement of LC micro-lens He-Ne laser 632.8nm; (b) beam expander; (c) polarizer; (d) LC micro-lens; (e) polarizer; (f) signal collect lens system; (g) PULNiX camera; (h) Amplifier; (i) Controlled computer with Labview program.
Fig. 2.25  Positive LC-DLA layer (a) beam profile image of the 25\( \mu \m\) positive microlens LC layer at focal plane; (b) Intensity profile with comparison of simulated results.
Fig. 2.26. (a) beam profile image of the 50µm negative microlens LC layer at focal plane  
(b) Intensity profile with comparison of simulated results  
Note: the voltage profile is for positive lens but with same focal length as the negative one
Chapter 3

Tunable liquid crystal polarization gratings

3.1 Introduction

Conventionally in the liquid crystal beam steering devices, for instance, the LC optical phased arrays (LC-OPAs), LC prisms, and LC decentered micro-lens arrays in Chapter 2, their steering mechanisms are based on the spatially varying retardation $\Delta n \cdot d$ ($\Delta n$ is the effective birefringence, and $d$ is the LC cell thickness) of liquid crystal material. These liquid crystal based devices follow the basic idea of generating a linear change of optical path difference (OPD) across the aperture, which tilts the incident phase front and thereby steers the optical beam. To achieve an optimized performance of continuous steering in this category, either a large thickness $d$ of LC cell is employed to achieve a large gradient over a large aperture with a continuous phase profile without any discontinuity; or the periodical resets is used to form the phase profile whose OPD step is an integer number of wavelengths of the light (such as LC-OPAs). The large value of $d$ leads to slow response, absorption and scattering of light by the device. The resets in Fig. 1.2, if mathematically ideal, will cause efficiency loss at large steering angle. Nevertheless, these resets would not be a large problem for a single frequency wavefront,
however, in real devices they are well known that they degrade the achievable device
efficiency since it is very hard to obtain an ideal programmed reset profile in the
continuous Liquid crystal director configurations, which is also known as fly back
regions. The existence of resets and fly back regions will lead to the efficiency losses of
LC OPA devices. In a word, to obtain a continuous phase gradient over a large aperture,
no discontinuity and limited thickness of LC cell are the important design considerations
to achieve high efficiency of LC beam steering devices.

In this chapter, a tunable liquid crystal polarization grating is proposed and studied
from a new viewpoint. This approach toward generating a phase gradient is based on
ancharatnam’s “QHQ” method.\(^{27}\)

Fig. 1.6 shows the optical model of the QHQ device of Pancharatnam: A light beam
passes through a polarizer, a Quarter-wave plate (\(\lambda/4\) plate), a Half-wave plate (\(\lambda/2\) plate),
another Quarter-wave plate, and another polarizer.

The incident light becomes a circular polarized light after the first \(\lambda/4\) plate, so that
the light incident on the half-wave plate can be defined as \(E_{in}\) according to Jones Calculus
notation:

\[
E_{in} = \begin{bmatrix} E_{x_{in}} \\ E_{y_{in}} \end{bmatrix} = \begin{bmatrix} E_{x_{in}} \\ i \cdot E_{x_{in}} \end{bmatrix}.
\]  

(3.1)

For convenience, we assume it is a right hand circular polarized light.

The transmitted light leaving the half-wave plate, \(E_{out}\), is defined as a linear mapping
of the incident light \(E_{in}\) by a Jones Matrix which represents the \(\lambda/2\) plate:

\[
E_{out} = R \cdot P \cdot R^{-1} \cdot \begin{bmatrix} E_{x_{in}} \\ E_{y_{in}} \end{bmatrix} = \begin{bmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{bmatrix} \begin{bmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} E_{x_{in}} \\ i \cdot E_{x_{in}} \end{bmatrix}.
\]  

(3.2)
Where R and P are defined as rotation and phase matrices of the $\lambda/2$ plate respectively, $\beta$ represents the angle between the slow axis of the $\lambda/2$ plate and the $x$ axis, and $\phi$ is denoted as the phase retardation of the $\lambda/2$ plate, which is equal to $\pi$ here. The final relationship can be simplified as:

$$E_{\text{out}} = \begin{bmatrix} \cos^2 \beta + e^{i\phi} \sin^2 \beta & \cos \beta \sin \beta (1 - e^{i\phi}) \\ \cos \beta \sin \beta (1 - e^{i\phi}) & \sin^2 \beta + e^{i\phi} \cos^2 \beta \end{bmatrix} \begin{bmatrix} E_{x_{\text{in}}} \\ E_{y_{\text{in}}} \end{bmatrix}$$

$$= \begin{bmatrix} E_{x_{\text{in}}} e^{i2\beta} \\ -i \cdot E_{x_{\text{in}}} e^{i2\beta} \end{bmatrix}. \quad (3.3)$$

In the Eq.(3.3) for the light leaving the half-wave plate, the transmitted light is a left hand circular polarized light with a common phase factor $\exp(i2\beta)$, which is the most important result from the simple model. The phase of the transmitted circular light can be accurately controlled by the azimuthal angle $\beta$. Considering Fig.1.6, where the half-wave plate is followed by polarizer and quarter wave plate that convert the circularly polarized light back to a linearly polarized state, the main point is that we have linear polarization in and linear polarization out with a phase shift due to the rotation of the half-wave plate.

The above result can be applied to a device where the slow axis of the half-wave plate rotates about the device normal. If we have a LC cell of half-wave optical retardation, with an in-plane director configuration where the azimuthal angle linearly rotates from 0 to $\pi$, the final spatial phase profile of circularly polarized transmitted light will linearly change from 0 to $2\pi$. If the gradient in this azimuthal angle is constant with the rotation angle increasing along a particular direction (the x axis in Fig.3.1), a device with linearly increasing phase without any “reset” or discontinuity is obtained. Theoretically, given such an ideal in-plane spiral director configuration in Fig.3.2(a,b), with an incident
circular polarized Gaussian beam with appropriate wavelength to meet the half-wave retardation condition, the exiting light will characterize with a phase profile in the near field as shown in Fig. 3.3, combined to be a circular polarized light with the x and y component. The final diffraction efficiency in the far field pattern of Fig. 3.4 can reach to 99.6% that is unprecedented. Diffraction gratings that are operated by periodically modulating the state of the polarization of transmitted light through them are generally named as “polarization gratings”. As far as the very thin thickness (only half-wave retardation) is concerned, the light loss from absorption and scattering can be minimized.

Several research groups have reported work based on the LC polarization gratings. Crawford and co-workers have demonstrated a LC diffraction grating through a polarization holography exposure on a linear photo-polymerizable polymer alignment layer. They disclosed several switchable LC polarization gratings based on the planar-periodic patterned surface alignment layers. Honma et al. have shown a lens fabricated through a micro-rubbing technique and demonstrated the liquid crystal gratings consisting of multidomain alignment regions fabricated through a micro-rubbing technique. Escuti et al. report their experimental results of a liquid crystal polarization grating (LCPG) modulating unpolarized light with high contrast for the first time. They also report LC polarization grating to modulate unpolarized or polarized light with a grating period as small as 6.3μm and observe nearly ideal diffraction into the first order at >99% for monochromatic light. These striking results have demonstrated the validity of this basic idea of what is called a polarization grating.
Unfortunately, all the above QHQ methods have utilized different alignment techniques to generate a fixed azimuthally distributed LC director. The devices are switchable, in that their steering effect can be turned on or off through the application of an electric field along the device normal, but are not continuously variable.

In summary, on one hand previously demonstrated continuously variable optical beam steering devices based on an increasing OPD need “resets” that limit the efficiency of the device. While on the other hand, high efficiency beam steering devices based on the Pancharatnam QHQ concept have been demonstrated, but they are not continuously variable.

It is the objective of our work to demonstrate a high efficiency, continuously variable, optical beam steering device that is based on the Pancharatnam QHQ concept which compromise the advantages of the above two different categories of devices: tunable and high diffraction efficiency.35 In addition to the convention name of liquid crystal polarization gratings (LCPG), we also call our device a V-COPA device because it is based on the OPA idea, but has a Continuous phase profile, and uses Vertical alignment.

3.2 Tunable liquid crystal polarization grating concept

To obtain a tunable LCPG, an ideal surface alignment might be characterized with the following three features: first, it should assist the initialization of the in-plane polarization gratings; second, it should not prohibit the tuning capability of the period of the polarization grating; third, the surface alignment should be consisted with few domains that are as simple as possible to reduce the difficulties of alignment fabrication.
In our design, a quasi vertical alignment with slightly modulation of the polar/azimuthal angle in three specific regions of the surface will satisfy all the above requirements.

The tunable LCPG device in this chapter uses a vertical alignment and a LC material that has a negative dielectric anisotropy. In the next chapter of dynamics of LCPG, we will employ the dual frequency LC material to enhance the performance of the tuning speed. The basic idea is that when a voltage profile is applied, the LC director will lie in the plane of the cell, but without a strong planar surface anchoring imposed in-plane direction. This allows for the pitch of the spiral (and the beam steering angle) to be changed. Two aspects of the design that need to be considered are: how is the initial spiral pattern formed, and how is it changed.

One way we have considered to form an initial, defect free, spiraling director configuration in the plane of the cell, is to slightly modify the vertical alignment as will be explained here with reference to Fig. 3.5.

In Fig. 3.5, the alignments at the bottom substrate are shown in the red arrows. They are approximately vertical, and the alignments at the top substrate (not shown) are identical as the one at bottom substrate. We call this a quasi-vertical alignment because the alignment is not exactly vertical in some domains, which are slightly tilted to the +y and −y directions (the director rotates about the x axis with alternating signs to tip in and out of the plane of the drawing). The red arrows near the bottom substrate in the cone represent the orientation of the surface alignment over the electrodes region. The alignment in region B and the two electrodes near B slightly tilts to the +y with 88° polar angle (measured relative to the surface), while alignment in region D and the two
electrodes near $D$ tilts to $-y$ with $88^\circ$ polar angle. All the other regions (such as the gap between the electrodes) are exactly vertical with $90^\circ$ polar angles. A liquid crystal material with the negative dielectric anisotropy $\Delta \varepsilon$, is used so that when an electric field is applied, the LC director will tilt to lie in the x-y plane. The directors in the LC bulk over region $B$ will lie in the x-y plane and towards the $+y$ axis, while directors over region $D$ will also lie in the x-y plane but towards $-y$ direction. To orient the directors of region $A$ or $C$ along $+x$ or $-x$ axis direction, we employ a specific voltage profile with voltage offsets and the vertical surface alignment. For example, the voltage profile on the electrodes of bottom substrate is: 10, 12, 12, 12, 10, 10, 12V; and 0, 2, 2, 2, 0, 0, 2V on the top. The above voltage profile will lead to the fringe field between the electrode #1 and #2, electrode #4 and #5, etc. The director in the region $A$ (between electrode #1 and #2) will try to reorient perpendicular to the fringe field from the voltage offset. Given an initial vertical director in the region $A$ near the surface, to be consistent with the vertical surface alignment, the director will reorient along the equi-potential line in the x-z plane to minimize the free energy of the system when the fringe field of the voltage offset is applied. With these specific regions’ orientations determined, one full period of spiral of grating in the bulk of LC cell can be formed in the x-y plane.

In a word, we consider that the RMS average voltage applied to the entire cell is approximately the same, but a DC offset, that is a function distance along the x axis in Fig. 3.5 is employed to effect the spiral configuration. It is anticipated that at a location where the DC offset is changed to a higher value, the director will tend to orient in the x-z plane with the director rotated slightly from the horizontal with a particular rotational
sense about the y axis. On the other hand, at another location where the DC offset is changed to a lower value, the director will tend to orient in the x-z plane with opposite rotational sense about the y axis from the horizontal. The intended effect of this will be to “trap” a pi-rotation of the director between these two locations. The DC offset is changed through the use of patterned electrodes. To illustrate this procedure, we can decompose the whole formation of grating into several snapshots as shown in Fig. 3.6.

It is interesting to know what the result is if we apply a “flip” offset of voltage profile from the initial vertical state, such as 12, 10, 10, 10, 12, 12, 12, 10V; and 2, 0, 0, 0, 2, 2, 2, 0V on the bottom and top substrates respectively. This “flip” offset voltage profile will also result in an in-plan spiral directory configuration but with an opposite sense of rotation compared with the previous results, as shown in Fig. 3.7. We may define the clockwise rotation of sense as “+” state, while the counterclockwise rotation of sense as “−” state, and the initial vertical state as “0” state. Either “+” or “−” state can be formed from “0” state with identical initial configuration and surface alignment. This simple algorithm implies a fast three states switching device when we switch the offset of voltage profile from the initial vertical state, for example, from “+” state to “0” state, next from “0” state to “−” state, then from “−” state to “0” state, et al.

To vary the pitch of the spiral, the location the DC offset changes can be moved by changing the voltage offset profile applied to the electrodes. Note that the director configuration in region A or C (Fig. 3.5) will be bonded with the offset region. Once the location of voltage offset region is shifted, the corresponding region A or C will also be translated. The quasi vertical surface alignment will not prohibit the formation of any
direction in x-y plane with applied voltage. A vertical director configuration in a region
can be lie toward any of direction in x-y plane theoretically. Therefore the bond regions
can be easily moved from on location to another. Because of the trapped pi-rotation
between their locations, if they are moved closer together, the pitch will be shortened.
Similarly, we can expand the period of LCPG by move these two “bonds” away. Now we
will simply introduce this approach and the equilibrium state modeling result. In chapter
4, we will focus on the dynamics study of the period tuning and propose a faster solution
to tune the LCPG device.

Combining the modified vertical alignment, with the “adjustable” voltage profile, the
V-COPA device can have a defined, tunable, defect free, initial spiral director structure.

3.3 Numerical Jones Calculus of Tunable LCPGs

Based on the above description of our tunable LCPG, we simulate the establishment
of the initial polarization grating and also demonstrate the tuning capability of the device.
We develop a specific modeling tool (V-COPA v3.0, as introduced in appendix I) to
study the formation of liquid crystal polarization grating and their optical characteristic.
The LC modeling is based on the LC3D subroutine with the applied voltage profile given
by several separated stripe electrodes on both of top and bottom substrates with the same
numerical modeling algorithm in Chapter 2. The optics simulation from near field to far
field is implemented by Kirchhoff’s scalar integral method introduced in the Chapter 2.
The light passing through the LCPG cell is calculated by Jones Calculus that will be
introduced in the following.
Fig. 3.8 shows the 2D rectangular grid points representing the director configuration in the LCPG. Each grids can be represented by \( n_x(i,j,k), n_y(i,j,k), \) and \( n_z(i,j,k) \). \((i, j, k)\) is the index of each grid along x, y and z axis. There are total \( \text{Num}_x \) grids along x axis, and \( \text{Num}_z \) grids along z axis. In 2D modeling, \( j \) is equal to 1. We can treat each row of the lattice as one layer, and in each layer we will perform the Jones Calculus for the wavefront of all the grids from 1 to \( \text{Num}_x \) that exits that layer, and the transmitted wavefront will be regarded as the incident beam for the next layer until the light exit the last layer represented by \( \text{Num}_z \). For every grid on each layer, the phase retardation of ordinary and extraordinary light can be defined by the birefringence:

\[
\varphi_o(i, j, k) = \frac{2\pi \cdot \Delta d \cdot n_o(i, j, k)}{\lambda}
\]

\[
\varphi_e(i, j, k) = \frac{2\pi \cdot \Delta d \cdot n_{eff}(i, j, k)}{\lambda}
\] (3.4)

Where \( \Delta d \) is the layer thickness, ordinary refractive index \( n_o \) is identical for all grids, the effective extraordinary refractive index \( n_{eff} \) is given by the director configuration:

\[
n_{eff}(i, j, k) = \frac{n_o(i, j, k) \cdot n_e(i, j, k)}{n_o^2(i, j, k) \cdot \sin^2(\beta) + n_e^2(i, j, k) \cdot \cos^2(\beta)}
\] (3.5)

Where \( \beta \) is \( \pi/2 - \theta \), here \( \theta \) is the polar angle given by \( \text{asin}(n_z(i,j,k)) \).

Know the polar and azimuthal angle on each grid, the Jones matrix on the grid can be calculated by:

\[
J(i, j, k) = \begin{pmatrix}
A & B \\
B & D
\end{pmatrix}
\]

\[
A = \cos^2(\alpha(i, j, k)) \exp\cdot\varphi_e(i, j, k) + \sin^2(\alpha(i, j, k)) \exp\cdot\varphi_o(i, j, k)
\]

\[
B = \cos(\alpha(i, j, k)) \cdot \sin(\alpha(i, j, k)) \cdot \{\exp\cdot\varphi_e(i, j, k) - \exp\cdot\varphi_o(i, j, k)\}
\]

\[
D = \sin^2(\alpha(i, j, k)) \exp\cdot\varphi_e(i, j, k) + \cos^2(\alpha(i, j, k)) \exp\cdot\varphi_o(i, j, k)
\] (3.6)
Apply the Jones matrix on each grid times with the incident beam $E_I(i,j,k)$, we will the $E_x(i,j,k)$ and $E_y(i,j,k)$ and final field with x and y component. Transforming the near field to the far field is implemented by the Kirchhoff’s scalar integral.

3.4 Modeling results of tunable LCPGs

3.4.1 Establishment of a spiral director configuration

As an example of a device built with the V-COPA concept, we consider a 5µm (gap thickness $d$ along $z$ axis) cell filled with negative dielectric anisotropy ($\Delta\varepsilon$) LC (MLC-6608): $\Delta\varepsilon = -4.2$, $n_o=1.4748$, $n_e=1.5578$, the elastic constant $K_{11}=16.7$ pN, $K_{22}=7.0$ pN, $K_{33}=18.1$ pN. The LC cell, as shown in Fig.3.5 consists of top and bottom substrates with patterned electrodes. The electrode stripe’s width $w_e$ (along $x$ axis) is 4µm, the length $l_e$ is 1µm (along $y$ axis), and the gap width $w_g$ between each electrode is 1µm.

To control the DC offset along the x direction while maintaining a constant RMS voltage, for example, voltages in the bottom electrodes can be 10, 12, 12, 12, 10, 10, 10, 12V, while 0, 2, 2, 2, 0, 0, 0, 2V are applied on the top.

Using the above LC parameters and modeling tool (V-COPA v3.0) we demonstrate the formation of a defect free spiral structure based on our concept. Initially the director field is determined by the surface alignment condition with no electric fields applied (nearly homeotropic). Then voltages are applied to the 8 electrodes (bottom electrodes: 10, 12, 12, 10, 10, 10, 12V; top electrodes: 0, 2, 2, 2, 0, 0, 0, 2V). After LC directors relax to the equilibrium state by the vector field method, we can get the final director configurations as shown in Fig.3.9 where a nearly perfect spiral director configuration is
formed. The arrows represent the director orientation, while the curves are the equipotential field line. We can define the period of the spiral configuration as the distance between the regions where the director is substantially along the y axis in the figure. We will refer to those regions as the Y-regions. Note that the Y locations are between the locations $x_1$ and $x_2$ in Fig. 3.9 (as the x values where the potential steps up and down respectively). Please note the twist sense of the helix (as observed in the top view of Fig. 3.9) would be opposite if the voltages on the bottom electrodes were exchanged (10V exchanged with 12V), and if the voltages on the top electrodes were also exchanged. A three-state switching digital beam deflector can be realized by this procedure.

3.4.2 Tuning the period of the spiral gratings

After the initial spiral director configuration is achieved, by translating the regions where the director is trapped in the x-z plane, we can expand or shrink the period of the grating. This is accomplished by moving the locations of the steps in the potential ($x_1$ and $x_2$). For this demonstration, instead of using periodical boundary condition, a “stress-free” boundary condition is used at the x locations of the left and right sides of the computed area shown in Fig. 3.10 and 3.11. The director orientation at these boundaries is determined by a linear extrapolation from the three grid points closest to the boundary along the x direction.

To show the ability to modify the spiral pattern we start with the director configuration in Fig. 3.9, and apply a new voltage profile to the LC cell, that is, 10, 12, 12,
12, 10, 12, 12V on bottom electrodes; 0, 2, 2, 2, 0, 2, 2V on top ones. Loading the previous director structure in Fig. 3.9 as the initial starting configuration, the director will reach a new equilibrium state. In Fig. 3.10, is shown the new director configuration with equipotential lines. It can be seen that due to the change in the applied potential, the $x_2$ and $x_1$ region on the right side of the figure are moved toward each other, while the $x_1$ region on the left side is held in position. By then changing the voltage profile on bottom to 10, 10, 12, 12, 10, 12, 12V, then 10, 10, 12, 12, 10, 12, 12V, and then to 10, 10, 10, 12, 12, 10, 12, 12V, (with similar schemes on top electrodes), we can move the $x_1$ region on the left side of Fig. 3.10 toward the right, while holding the position of the $x_2$ regions in Fig. 3.10. The final resulting potential and director configuration is shown in Fig. 3.11.

While Fig. 3.10 and 3.11 demonstrate the concept of controlling the director configuration of in this device, in many applications we are interested in changing the period of a spiraling director configuration. To demonstrate this, we can start with the director and potentials shown in Fig. 3.9, move the periodic boundary conditions to the new pitch length, and then adjust of voltages on the electrodes to provide the new director profile. Fig. 3.12 shows the result of this procedure, where the left and right sides of this figure correspond to the new locations of the periodic boundary conditions. The location of the new boundaries were placed in the director profile of Fig. 3.9 at the x values of 9.75 and 29.75, and the voltages on the electrodes in the included region was changed to 10, 12, 12, 10, 10V, on the bottom and 0, 2, 2, 0, 0V on the top. The new spiral period is 10.25 microns.
3.4.3 Optical efficiency of tunable LCPGs

Using the Jones Calculus and scalar integral modeling methods and cell parameters previously described, we calculate the far field intensity pattern for the case of calculated periodic spiral director fields with the periods shown in the previous section. In these calculations a linear polarized beam (632.8nm) passes through the QHQ system in Fig.1.6, except the \( \lambda/2 \) plate is replaced by the V-COPA LC cell. A Gaussian profile beam is used as shown in Fig.3.13(a).

Fig. 3.13(b) is calculated for the spiral period of 15.75\( \mu \)m shown in Fig.3.9 and shows a deflection angle of 2.302 degrees and a steering efficiency of 98.27%. In Fig. 3.13(c), the transmitted light across a smaller spiral period (10.25\( \mu \)m) from Fig.3.12 is also calculated, showing a steering angle of 3.54 degrees with and efficiency of 96.77%. Once the desired director configuration is established it will likely be possible to apply a uniform voltage to the top and bottom electrodes (for example 10 volts on all of the top electrodes and 0 on the bottom). When doing this, we find the efficiency climbs to very close to 100%.

It is interesting to investigate the dispersion effect of the LCPG device. Known by Eq.(3.4), as far as the different wavelength of incident light is concerned, given a fixed applied voltage profile, the requirement of half-wave retardation can not be satisfied for some other wavelengths, even we assume the birefringence is constant and wavelength independent. Our LCPG design with vertical alignment can resolve this issue easily, within a certain range of wavelength, we can modify the overall value of RMS voltage (for example, 10V used in previous example), squeeze or expand the \( n_z \) component across
the LC bulk, to meet the half-wave retardation condition. However, even this half wave retardation requirement is met, in the LCPG device, not like the LC-OPA device that the steering angle is only related to the Δnd and the length of period, the steering angle of LCPG is given by Eq. (3.7) in principle and wavelength dependent.

\[ \theta = \sin^{-1} \left( \frac{\lambda}{\Gamma} \right) \]  

(3.7)

Where \( \Gamma \) is length of period, \( \theta \) is the steering angle.

Therefore, for different wavelength of incident light, the deflection angle will be different. Additional angular calibration component should be used to compensate this dispersion error when the broad band application is concerned.

### 3.4.4 Discussion of modeling results

A key aspect of the V-COPA device is the trapping of a pi-twist region of the in-plane director configuration through the use of voltage offsets.

As may be clear from inspecting Fig. 3.9- 3.11, this is accomplished, in part, by the fixing of the director in the x-z plane in the regions \( x_1 \) and \( x_2 \). A director fixed in this way “traps” a pi-twist of the director in the space between them. The sense of this twist is fixed by the initial spiral sense (set by the spatially patterned quasi-vertical surface alignment and the DC offsets).

The reason why the director at the regions \( x_1 \) and \( x_2 \) near the surfaces is oriented as shown is primarily due to the torques imposed on it by the electric field and the vertical surface alignment layer. Because the liquid crystal material used has a negative dielectric
anisotropy, the director (especially in the high field region near the surface) will tend to align perpendicular to the electric field direction. This effect coupled with the effect of the alignment layer to tilt the director perpendicular to the surface, causes the director to tend to align perpendicular to the axis of the electrodes and along the equipotential lines.

The above results show that a device built as described can provide exceptional performance. However modifications of this example device can be considered. For examples, two-frequency LC materials could be used (details in Chapter 4). Also, flexoelectric or smectic C materials can be considered for the used liquid crystal. Other types of optical devices, such as lenses, can be made by causing the spiral to have a spatially dependent period.

3.5 Fabrication and characterization of tunable LCPGs

3.5.1 Fabrication of tunable LCPGs

3.5.1.1 Three-domain quasi vertical surface alignment

To realize the above design and modeling results, the first task is to obtain the three-domain quasi vertical alignment that has been implemented by Dr. Ke Zhang in liquid crystal institute of Kent State University. Polyamic acids SE-1211 is used as the quasi-vertical surface alignment medium, since SE-1211 has a long alkyl sidechain that promotes the vertical alignment of liquid crystals. By varying the baking temperature and the rubbing times and strength, we will obtain different controlled pretilt angle closed to 90°.
Fig. 3.14 shows the detailed procedures to fabricate the three-domain patterned quasi-vertical alignment. First we spin coat SE-1211 on the ITO substrate with electrode pattern for 5 seconds of 500 rpm, and thereafter 20 seconds of 2000 rpm, and soft baking at 95°C for 2 minutes, and hard baking at 200°C for 1 hour. Soft-baking is the step during which almost all of the solvents are removed from the SE-1211 mixture. Hard-baking is necessary in order to harden the side-chain and improve adhesion of SE-1211 to the wafer surface. The un-rubbed vertical alignment layer is thereby formed on the substrate. Second we will coat the photoresist material (S-1818 with ratio of 1:3) on the SE-1211 coated ITO substrate for 5 seconds of 500 rpm, and thereafter 30 seconds of 1500 rpm, and soft baking at 95°C for 2 minutes. In the next step, attaching the designed photomask on the coated substrate, shining the UV light for 6 to 10 seconds, we are able to register the first alignment domain, for example, polar angle of 88° and azimuthal angle of 90°, in the regions as shown in Fig.3.14. After rinsed by deionized water and dried by air, we perform the first round of rubbing (5 to 10 times with rubbing block depends on the pretilt angle requested). Washing off the photoresist by a series of steps including P-thinner for 60 seconds, deionized water rinsing, methanol rinsing, deionized water rinsing, isopropanol rinsing, and dried in over at 80°C for 10 minutes. Repeat the step 2 to step 5 to register the second alignment domain. By this procedure, a patterned ITO substrate with three-domain quasi vertical alignment is ready to be assembled and be filled with liquid crystal materials (MLC-6608).

To remove the defects in the bulk, further thermal treatment is also conducted on LC cell with three-domain surface alignment. First we apply high voltage (5V) to the cell.
Heating the cell to the isotropic phase with voltage applied. Then cool down the system slowly with 5 dpm to the room temperature with voltage applied to obtain a uniform vertical director configuration in the bulk of LCPG.

### 3.5.1.2 Patterned ITO substrate

In this work, both of the bottom and the top substrate will be accurately controlled with inter-digital electrodes coated on the substrates by photolithography technique. We design the electrode pattern and assemble the LC cell with four arms of electrode bonds as shown in Fig. 3.15. All the electrodes are applied voltage that controlled by the Labview program.

### 3.5.2 Polarized Optical Microscopy of tunable LCPGs.

As we predicted the director configurations of the initialization procedure of the V-COPA device for the single frequency material with a negative dielectric anisotropy, we have fabricated a V-COPA LC cell with the initial period of 23 µm filled with MLC-6609, a liquid crystal material with negative dielectric anisotropy of -3.7 at the temperature of +20°C and the applied voltage of 1 kHz. The surface alignment is approximately similar to the configuration in Fig. 3.5, except the different alignment domains are interchanged with 1 pixel, not three pixels in Fig. 3.5. The photo of the device with four interface board is shown in Fig. 3.16. For the initialization process, we apply the following voltage profile: 10, 12, 10, 12, 10, 12, 10…V on the electrodes of bottom substrate and 0, 2, 0, 2, 0, 2, 0…V on the top. The polarized microscopy verifies the periodical in-plane spiral
director configuration in Fig. 3.17(a) as alternate dark-bright bands from the view of polarized microscope. In the case of crossed polarizers that are parallel and perpendicular to the electrodes, Region A or B (in Fig. 1.7) where the director is parallel or perpendicular to the electrodes will appear to be dark, while the transition region between A and B will be bright in the polarized microscopy. The initial spacing between the dark bands is equal to the pixel spacing of electrodes as 23 µm. As long as the azimuthal angles of directors increase linearly along x or –x axis, the dark-light bands will shift towards one uniform direction as shown in Fig. 3.17(b-c) when rotating the crossed polarizers. It demonstrates that the correct rotation sense and in-plane spirals are formed in the LCPG cell.

### 3.5.3 Characterization of tunable LCPGs

We use the jumping method (details will be introduced in Chapter 4: the dynamics of tunable LCPG) to tune the period of the single frequency V-COPA device. Based on the initial formed period, if continue to switch the voltage profile, the period of the grating can “jump” from the initial 23 µm to 46 µm, 69 µm, and 92 µm, as shown in Fig. 3.18(a-d). For example, Fig. 3.18(a) is step 1 with the initial period with 10, 12, 10, 12…V on the electrodes of bottom substrate and 0, 2, 0, 2…V on the top. In Fig. 3.18(b) of step 2, we simply switch voltage profile to 10, 10, 12, 12, 10, 10…V on the bottom substrate and 0, 0, 2, 2, 0, 0…V on the top. Similarly, to obtain the period in Fig. 3.18(c) of step 3, we switch the voltage profile to 10, 10, 10, 12, 12, 12…V on the bottom and 0, 0, 0, 2, 2, 2…V on the top from step 2, and so on. The jumping steps must be performed in a
correct sequence. One can not jump from step 1 to step 3 directly, otherwise the desired spiral configuration will not be obtained. It should be noted that during the transition process, disclination lines are formed due to the topological difference between the two states.

Given a circular polarized light at the wavelength of 1.5 μm normally incident on the V-COPA device with the effective thickness of half-wave optical retardation, the transmitted light will deflect to the different steering angle as a result of period tuning. Initially, when the period width is 23 μm, the deflected angle is 3.4° in Fig. 3.19(a). And different steering angles will be available, such as 1.7° steering angle for the period of 46 μm, etc, as shown in Fig. 3.19(b-d). When the requirements of half-wave retardation and constant gradient are met, the theoretical throughput of the deflected light will reach to 100% diffraction efficiency. The measured diffraction efficiency by peak ratio method is over 97.49% in Fig. 3.20 when the periods are in the range of 23 to 69 μm. However, when the width of period reaches to about 92 μm, the applied voltage profile will not be able to hold the gradient of the azimuthal angle of the directors as a constant, and the final efficiency will consequently drop to 70.46%.

One limitation of the above single frequency V-COPA is the tuning speed. It turns out that the response speed of the deflected light from 3.4° to 1.7° is about 650 ms. The response time will increase up to several seconds especially for the periods greater than 92 μm. To provide an adaptive beam steering technology with short response time, the need for the fast switching between different steering angles is critical. To resolve this issue and improve the tuning speed, in Chapter 4 we will concentrate on the dynamics
mechanism of tunable LCPG device, and propose a dual-frequency LCPG with fast tuning capability.

In addition, as we described in section 2, we can easily implement a three-state switching device by flip the voltage offset profile, as shown in Fig. 3.21 and Fig. 3.22 with 1.5 µm of incident light switching between +3.4°, 0° and -3.4°. The efficiency of each state is above 98%.

3.6 Summary

A tunable LCPGs device, that is characterized with an in-plane spiraling optic axis, has been studied in this Chapter. Employing a liquid crystal material with a negative dielectric anisotropy, quasi-vertical surface alignment and an electric field with an offset voltage profile, excellent spiral configurations have been demonstrated. The resulting structure shows very high diffraction efficiency (95-98%). Compared with conventional LC prisms and OPA devices, the LCPGs device inherently has a continuous phase profile with no resets, while its thin (half wave retardation) cell thickness yields low absorption and low scattering. Moreover, the angle tune-ability of this device based on Pancharatnam's idea is achieved. Other optical devices such as electrically controlled lenses can also be envisioned based on this approach.
Fig. 3.1  The spatially varying orientation of the slow axis of the half-wave plate in the x-y plane of the LCPGs
Fig. 3.2  Ideal director configuration of a LCPG device (one period)

(a) Side view of the LCPG director configuration

(b) Top view (middle plane) of the LCPG director configuration
Fig. 3.3 Wrapped ideal phase profile of x and y component in the near field of a LCPG device (with 10 periods)
Fig. 3.4  Ideal diffraction pattern of intensity in the far field of a LCPGs device (with 10 periods)
Fig. 3.5 A typical electrode pattern and in-plane spiral director configuration of a LCPGs device with 2 periods
Fig. 3.6 Snapshots of the initialization of LCPGs (boundaries and center)
Fig. 3.7 Top view of director configuration of LCPGs in x-y plane:

(a) Counterclockwise rotation of sense (– state, top one)

(b) Clockwise rotation of sense (+ state, bottom one)
Fig. 3.8 2D rectangular grid of lattice for LC modeling and Jones calculus
Fig. 3.9 Tunable LCPGs spiral grating starting with 15.75μm period

The top one is the view from normal of the cell and in the middle x-y plane along z. The bottom one is the side view of director configuration. The curves show the equipotential field with 0.33V between each level.
Fig. 3.10 Tuning of LCPGs with 13.5 µm period
Fig. 3.11  Tuning of LCPGs with 7 μm period
Fig. 3.12 A repeated LCPGs spiral of grating with 10.25 µm period
Fig. 3.13 Scalar Theory Calculation Results of tunable LCPGs

(a): Incident Gaussian Beam; (b): Far Field Intensity vs. Angular Position for case in Fig.5, which is 15.75µm period; (c): Far Field Intensity vs. Angular Position for a case with 10.25µm period
Step 1: Spincoat SE-1211 on patterned ITO, baking

Step 2: Spincoat Photoresist S-1818, thermal treatment

Step 3: Register one alignment domain by UV light

Step 4: Rub 5-10 times

Step 5: Wash off photoresist

Multi-domain quasi vertical Alignments on patterned ITO

Fig. 3.14 Procedures of three domain quasi-vertical surface alignment
Fig. 3.15 Patterned electrodes in bottom and top substrate of LCPGs
Fig. 3.16  Photo of LCPGs device with four interface board
Fig. 3.17 Polarization Microscopy of LCPGs device

(a) rotate polarizers with 0 degree; (b) rotate polarizers with 22.5 degree; (c) rotate polarizers with 45 degree
Fig. 3.18  Period tuning of LCPGs device in Polarized microscopy

(a) Initial period of 23µm; (b) tuned period of 46µm; (c) tuned period of 69µm; (d) tuned period of 92µm
Fig. 3.19 Deflection beam in different period of Tunable LCPGs device
(a) 0 degree without voltage applied; (b) 3.4 degree deflection with 23 µm period (c) 1.7 degree deflection with 46 µm period; (d) 1.1 degree deflection with 69 µm period; (e) 0.85 degree deflection with 92 µm period
Fig. 3.20  Intensity profile of deflection beam for different period
Fig. 3.21 Polarized microscopy of three-state switching of LCPGs

(a) “–” state; (b) “0” state; (c) “+” state
Fig. 3.22  Intensity profile along x of three-state switching of LCPGs
Chapter 4

Dynamics modeling of dual frequency LCPGs

4.1 Introduction

In Chapter 3, we have demonstrated the basic concepts and mechanisms of tunable liquid crystal polarization gratings (LCPGs) by the modeling and experimental results. The excellent steering efficiency and continuous tunable steering angles have been implemented by the fabricated LCPGs device filled with a negative dielectric anisotropy liquid crystal material.

However, one critical limitation of the LCPGs is the slow tuning speed. From a series of snapshots of the polarized optical microscopy of the tunable LCPGs (Fig. 4.1), we explicitly show the detailed transforming procedures with three steps. The greenish snapshots at the beginning and the end of each step are the equilibrium director configurations applied with 10V on bottom and 0V on top, and no offset is applied, while the red snapshots are inter-medium state, for example in step 1 with 8, 5, 8, 5, 8, 5V…on bottom, and 3, 0, 3, 0, 3, 0V…on top. Appropriate high voltage offset will benefit the response time. Step 1 is the tuning procedure from the initial period (23 µm) to the expanded period (46 µm). The period varies from 46 µm to 69 µm in step 2, and from 69 µm to 92 µm in step 3. The arrow along x axis represents the response time scale of the
snapshots. “Jumping” method is employed here to realize the tuning process in three steps. The response time is approximately about 640 ms in step 1, around 1.6 seconds in step 2, and it will increase up to 3-5 seconds in the case of step 3. The relatively slow tuning speed will seriously limit the practicality of the tunable LCPGs device, since the fast and agile angular switching or tuning is preferred or required in many beam steering applications.

To improve the response time, we first study the general concept of the tuning process of our LCPGs device. Then we will introduce three major tuning approaches, which are “walking” method, “jumping” method and “resetting” method. Based on the dynamics modeling of these approaches, we will propose a dual frequency tunable LCPG (V-COPA) device that is characterized with the fast tuning capability.

4.2 General concepts of driving scheme

To illustrate the tuning algorithm, as a starting point, we can first consider the method of single frequency LCPGs device discussed in Chapter 3. The voltage offsets are translated to the new location $A'$ in Fig. 3.5. Before the voltage adjustment, the orientation of LC director in region $A'$ was towards the x axis with very small azimuthal angle $\beta$. The effect of the fringe field from the voltage offset will reorient the LC director in region $A'$ along the x axis with the new $\beta'$ equal to 0°. As we know, the issue with this approach is that the response time is longer than the desired for some applications.

To improve the response speed of the period tuning, it is helpful to consider what the driving force of the period tuning is. The general strategy of period tuning is to translate
several specific orientation regions, such as the regions $A$, $B$ and $C$ in Fig. 4.2, (along $+x$ or $-x$ axis) by translating the locations of the external torque that hold the director along the $x$ or $y$ axis in the figure. We denote the region $A$, where the directors orient towards $+x$ axis with azimuthal angle $\beta$ equal to $0^\circ$, as the left boundary of one full period. Similarly, the right boundary of the period is region $C$ where the directors orient towards $-x$ axis with $\beta$ equal to $180^\circ$. Region $B$, where the director is along $+y$ axis with $\beta$ equal to $90^\circ$, is denoted as the center of the period. We decompose the overall procedure which the period changes from a longer distance to a shorter one step by step as shown in Fig. 4.2. That is the typical “walking” method that we will introduce the details in section 4.4.1.

Three assumptions are set to explain the general concept of driving scheme. First, assuming the initial period of spiral director configuration has already been formed in step 1 of Fig. 4.2, we are able to vary the period based on the initial spiral configuration. Second, the surface alignment will not prohibit the translation of the spiral configuration along $x$ axis, especially the center and boundaries regions. In our case, the quasi-vertical alignment is simply a trigger to initialize the in-plane spiral structure, and the homeotropical director configuration (along $z$ axis) near the surface can gradually reorient towards any direction in the $x$-$y$ plane of the bulk in principal. Third, we have a means that can reorient the directors in region $A'$ (a region near the left boundary $A$) towards the $x$ axis, and also have a means to reorient the directors in region $B'$ (a region near center $B$) towards the $y$ axis. By this approach, the orientation of the left boundary ($\beta = 0^\circ$) in the left shadow area and the orientation of the center in the center shadow ($\beta =
90°) will transit to a new location towards +x direction, while the orientation of the right boundary (β = 180°) will keep as the initial location. As a consequence, the total length of the period will become shorter. Or we may translate the left boundary and center towards –x direction. In this case, the total length of period will be extended. Note that the external forces only focus on three specific domains (left or right boundary, and center), since the directors in all the other regions can be correctly oriented by the liquid crystal elasticity itself if the period is not too large. The concept can be analogous with holding one end of a spring, while pushing or pulling another end. All the other segments of the spring will be adaptive to the external force automatically unless the stiffness condition is destroyed.

Considering the single frequency LCPG device described in Chapter 3, we can only have a torque to cause the director to align in one direction. However, by using a liquid crystal material whose dielectric anisotropy can change sign, we can consider to have torques to cause the director to align along the x or y axes. Liquid crystal material called “two frequency” materials have this property.

A two frequency liquid crystal is a material whose dielectric anisotropy is negative at high frequencies and positive at low frequencies. These materials will align along an electric field direction with a low frequency applied voltage (denoted as the positive mode). However when a high frequency voltage is applied, the LC will orient perpendicular to the field direction (denoted as the negative mode). The two modes can coexist if both high frequency and low frequency field are applied to the same region at the same time.
To numerical model the director configuration of dual frequency liquid crystal material, and study the dynamics characteristic of such device, we will first briefly introduce the basic concepts of the numerical modeling of dual frequency LCPGs.

4.3 Numerical dynamics modeling of dual frequency LC

4.3.1 Numerical modeling of dual frequency LC

The approach to simulate dual frequency LC device is to create two set of numerical arrays of voltage in the simulation. With low frequency voltage, a positive dielectric anisotropy is used to calculate the contribution to the electric free energy of the system, while a high frequency applied voltage, a negative dielectric anisotropy will be employed in the contribution to the electric free energy. Both of the voltage profiles will contribute to the total free energy which led to the equilibrium state of the LC director configuration.

When we calculate the derivative of the electric free energy, an additional term should be included as Eq. 4.1:

\[
\frac{df_E}{dn_i} = \frac{1}{2} e_0 \left[ \frac{dV_+}{di} \cdot \sum_j \left( \frac{1}{2} \cdot \frac{dV_+}{dj} \cdot n_j \right) \cdot \Delta \varepsilon_+ + \frac{dV_-}{di} \cdot \sum_j \left( \frac{1}{2} \cdot \frac{dV_-}{dj} \cdot n_j \right) \cdot \Delta \varepsilon_- \right]
\]

\( i, j = x, y, z \)

Where \( V_+ \) and \( V_- \) are the voltage for the positive and the negative mode separately. The two sets of voltage profile are relaxed and calculated separately. Each voltage profile is then used to obtain the separate contributions to Eq. 4.1. The director configuration will be relaxed until the system reaches the equilibrium state.
4.3.2 Dynamic modeling

To study the dynamics of liquid crystal director relaxation, a simultaneous displacement approach is generally used. With simultaneous displacement, the modeling will calculate the director orientation on the entire lattice, and then update the entire director configuration at the same time.

We discretize the time of the LC director relaxation into \( n \) steps with defined time period \( \tau \) (such as 25 ms) for each step. The voltage applied on the system will be updated immediately once a new step starts. For every step, the stopping condition is either the system reaching to the equilibrium state, or the accumulated modeling time for that step greater than \( \tau \). With the dynamics LC3D tools that we develop, we are able to simulate, investigate and improve the performance of tuning speed of the LCPGs device.

To validate the response time calculated from the dynamics modeling, we compare the dynamics modeling results of the tuning by jumping method with the experiment tuning results. It turns out that the modeling results are reliable since it takes approximately 1/5 times of the experimental process with exactly the same configurations, setup and procedures.

4.4 Tuning methods of LCPGs

From the perspective of driving scheme of the applied voltage, there are three approaches to tune the LCPGs device, which are “walking” method, “jumping” method, and “resetting” method. Walking method is a continuous tuning approach to vary the period by a series of gradual changed voltage steps. This method is reliable and robust to
have defect free tuning process. The disadvantages are the relatively slow speed compared with the other two methods, and complicated driving scheme with a series of tuning steps. “Jumping” method and “resetting” method are two discrete tuning approaches with voltage profile changed abruptly. Compared with the walking method, they are possibly faster to accomplish the tuning steps, and very simple algorithm to realize. Nevertheless, they also come with the high risk of generating unexpected defects or disclinations in the system that will lower the final steering efficiency.

4.4.1 “Walking” method

As we described in Fig. 4.2, “walking” method is a process that the pitches of the period of LCPG are continuously changed by modifying the voltage profile gradually. With this approach, we are able to expand or shrink the pitch of the LCPGs with low risk of forming defects or disclinations. Table 4.1 shows the typical scheme of driving voltage of “walking” method. As a consequence, the director configuration in Fig.4.3 will reorient and modulate the period from the initial large pitch to a small one.

To illustrate the details of continuous tuning method, we can first investigate the initialization of voltage pattern of single frequency LCPGs in Chapter 3 that provides a voltage “offset” between two areas of the device. At the location of the offset, the director tends to tilt to be perpendicular to the electrodes as discussed in Chapter 3. This concept works well for initializing the desired spiral pattern, but once the pattern is formed the effect of the offset is not ideal for holding or changing the spiral pitch, in other words, it can not modulate the period within a short response time. With the
director being held in the plane of the cell (the x – y plane) it is more likely that the lowest energy director configuration will be with for it to lie parallel to the electrodes at the offset region. We find that applying an “offset”, to a single electrode width can effectively trap the director to be parallel to the electrode direction as shown in Fig. 4.4.

It seems to be conflict with the initialization process that the offset will trap the boundary region A or C, instead of the center region B in Fig. 4.2. Actually both configurations (boundaries or centers) are possible to trap for the applied fringe field with the offset, since they are both perpendicular to the fringe field for a negative dielectric anisotropy LC material. When the initial director configuration is vertical, and the offset is applied to the boundary region A or C, the director in A or C near the surface will prefer to align along the equi-potential field line (Fig. 3.9, Chapter 3), which is in x-z plane and towards x axis. To be consistent with the director near the surface and lower the free energy, the LC directors in the bulk of the fringe field region will thereafter reorient towards the x axis and form the boundary regions. It is a different story when we apply an offset voltage on the existing LC director that have been approximately aligned towards y axis (region B’ near the center). The director will prefer to reorient towards y axis and form a new center region to minimize the free energy of the system. It turns out that this process is much more effective and faster than the other one.

An added advantage of this method of using the negative dielectric anisotropy of the LC material to fix region B in Fig. 4.2 is that when “two frequency” liquid crystal material is used, we can also apply a voltage that couples with the positive mode of the
material to trap the director perpendicular to the electrode direction (regions A and C in Fig. 4.2) as shown in Fig. 4.5.

An issue with continuous tuning is the ability to absorb or nucleate spirals. This can be accomplished by having regions in the aperture that have a vertically aligned director field (without any voltage applied) that will absorb spirals, and that can be used to nucleate spirals that are shifted into the active area. Details of this approach will be shown in the calculation section 4.4.

4.4.2 “Jumping” method

We consider two discrete tuning approaches: “jumping method” and “resetting method”. A single frequency LCPGs or a two frequency LCPGs device in the negative mode can be tuned with discrete periods. As for jumping method, we switch the voltage profile abruptly from one period to another period without any intermediate steps. The typical voltage scheme is shown in Table 4.2. The relevant director configurations of each step are illustrated in Fig. 4.6. From the program point of view, it is very simple and easy to setup the driving scheme to control the “jumping”. In the section 3.5, all the tuning results are implemented by the “Jumping” method. Nevertheless, as we have shown in Fig. 4.1, especially in step 3, since the applied voltage is abruptly changed without any buffering procedures, it is very easy to form any topology difference that come with wrong rotation sense or disclinations. The external torque of the fringe field will try to minimize or eliminate these regions, but it turns out to take very long time to reach the final equilibrium state with acceptable polarization gratings. This process is up
to several seconds or even longer. That will severely limit the performance of tuning speed of our device. We have expected the simple “jumping” method to be characterized with faster tuning speed, but unfortunately the above issue would rather lead to the relatively long response time, especially in the case of switching between the longer period.

### 4.4.3 “Resetting” method

The “resetting method” resets the voltage profile to 0V for all electrodes every time once we want to switch to a different period, and then apply relevant voltage schemes to form a new period.

The resetting method will be described through an example. Consider the surface alignment will designed as shown in Fig. 4.7 with the different domain alternating over every electrode. To initialize the in-plane spiral of grating, similar to the process in Chapter 3, we apply the voltage profile: 10, 12, 10, 12, 10, 12, 10, 12V on the electrodes of bottom substrate; 0, 2, 0, 2, 0, 2, 0, 2V on the top.

To switch the deflection angles between different periods, as shown in the Table 4.3, firstly we reset the voltages on all electrodes to 0V. This step recovers the whole LC director back to the initial homeotropical state (actually a further speed improvement could be obtained by applying a low frequency (positive mode) voltage between the top and bottom electrodes). Thereafter we are able to apply a different voltage scheme to form another period. For instance, after reset, we apply a field with low voltages (negative mode) on several specific electrodes: 0, 0, 2, 0, 0, 2, 0V on the bottom
substrate, with zero voltage is applied on the top. With this “pre-initialization” step, the
directors over electrode #3, and also the directors near the electrode #3, i.e., electrode #2
and electrode #4, will all have slight tendencies to tilt towards the –y direction, even
though the quasi-vertical alignment over electrode #2 and electrode #4 are towards +y
direction. With this formed orientation tendency by the pre-initialization voltage applied
on electrode #3 and #6, in the subsequent initialization step, we will be able to form a
new period by applying the following voltages (negative mode): 10, 12, 12, 12, 10, 10, 10,
12V on the electrodes of bottom substrate; 0, 2, 2, 2, 0, 0, 0, 2V on the top. The opposite
direction of azimuthal angle from the quasi-vertical alignment will not affect the
formation of the period since the orientation preferences in these domains have already
been determined. With the above procedures, we are able to form the “odd” periods with
such length as 1, 3, and 5 etc pixel spacing. By modifying the voltage profile the sense of
the helix can be changed so the number of steering angles is twice the number of possible
periods.

The resetting method has the fast speed switching capability because it does not
involve any disclination motion associated with a topological change. However, the
deflection angles by resetting method are limited to several specific states.
The V-COPA device tuning with resetting method is promising to make a digital beam
deflector device.

In order to validate the concept of “resetting method” for digital beam deflector,
similar procedures (three steps: reset, pre-initialization, and initialization (of final state))
were modeled in Fig. 4.8(step 0-step 3). The device parameters are similar to the setup in
Chapter 3.4 of single frequency LCPGs device. The voltage profiles applied for each step were listed in Table. 4.3. Since no intermediate steps as the continuous tuning method are required for this approach and also no equilibrium states are necessary for step 0 and step 2, the switching speed can be improved to the range of 50 to 100ms.

The modeling results are demonstrated by the polarized microscopy images of the director configuration in x-y plane of the four steps: initialization (of the first period), resetting, pre-initialization, and initialization (of the 2nd period) are shown in Fig. 4.9 (step 0-step 3) respectively.

It is interesting to study what is the limit of the shortest period. Based on the similar initialization process, we investigate a V-COPA device with 3 µm thickness and three electrodes as a surface alignment group, with the sizes of electrodes and gaps are equal to 1 µm and 0.5 µm respectively. We modeled the initialization of the spiral director configuration in this device and found it formed correctly as shown in Fig. 4.10. Note that a full 9 micron period of in-plane spiral director configuration will result in two full waves of phase difference, since the output phase gradient is two times of the gradient of director rotation. Therefore we get a phase grating with period as short as 4.5 µm. The deflection angle for a 4.5 µm period is 19.47 degree at the wavelength of 1.5 µm.

4.5 Dynamics modeling of dual frequency LCPGs

4.5.1 Continuous tuning of dual frequency LCPGs

In Chapter 3, we have introduced the details of modeling results of tuning the single frequency LCPGs device. Since the single frequency tuning is actually a subset of two
frequencies LCPGs, we will focus on the continuous tuning of two frequency LC material in this section.

Considering a cell with a 3 µm gap filled with dual frequency liquid crystal MLC-2048, which has a positive dielectric anisotropy $\Delta \varepsilon$ of +3.22 at 1 kHz and a negative dielectric anisotropy of -3.08 at 50 kHz. The cross-over frequency for MLC-2048 is slightly exceeds 10 kHz. The electrode stripe’s width (along x axis) is 1 µm, and the gap between two electrodes is 0.5 µm. There are totally 25 full electrodes in the simulation region as 37.5 µm. Note that the first electrode and the last one are modeled as two halves of the same electrode. Therefore, totally 26 electrodes appear in the simulation range. The surface alignment has three different domains. The alignment over electrode #1 has the azimuthal angle of 90° and polar angle of 88°, which is also the same alignment as the one over the last electrode. For the other 24 electrodes, denote every 6 electrodes as a group with the same surface alignment. For example, the alignment over electrodes #2 to #7, and #14 to #19, has the azimuthal angle of 270° and polar angle of 88°, while the alignment over electrode #8 to #13, and #20 to #25 has the azimuthal angle of 90° and 88° polar angle. With this alignment setup, we are able to form the initial in-plane spiral director configuration in Fig.4.11(a-b) with the applied voltage profile as: 12, 10, 10, 10, 10, 10, 10, 12, 12, 12, 12, 10, 10, 10, 10, 10, 10, 10, 12, 12, 12, 12, 12, 12, 12, 12, 12, 10V on the electrodes of bottom substrate; 2, 0, 0, 0, 0, 0, 0, 0, 2, 2, 2, 2, 2, 12, 12, 10, 10, 10, 10, 10, 10, 10, 10, 10, 12, 12, 12, 12, 12, 12, 10V on the top. Two full periods of in-plane spiral have been formed.
To tune the period of dual frequency V-COPA device with fast speed, we use two sets of voltage profile at the same time.

One is in the positive mode to translate the boundaries to the left or right direction. The driving scheme of the low frequency voltage applied on bottom substrate is shown in Table 4.4, which is also the same value for the electrodes on the top substrate. The voltage profile of each step will last for a user defined time period, such as 50, 25, 15 or 10ms, etc. The liquid crystal directors are only allowed to relax within this time period. And then the voltage profile will be updated in the next step as shown in the table.

Another is in the negative mode to shift the center to the left or right direction. The relevant driving scheme on top substrate is shown in Table 4.5. As for the voltages of bottom substrate, all the relevant voltages are added with an additional 80V compared with the voltages on top substrate.

Both the low frequency voltage profile and the high frequency one are updated with the same speed rate. If the boundaries and centers are able to follow the update rate of the applied voltage, these specific regions will transit with an equivalent translation speed. Then the user defined time period for updating voltage profiles can be regarded as a “good” response time for the device. From the modeling for the above setup, we find 10 ms is the minimum time period that is “good” for the device. The in-plane director configurations in the middle plane of the cell (in x-y plane) are listed in Fig. 4.12(a-f) from step 1 to step 6. The odd shadowed regions (1st, 3rd, etc) are over the electrodes that provide the low frequency (positive mode) voltage, while the even shadow regions
provide the high frequency (negative mode) offset voltage. The length of each period changes from the initial 18.75 μm to 13.75 μm after 6 steps.

The new period can be further suppressed to about 9.75 μm by another 6 steps, which is almost half of the original one by the driving scheme listed in Table 4 and 5, with 10 ms time period between each step. When the average period is squeezed, it turns out the torque from the low frequency voltage will increase much faster than the high frequency one. To maintain the balance between them, we decrease the low frequency voltage offset to 5V. From Fig. 4.13, we note that during the period suppression process, in the fixed simulation region, some blank areas with no period will be formed as a result of period shrinking. The directors are oriented all the way towards –x axis direction. To obtain as high diffraction efficiency as possible, we need continuous periods without any blank regions.

4.5.2 Nucleation of spirals

If we are able to nucleate some additional periods with correct rotation sense and same period width in these blank regions, we will keep the continuous in-spiral gratings. The basic concept to nucleate some addition periods is based on the similar procedures as the initialization. To save some tuning time, we began to relax these blank regions from step 4 to 6 in Table 4.6-4.7 which are the voltage profiles in the top substrate. The tuning results with relaxation of the blank regions are shown in Fig. 4.13(a-f). Applying a high frequency voltage as 12, 10, 10, 10, 10, 10, 12, 12, 12, 12, 10, 10, 10, 12, 12, 12, 10, 10, 10, 12, 12, 10, 10, 10, 12, 12, 12, 10V on the bottom, while apply 2, 0, 0, 0, 0, 2, 2, 2, 2, 2,
0, 0, 2, 2, 0, 0, 2, 2, 0V on the top. We will form another one full period of grating in the blank region along with the squeezed two full periods in Fig. 4.14.

While in Fig. 4.14 we show that the nucleation area is half of the total area of the device, but we visualize that in an actual device the nucleation area is a small fraction of the total device area. In the case of a shrinking period, new spirals will be nucleated in the nucleation area and shifted out into the active area, while in the case of an expanding period spirals will be shifted into the blank area which as no voltage applied so that the director alignment is vertical and the spirals are absorbed.

4.6 Summary

In chapter 3, the single frequency LCPGs device that we fabricated has shown high efficiency with variable steering angle as predicted by numerical modeling. But it also has the limitation of response time in the range of 650 ms and up to several seconds. A faster tuning beam steering device using “two frequency” liquid crystals has been proposed and modeled in this chapter. By tuning the dual frequency LCPGs device in both of negative mode and positive mode, we are able to translate the boundary and the center of the in-plane spiral of grating with a shorter response time. The total switching time is about 120 ms from initial period of 18.75 µm to 9.75 µm for a LCPGs device with 3 µm thick and 1.5 µm pixel spacing. In addition, the modeling of LCPGs device with period of 9 µm shows a high efficiency digital beam deflector with large angle that is up to 19.47 degrees for 1.5 µm light. We have also shown how spirals can be nucleated or
absorbed in isolated regions of an aperture. Other studies based on the LC3D modeling technology, such as the electro-optic liquid crystal lenses, was one extension of the work.
Fig. 4.1 POM Snapshots of tuning between different states of LCPGs
Fig. 4.2  Period tuning of dual frequency LCPGs by “walking” method
Fig. 4.3 Period tuning by “walking” method in x-y plane (middle of cell)
Fig. 4.4 Translation of the center in negative mode of dual frequency LCPGs
Fig. 4.5 Translation of the boundaries in positive mode of dual frequency LCPGs
Fig. 4.6 Period tuning by “Jumping” method
Fig. 4.7 Surface alignment of a large angle digital beam deflector
Fig. 4.8 Modeling of resetting method for a digital beam deflector
Fig. 4.9 Polarized optical microscopy of resetting method
Fig. 4.10  A digital beam deflector with full period of 9 µm
Fig. 4.11 Initialization of a dual frequency LCPGs in the negative mode

(a) director configuration in x-z plane with equi-potential field line

(b) director configuration in x-y plane
Fig. 4.12  Period tuning of dual frequency LCPGs device (director configuration in x-y plane of middle of the cell) with 15ms time period between each step.
Fig. 4.13 Continue to squeeze the period of LCPGs device with relaxation to vertical state in the blank region with 15ms time period between each step.
Fig. 4.14  Two squeezed full period of grating with a nucleated full period of grating in the previous blank region
Table 4.1 Driving scheme of walking method

(a) Voltage on bottom substrate (V)

(b) Voltage on top substrate (V)
Table 4.2 Driving scheme of Jumping method

(a) Voltage on bottom substrate

(b) Voltage on top substrate
Table 4.3  Driving scheme of resetting method

(a) Voltage on bottom substrate

(b) Voltage on top substrate
Table 4.4  Driving scheme for translating the boundaries in positive mode (first six steps, unit: V)

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<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>

Electrodes Number
Table 4.5  
Driving scheme for translating the center in negative mode (first six steps, unit: V)

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Electrodes Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
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</tr>
<tr>
<td>5</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>6</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

| Electrodes Number | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 1                 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 2                 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 3                 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 4                 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 5                 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 6                 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Step Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
|-------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1           | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 0 | 0  | 0 | 0  | 0 | 0  | 0 | 0  | 0 | 0  | 0 | 0  | 0 | 0  | 0 |
| 2           | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 |
| 3           | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 5 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 |
| 4           | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 0 | 5 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 |
| 5           | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 0 | 5 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 |
| 6           | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 0 | 0 | 5 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 | 5  | 0 | 0  | 0 |

Electrodes Number

Table 4.6  driving scheme for translating the boundaries in positive mode

(next six steps, unit: V)
### Table 4.7  driving scheme for translating the center in negative mode

(next six steps, unit: V)
Chapter 5

Tunable electro-optic liquid crystal lenses

5.1 Introduction

An “optically perfect” eye is known as the “gold standard”. In Fig. 5.1, all rays from the distant object point P will focus at a common point P’ on the retina of eye. The optical path delay (OPD) from the object P to the image point P’ is the same for all the rays. The ideal wavefront converging on the retina is spherical. However, the deviations of the wavefront from the perfect sphere will lead to presence of the optical aberrations, and will blur the retinal image into our eyes. We need some instruments or approaches, such as eyeglass or contact lenses, to compensate this wavefront error. The developments of vision technique, which measure and correct the eye’s spherical aberration, even some higher order aberration beyond defocus and astigmatism, raise the issue of the possibility to compensate most of these aberration errors. In addition, every eye is unique. The required optical aberration correction for different eye is varied. An adaptive approach is preferred to obtain the optimum vision performance for every individual.

It is known that electro-optical lenses can utilize liquid crystal material to alter their optical power. Compared with the conventional glass or plastic lenses, they have the inherent advantages of being able to achieve the varied optical phase profile by
modulating the applied electric field. Theoretically, if all the optical aberrations can be corrected by altering the liquid crystal phase profile, we are able to realize the “supervision” that has a pair of “optical perfect” eye.

With the electric field established on the patterned electrodes across the liquid crystal lenses, a phase gradient is created by modulating of the refractive index of liquid crystal material. The object phase profile can be exactly the ideal lens profile, or compromising the correction of higher order aberrations that is defined by the Zernike functions.\textsuperscript{42}

In this chapter, we propose, design and fabricate a liquid crystal based electro-optic lens including hundreds of circular ring electrodes. Several different optical powers can be obtained in the LC lenses. The spherical aberration or higher order aberration corrections will be considered for future research.

5.2 Fabrication and characterization of tunable LC lenses

5.2.1 Circular ring electrode pattern

The basic structure of an electro-optic LC lens is consisted by hundreds of circular ring electrodes, which are electrically connected by resistive bridges, as shown in Fig. 5.2. The width of ring electrodes is set to be matched with maximum phase difference between them. Since the phase change between ring electrode should be less than 1/8 wave and the total phase change across a lens might be around 100 waves at least, it first appear that hundreds of connections are needed for continuous tuning too. That is an overwhelming task in the electrical board design and making the final device extremely complex and difficult to manufacture.
The concept of phase-wrapping can help on resolving this problem. In short, these electrodes can be grouped in such a way that the phase change over one group is approximately one wave. The number inputs are equal to the number of ring groups. This scheme only provides high efficiency when the phase change across each group is approximately equal to one wave. Consequently the lens can tuned to several discreted focal lengths instead of continuous tuning.

5.2.2 Voltage optimization on ring electrode groups

The voltage optimization routine is similar as what we have introduced in Chapter 2. Starting from the objective ideal lens profile as shown in Fig. 5.3, and with the known OPD dependence with respect to the applied voltage in 1D LC simulation in Fig. 5.4, we are able to convert the phase profile of ideal lens to the first entry of voltage that will be applied onto the ring electrodes or groups. We can optimize the voltage profile by looping the optimization until the phase tolerance condition is met, as shown in Fig. 5.5(a-b) with 6 optimization loops.

The phase profile of the LC lens based on the simulated voltage profile can be investigated by the polarized optical microscopy (POM). Fig. 5.6(a-b) is the POM of a stack of two positive LC lenses at the wavelength of 0.55 μm under crossed polarizers and parallel polarizers respectively. Map the data from the image to an intensity profile along the x axis in Fig. 5.7(a-b), subtract the two intensity profiles as shown in Fig. 5.8, localize the peak and valley position, we will figure out the phase profile of the stack of two LC lenses that designed for +1.16m focal length in Fig. 5.9. Similar procedures can
be implemented for a stack of LC lenses with negative focal length. We prefer to use two LC lenses as one unit. Since the pretilted angles of the two LC lenses are rubbed in the way of opposite direction, the view angle limitation can be minimized.

However, it turns out that the optimized voltage profile based on modeling results are only the first level of entry. The errors between the ideal phase profile and measured one are shown in Fig. 5.9. To minimize this realistic error caused by different complex conditions, we perform the following correction procedures. In Fig. 5.10, both measured OPD (blue circle) and ideal OPD profile (green star) are known for every individual electrode group. To obtain the objective ideal OPD profile and minimize the errors, first we need to figure out what is the commanded OPD at the measured OPD profile of the LC lens, as shown in the black dot in the measured curve. Each commanded OPD value at the black dots is corresponding to a new voltage value. To get the commanded OPD at each individual electrode group, we can simply replace the previous modeled voltage profile with the voltage data shown in the black dot. Similarly, by measuring the POM, we can obtain the phase profile by the corrected voltage profile as shown in Fig. 5.11. At this stage, the measured LC lens profile is optimized and closed to objective ideal lens.

### 5.2.3 Tunable LC lens characterization

To demonstrate the performance of the fabricated tunable LC lens, the setup of the diagram as shown in Fig. 5.12 is employed to characterize the properties of the LC lens. A 1951 USAF resolution test chart is placed in location A with white light incident at one side. The digital camera is located at B. The distance between A and B is 1.3m. The
lenses system (LC lenses, or glass lens or the combination) with polarizer and aperture can be placed just in front of the camera lens.

As a comparison, first we take a picture without any lenses into the system. As shown in Fig. 5.13(a), the camera is focused with 1.3m. In the figure, d is the distance between the test chart and the camera lens, while \( f \) is the focal length of the camera.

Note that we have three lenses as one combination into the system: two LC lenses and a glass lenses (focal length = +1 m, denote it as +1 diopter). When the positive voltage profiles are applied on both of the LC lenses, denote the stack of two positive LC lenses with +1.16m focal length as +1 diopter. Each of them is +0.5 diopter, and the negative LC lens with -1.16m focal length as -1 diopter.

With the two LC lenses plugged into the system, but without any voltage applied, the image is shown in Fig. 5.13(b).

Considering the case wherein the two LC lenses and the glass lens are all placed in the system, and the two LC lenses are placed together with -1 diopter totally, it will approximately cancel with the glass lens which has +1 diopter. As shown in Fig. 5.13(c), we find a relatively sharp image without any focus changing of the camera.

With the same configuration, move the test chart to the new location at C, where d is 0.5m. If we keep the same focus of the camera (\( f = 1.3 \)m), the image will be blurred as shown in Fig. 5.13(d). Switch the two LC lenses from the negative focal length (-1 diopter) to positive one (+1 diopter) with the glass lens, keep the same focus of camera (1.3m), the image will recover to the sharp, clear chart with +2 diopter lens in the system.
as Fig. 5.13(e). Remove the three lenses, refocus the camera and take the picture until we find the sharpest picture in Fig. 5.13(f) at the focus of camera as 0.5m.

5.3 Summary

We design, fabricate and characterize the tunable LC lenses in this chapter. The experimental measurements are consistent with our modeling expectations. A tunable electro-optic LC lenses, wherein the focal power of the device can be modified by the application of an electric field. The liquid-crystal based lenses include ring electrodes with phase wrapping and limited connection inputs make it possible for the manufacture of the LC lenses. Image experiments are performed to validate the LC lenses properties. We are able to switch the +1 diopter LC lenses into -1 diopter LC lenses by switching the applied voltage profile. Further aberration correction, such as the spherical aberration, and higher order aberration will be encoded into the LC lenses in the future work.
Fig. 5.1  Gold standard of “perfect” optical eye
Fig. 5.2 Electrode ring pattern with resistive bridge
Fig. 5.3 An ideal lens OPD profile with lens radius as 4.7mm, focal length as 1m.
Fig. 5.4 LC lens OPD dependence with respect to the applied voltage
Fig. 5.5 (a) OPD profile of LC lens after 6 optimizations loops

(b) Voltage profile of LC lens after 6 optimization loops on each electrode
Fig. 5.6 (a) Polarized optical microscopy of positive LC lenses with crossed polarizers; (b) polarized optical microscopy of positive LC lenses with parallel polarizers
Fig. 5.7 (a) Intensity profile along the x radius of positive LC lenses with crossed polarizers; (b) Intensity profile along the x radius of positive LC lenses with parallel polarizers
Fig. 5.8 Subtract of the intensity profiles after center calibration and curve smoothing, and localize the peak and valley
Fig. 5.9 Calculated LC lens OPD profile (blue curve) and ideal LC lens OPD profile (green curve) at the focal length as +1.16m.
Fig. 5.10 Algorithm of phase correction for measured LC lens profile on the electrode groups
Fig. 5.11  Corrected LC lenses OPD profile with +1.16m

Focal length
Fig. 5.12 Experiment setup diagram of characterization of the tunable LC lenses
Fig. 5.13  
(a) Test chart picture without any lenses in the system \((f = d = 1.3m)\) 
(b) Test chart picture with two LC lenses but no voltage \((f = d = 1.3m)\) 
(c) Test chart picture with two LC lenses (-1 diopter) and glass lens (+1 diopter) 
   LC lenses and glass lens cancel each other \((f = d = 1.3m)\) 
(d) Test chart picture with two LC lenses (-1 diopter) and glass lens (+1 diopter) 
   \((d = 0.5m, f = 1.3m)\) 
(e) Test chart picture with two LC lenses (+1 diopter) and glass lens (+1 diopter) 
   \((d = 0.5m, f = 1.3m)\) 
(f) Test chart picture with no LC lenses and glass lens \((f = d = 0.5m)\)
Chapter 6

Conclusions and suggestions for future work

In this dissertation work, we have shown both the numerical modeling and experiment characterization results of two categories of liquid crystal beam steering devices. One is liquid crystal decentered micro-lens array, and the other is tunable liquid crystal polarization gratings (LCPGs). We also study the dynamics features of a fast tuning dual frequency LCPGs device.

In chapter 2, we discussed and analyzed several important factors that contribute to the final efficiency losses of a LC decentered micro-lens array system, such as the robust lens condition for all positive DLA system, and the out-of-lens leakage due to diffraction. With the software package of LC-DLA v3.4 that we developed, we are able to numerical model the liquid crystal director configuration, simulate the optical properties of the three-layer LC system, and evaluate the diffraction efficiency of the device. Three major phase correction approaches are proposed and investigated, including aberration correction for positive or negative lens, phase-up correction for the third layer of DLA system, and mirror symmetry correction for the second layer of mixed LC-DLA system. After compensated with all the phase corrections into the phase profile of liquid crystal by modulating the applied electric field, the optimum efficiency of the
system can be improved from 84.2% to 94.4% at the steering angle of 1.008 ° and with the lens radius of 552 µm.

In chapter 3, we designed and demonstrated a tunable liquid crystal polarization gratings characterized with high efficiency and varied steering angles. The tunable LCPGs are able to implement high efficiency steering that is close to 100% with a continuous phase gradient over a large aperture with out any discontinuity and resets. A liquid crystal material MLC-6609 with negative dielectric anisotropy is used in this device with a specific quasi-vertical surface alignment. With the designed voltage input, an in-plane spiral director configuration is achieved. In addition, a voltage driven scheme with offsets is developed to expand or squeeze the period electronically. Compared with conventional LC-OPA and LC-DLA devices, the tunable LCPGs device inherently has a continuous phase profile without resets. Meanwhile, the LCPGs only request for half-wave retardation of thickness, which lead to low absorption, low scattering and high transmission. The resulting structure shows very high diffraction efficiency (95-98%) including the tuning process of several angles. The measurement results of the fabricated device shows the excellent consistence with our numerical modeling. However, one limitation for the single frequency LCPGs (with negative dielectric anisotropy only) is the slow response time around 650ms at least.

To improve the performance of tuning speed, in Chapter 4, we studied the details of the dynamics of the LCPGs. Three tuning algorithms were studied in details and were compared about the advantages and disadvantages. A continuous tuning method, “walking” method can obtain a defect free tuning of the gratings. However, a lot of
complicated steps of driving voltage scheme are required to implement the “walking”. The tuning speed was severely slowed by the step-by-step “walking” process. Also, extra period need to be eliminated when we expand the period, while new period have to be formed to maintain the continuous phase gradient over the whole aperture. Two discreted methods, “jumping” method and “resetting” method, are very easy to setup and implement in practical and experiments. Only two or three steps are performed to tune the period of LCPGs. For the jumping method, since the abruptly jumping of the voltage from one period to two periods, et al, will cause the topology difference to the supposed spiral, it actually will cost even more time to reach the equilibrium state when we jump the period from one to two, especially when the period is large. As for the resetting method, there are only odd numbers of period can be achieved. But it is promising to use as a large angle digital beam deflector device. Based on the dynamics study, we proposed a fast tuning LCPGs device by the use of “two frequency” liquid crystal materials. Numerically, we demonstrate the tuning speed of the dual frequency LCPGs that is no less than 120ms from initial period of 18.75 µm to 9.75 µm for a LCPGs device with 3 µm thick and 1.5 µm pixel spacing. To have continuous period, we have also shown how the spirals can be nucleated or absorbed in some isolated regions.

Other studies based on the LC3D modeling technique, like the electro-optic liquid crystal lens, are important and potential extensions of the LC beam steering work. We fabricated and characterized the tunable LC lenses. In the experiment, we were capable of switching the +1 diopter LC lenses into -1 diopter LC lenses by altering the applied voltage profile.
Though we have successfully demonstrated our numerical models for the above devices and explain some aspects of the liquid crystal beam steering technologies, several limitations are still the important concerns that will be improved in future research. For example, in the LC-DLA system, the multi-reflection inside the three-layer system will degrade the light transmittance a lot. The coating or medium will be selected to minimize the inner layer reflection. The dependence of the view angle is another concern. It is interesting to study the case that every individual LC layers is split into two LC cells with opposite pretilt direction. It will help the system to minimize the angular error and transmission losses from different view angle of incident light.

As far as the dispersion effect that inherently existed in the LCPGs device is concerned, our current design of LCPGs is not ready to be used in the broad band application. Additional angular calibration devices must be integrated in the device to fix the angular dispersion for different wavelength of incident light.

Switching or tuning speed is still an important issue for the device. We demonstrate our dual frequency device with 120ms response time at least. In the future, we may fabricate the dual frequency LCPGs to demonstrate the fast tuning properties. In addition, 120 ms is still not fast enough especially for some beam steering applications. Is it possible to reduce the response time in the range of several milliseconds?

Instead of the typical nematic liquid crystal used in our work, other materials such as flexo-electric or smectic C materials can be also considered for the design of LCPGs. They are characterized with inherent spiral configurations, and it might be easier to form
the in-plane spiral configuration by some means instead of using complicated surface alignment and driven schemes of electric field.

Now the quasi-vertical alignment is utilized with three different domains. From the viewpoint of manufacturing, it is still a very complicated process to prepare the rubbed substrates. We may take effort to simplify the surface alignment pattern and reduce the complex and difficulties of the cell assembling and manufacture.

From the numerical calculation to the experimental evaluation, we basically set up an overall robust “optimization loop” of developing the LC related device. It turned out that a detailed and user friendly numerical modeling program is helpful for the later device’s fabrication and characterization, also will benefit the later researchers and users. The numerical program is one of the useful facilities to point out the potential failures and limitations to our manufacture process. With the guidance of the modeling, we may spend much less time and costs during the experimental setup and characterization. Moreover, the feedback from the device demonstration will again contribute to keep improving our designs and numerical model. Just like our optimization loop in the LC-DLA program, such an optimization loop also plays a very important role in the research studies. Moreover, the study of the electro-optic LC lens is actually not in the category of liquid crystal beam steering devices. However, the basic undergoing principles are the same in general. For instance, a common algorithm is to set up an ideal target at first, such as the objective ideal lenses profile, microscopic or macroscopic. Then we can try to minimize the error between the device and the ideal target by simulation. We may continue to improve the accuracy by considering the empiricism differences since the
realistic experiment conditions are always complicated and unpredictable in some cases.

In a word, it is interesting to relate the numerical modeling and experimental measurement together and have a positive optimized “loop” between them.
Appendix I

V-COPA v3.0 Program Overview

1. Introduction

V-COPA v3.0 is a user friendly numerical program with GUI based on MATLAB for numerical modeling the tunable liquid crystal polarization gratings (LCPGs) device. It integrates equilibrium LC3D modeling, dynamics LC3D modeling, LC director visualization, Polarized optical microscopy visualization, and optical simulation based on scalar integral method or FDTD method in an easy-to-use graphic environment. Its typical function includes:

- Device parameter setup
- Control parameters setup
- Optical parameters setup
- Voltage pattern setup and design
- LC3D simulation
- 2D scalar integral
- FDTD simulation
- Liquid crystal director visualization
- Polarized optical microscopy visualization
V-COPA is a numerical modeling program based on MATLAB environment that allows the user to design, investigate and demonstrate the features related to the liquid crystal polarization gratings, especially with different options, such as single frequency LCPGs, dual frequency LCPGs. Both the equilibrium and dynamics modeling are encoded in the package to study different perspective of LCPGs device.

2. V-COPA v3.0 System

On Windows platforms, such as Windows XP, and Vista, there are two ways to start the V-COPA program. One is run the executable file in the folder of V-COPA v3.0. Another is first starting MATLAB v7.1 (or any later version), then run the Matlab .m file from the Matlab Editor. The first method can simply start the program by clicking the VCOPA_main.exe. However, it requires the Windows platform to be installed compatible MCRInstaller.exe first as shown in Fig. 7.1. The second method is shown in Fig. 7.2. Run the program VCOPA_main.m from the Matlab editor.

After run the program, the main graphic interface will pop up as shown in Fig. 7.3. The main dialog consists eight functional buttons, including device setting, control setting, optical setting, voltage input, V-COPA OPM, run 2D scalar, director draw, and polarized optical microscopy. In general, the user can set up the device parameter, control setup, optical setup. Then design the input voltage profile on the bottom substrate and top substrate. Next run VCOPA_OPM to implement the Liquid crystal director modeling. Given the LC director configuration, 2D scalar integral is able to investigate the optical performance, such as the near field and far field phase profile, diffraction pattern, etc. To
visualize the results, LC director draw and Polarized optical microscopy draw are several important features of the V-COPA program. Such buttons as “about”, “updates”, “demo”, and “help” are also provided to guide the user to start the program.

- **Device setting**

  Click the “device setting” button in the main window, the program is proceeding to the device setting panel as shown in Fig. 7.4. The device configuration features with liquid crystal material properties, LC panel properties, and specific surface alignment.

**Liquid crystal material properties:**

**Liquid Crystal Name:** input the LC material name, such as MLC-2048, MLC-2049 or some other materials.

**Elastic constant:** input the value of splay, bend, and twist elastic constant, and $q_0$.

**Dielectric anisotropy:** the top one is the default dielectric anisotropy if using single frequency LC material; If checked with dual frequency option, the top one is the default positive dielectric anisotropy with low frequency electric field, while the bottom one is the negative dielectric anisotropy with high frequency electric field.

**Birefringence (refractive index):** the ordinary and extraordinary refractive index, no dispersion considered in the V-COPA program.

**n_glass/ep_glass:** relevant refractive index, and dielectric constant for simple glass

**LC panel properties:**

**Thickness:** cell gap (thickness) of the V-COPA LC cell.
**Surface alignment:** the pretilted and rubbing angle of top and bottom substrate respectively. If checked with the option of detailed alignment design, and click the button of details, the program will pop up the surface alignment design panel that has the capability of multi domain alignment with different pixel groups. Details of designing surface alignment will be introduced in the next section.

**Option to extrapolate the surface alignment to bulk:** If checked, the program will extrapolate the surface alignment configuration to the bulk of LC cell. Otherwise, will simply using the initial vertical alignment.

**Electrode width:** width of each electrode in the substrate

**Gap width:** width between two electrodes

**Electrode number:** define the number of electrodes that will be modeled in the top or bottom substrate. Note that to meet the periodical boundary condition in some cases, we split the first electrode into half, place the first half as the first electrode, and the second half as the last one. For example, input 10 electrodes, the system will generate 0.5, 9, and 0.5 electrodes. From the visual viewpoint, it seems like 11 electrodes in the system.

**Save/load:** in general, all the parameter setting panels have the functions to save/load the parameter configuration to the user defined directory and filename, as shown in Fig. 7.5.

**Specific surface alignment:**

Check the option of design specific alignment, and click the details button, the program will pop up the specific surface alignment panel as shown in Fig. 7.6. According to the defined electrode number, e.g., 10, and the pixel size (electrode width, gap width),
the surface alignment panel will automatically load the electrodes and gaps as shown in the Fig. 7.6. Extra one will be shown because of the periodical boundary condition definition. Click every electrode number in the left listbox, or the gap number in the right listbox, the relevant values of the polar angles and azimuthal angles in that electrode or gap region will be shown in the right of listbox. User is able to input or change the value according to the design. The revision or input will be automatically updated and saved into the database of the system. Additional reset functions are added to make it easy to access and define all the angles of top or bottom electrodes in Fig. 7.7(a). Duplicate functions are provided to fast copy the design from the top/bottom to the bottom/top substrate in Fig. 7.7(b). Once the user is done with the surface alignment design, click the alignment table button, one can check and view the surface alignment tables as shown in Fig. 7.8. If there are any typo or mistakes when inputting the values, the user is able to figure it out easily.

- **Control setting**

To numerical model the program, we need to define the control parameters required for the simulation program, as shown in the Fig. 7.9. It includes LC3D control settings, boundary conditions, initial condition control, fixed parameters, and modeling methods. **LC3D control settings:**

- **X/Y/Z grid size:** define the grid size of the lattice along x, y and z axis of each micron.
- **C:** define the relaxation speed of LC3D modeling.
**tol**: define the stopping condition of the relaxation loops if the convergence condition is satisfied.

**Maxloops**: define the stopping condition of the relaxation loops if the convergence condition is not meet and the number of total iterations will be processed in the simulation.

**W, maxVerr, MaxViter**: define the corresponding parameters in the voltage relaxation process, similar as c, tol, maxloops respectively.

**Boundary condition**:  
**Boundary Condition (B.C.) for x**: if check the option, the system will use free boundary condition, that is, at the boundary, the virtual grids (using for the calculation) is linear extrapolated from the two closest grids near the boundary. If not check, the system will employ the periodical boundary condition, that the left/right boundary (x=1 or Numx) is equal to the right one (Numx or 1).

**Boundary condition for V**: if check the option, along z axis, dV/dz = 0 at the boundary of glass substrate region in top or bottom. If not check, V = 0 at the boundary along z axis.

**Initial condition control**:  
**Restart/continue**: if check the box, the system will load the previous simulation results of director configuration as the initial condition for the current simulation. If not, the system will initialize the director configuration based on the surface alignment or vertical configuration.
Initial voltage: If check the box, the system will first run and relax the applied voltage without considering the LC configurations. If not, the system will load the voltage profile obtained from the previous simulation.

Display figures: If check the box, after the simulation, the results will be popped up as displayed figures. If not, figures will not be shown to reduce the memory requirement of system.

Fixed parameters:
There are several fixed parameters originated from the Fortran code of LC3D. The user can not revise these parameters unless the Fortran code is revised on these parameters and compile with the dll file for Matlab program again. The fixed setting includes: Dimension of simulation (2D in V-COPA program), the maximum size of the lattice in x, y and z axis. (sizex = 300, sizey = 10, sizez = 70)

Calculation methods:
Vector method: using nx, ny, and nz to represent the free energy of LC, the order parameter S is fixed. If check the option of using dynamics method, the system will employ the dynamics simulation of LC3D, instead of equilibrium simulation of LC3D.
Dickman’s Q tensor/Berreman’s Q tensor method: not applicable in the current version of VCOPA program.

- Optical control setting
The parameters as shown in Fig. 7.10 will be employed in the scalar optics simulation or Finite difference Time domain (FDTD) simulation. The settings include:

**Wavelength**: define the wavelength of incident Gaussian beam

**RHC or LHC**: define the polarization state of the incident light, right hand circular polarization or left hand.

**Beam width/aperture**: define the percentage of the clear aperture.

**Near field resolution**: define the grid size in the near field of the model

**Far field resolution**: define the grid size in the far field transformation.

**Far field angle range**: define the total angle range in the far field.

Several typical parameters are employed in the FDTD simulation as shown in Fig. 7.10.

- **Voltage pattern design**

  In the device setting panel, the user may choose which kind of LC materials to be used in the modeling, single frequency LC or dual frequency LC material. If choosing single frequency LC, click the voltage input panel, the voltage design panel will be popped up as shown in Fig. 7.11. If choose dual frequency, another two options will be displayed, one is voltage profile of dual frequency LC in equilibrium relaxation of LC3D as shown in Fig. 7.12. Another is defined based on the dynamics relaxation routine, as shown in Fig. 7.13. Step number is to define how many different voltage profiles are employed in the total simulation of the dynamics processing. Time delay is the parameter defined for the period of time for each applied voltage profile. It features the tuning speed of the system. If the LC director is able to follow the updating of applied voltage profile,
the time delay is the available response time, otherwise, the user has to modified the time delay to figure out the appropriate response time.

For single frequency voltage profile design, click input voltage button, the system will pop up the voltage input panel as shown in Fig. 7.14. Click each electrode number, the user is able to define the voltage value in the top and bottom substrate respectively. Additional reset function is provided to be easily access and control all the electrodes in top or bottom substrates. As for the equilibrium relaxation of dual frequency LC material, the voltage input is shown in Fig. 7.15. Each electrode has the inputs for both low frequency voltage value and high frequency voltage value on top and bottom substrate. As far as the dynamics relaxation is concerned to study the tuning speed of the V-COPA, the voltage input will be modified as Fig. 7.16. Several steps of voltage input are listed from the left to the right.

To check the input voltage profile on top or bottom substrate, click view voltage profile button, the system will pop up the current voltage design as shown in Fig. 7.17 (equilibrium modeling), and Fig. 7.18 (dynamics modeling). Given the designed voltage profile, click the button of “initialize the input voltage profile”, the program will actually apply the voltage profile to the lattice of model. For a single frequency LC, no low frequency voltage is required in Fig. 7.19(a), while the negative mode with high frequency field is shown in Fig. 7.19(b).

- **VCOPA OPM: LC3D simulation**
This function features with the numerical modeling of LC director configuration by LC3D from Fortran subroutine.

When the user click the VCOPA OPM button in the main window, based on the defined device settings, control settings, and the voltage profile applied to the system, the program will try to reach the equilibrium state of LC director configuration. At first, the system will initialize the director configuration (or load the previous director configuration if the related option is selected). A three domain surface alignment on top or bottom substrate is shown in Fig. 7.20(a) (top view) and Fig. 7.20(b) (side view).

Secondly, the LC3D will relax the applied voltage profile, and have an initialized voltage profile on the lattice, as shown in the side view of equi-potential field line in Fig. 7.21. According to the stopping condition, either convergence to the defined tolerance or reaching the maximum loop numbers, the program will obtain a final director configuration based on the designed voltage profile and surface alignment. For example, a typical liquid crystal polarization gratings is implemented in Fig. 7.22(a-b).

- **Run 2D scalar modeling**

With the simulated director configuration of liquid crystal cell, we may study the optical properties if incident a circular polarized light into the V-COPA cell. The program will automatically pick one whole period of polarization grating (from one left boundary to the next right boundary), duplicate the period by 5 times or more, perform the Jones calculus through the cell and scalar integral from the near field to far field. The phase retardation of LCPGs is closed to half wave of the light as shown in Fig. 7.23. The
deviation in Fig. 7.23 in some regions will cause the downgrade of the final efficiency. The near field intensity and phase profile are shown in Fig. 7.24(a, b). By scalar integral from the near field to far field, the final diffraction efficiency can be obtained in Fig. 7.24(c).

- **Run FDTD modeling**

  Since Dr. Bin Wang has developed a robust FDTD subroutine, we will simply load the subroutine to simulate the FDTD, and compare with the results from Scalar integral. Click run FDTD, the program will start the FDTD modeling panel as shown in Fig. 7.25(a). Load the modeled director configuration (in matlab data file with extension .mat) in Fig. 7.25(b), convert to the required format (data file with extension .dat) of the FDTD subroutine as shown in Fig. 7.25(c). Denote the directory to save the data, click “calculate” button, and the subroutine will perform the FDTD simulation and obtain the optical performance of the device.

- **Director draw**

  To investigate the LC director configuration, a simple tool named as director draw is shown in Fig. 7.26. The user can pick up and view the x-y, x-z, and y-z plane of LC director configuration that modeled by the VCOPA_OPM subroutine.

- **Polarized optical microscopy draw**
As shown in Fig. 7.27, to compared with the experiment results, a visualization tool of polarized optical microscopy draw is also one of the program’s features.

3. General simulation procedures

Based on the above functions of VCOPA v3.0, we can design or demonstrate a VCOPA device as shown in the flow diagram of Fig. 7.28.

4. Summary

In this section, we browse and surf the V-COPA v3.0 program programmed for the LCPGs device. With this user friendly program with GUI, the user can easily demonstrate the current design of liquid crystal polarization gratings, or propose, design, and develop other potential model. Since the program is based on the multi-domain surface alignment design and interdigital electrode pattern, the application of the V-COPA v3.0 is not only limited to the applications of LCPGs, other study can also employ this graphic program.
Fig. 7.1 Executable VCOPA_main.exe in the program folder
Fig. 7.2 Start the VCOPA program from Matlab editor
Fig. 7.3  Main window of VCOPA v3.0 program
Fig. 7.4 Device setting of VCOPA v3.0 program
Fig. 7.5  Save and load function of VCOPA v3.0 program
Fig. 7.6 Surface alignment design panel of VCOPA v3.0
Fig. 7.7 (a) Reset function of surface alignment

(b) Duplicate function of surface alignment
**Fig. 7.8** View table of surface alignment on electrodes and gaps

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### Table of Surface Alignment in Electrodes Region

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Fig. 7.9 Control settings of VCOPA v3.0 program
Fig. 7.10 Optical control settings of VCOPA v3.0 program
Fig. 7.11 Voltage initialization panel of single frequency LC
Fig. 7.12 Voltage initialization panel of dual frequency LC in equilibrium modeling
Fig. 7.13 Voltage initialization panel of dual frequency LC
in dynamics modeling
Fig. 7.14  Voltage profile settings in single frequency VCOPA
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Fig. 7.16 Voltage profile settings in dual frequency VCOPA in dynamics modeling
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Fig. 7.18  Voltage table of single/dual frequency VCOPA in dynamics modeling
Fig. 7.19  (a) Voltage pattern of low frequency field  
(b) voltage pattern of high frequency field
Fig. 7.20 (a) Top view of initial LC director configuration at one substrate; (b) Side view of initial LC director configuration
Fig. 7.21 Equi-potential field with high frequency voltage in x-z plane of dual frequency VCOPA
Fig. 7.22 (a) Top view of modeled VCOPA director configuration

(b) Side view of modeled VCOPA director configuration
Fig. 7.23 Phase retardation of VCOPA along x and comparison with half-wave retardation
Fig. 7.24  (a) Near field intensity pattern of VCOPA; (b) Near field phase profile of VCOPA;  (c) Far field intensity pattern of VCOPA
Fig. 7.25 (a) FDTD subroutine programmed by Dr. Bin Wang
(b) load the .mat file from VCOPA v3.0
(c) convert the .mat file to .dat file that can be used in FDTD
Fig. 7.26  LC director draw of VCOPA v3.0 program
Fig. 7.27  Polarized optical microscopy draw of VCOPA v3.0
Fig. 7.28  Flow chart diagram of VCOPA simulation procedures
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