APPLICATIONS OF PHASE AND AMPLITUDE SPATIAL LIGHT MODULATORS

by

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STATEMENT BY AUTHOR

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ABSTRACT

Spatial light modulators (SLM) have been widely adopted for applications such as optical data storage, optical tweezers, laser beam shaping including generation and detection of Optical Angular Momentum. In this thesis, we experimentally demonstrate two applications of Liquid Crystal (LC) SLM for eigenmode multiplexing for holographic data storage, and fast binary modulation by using MEMS and amplitude based SLM. In the holographic data storage system (HDSS) research, we successfully achieved nine holograms recording with angular multiplexing and eigenmode multiplexing methods using projector hacked low-cost SLM. In DMD (digital micromirror device) beam scanning, we realized beam scanning with single DMD binary amplitude holography and phase holography. With the phase modulator, total efficiency of the system reaches around 16% and is expected to be 32% with light recycling method. In the last part of the thesis, we also introduce our work on repurposing a commercial video projector as a $\pi$ phase-only SLM for our research. Phase modulation accuracy was tested with a Linnik microscope interferometer. Detailed modification procedures are given at the end of the thesis for future application of the projector hacked SLMs.
Chapter 1. Introduction

Spatial Light Modulators (SLMs) are widely adopted for applications such as optical data storage\cite{1-4}, optical tweezers\cite{5-8}, laser beam shaping including generation and detection of Optical Angular Momentum\cite{9-13}. SLM are implemented in liquid crystals (LC), Micro Electro Mechanical Systems (MEMS), Magneto-Optical (MO) materials\cite{14,15}. Due to the variety of implementations, SLM devices themselves are of interest in research community along with their applications. In this thesis, we experimentally demonstrate two applications of Liquid Crystal (LC) SLM for eigenmode multiplexing for holographic data storage, and fast binary modulation by using MEMS and amplitude based SLM. In Chapter 1, operations of LC SLM and MEMS SLM are overviewed. General principles of amplitude modulation and phase modulation are also described. Two applications that actively use SLMs are introduced with basic theory backgrounds. In Chapter 2, we describe our research on eigenmode multiplexing for holographic data storage system. Eigenmode were generated by using a projector hacked and low-cost phase-only SLM. Experimentally nine volume holograms were multiplexed in a single data location in the storage medium by employing eigenmode multiplexing. In Chapter 3, we introduced our research on improving beam steering angular resolution with DMD based scanning holography. We demonstrate a Computer-Generated Holograms (CGH) displayed on DMD are usable for beam scanning beyond its limitation in field of view. For the experiment, a DMD-based binary amplitude modulator and a binary phase modulator were built and tested. In our experiments, the we confirmed that latter has a higher output efficiency. Single sideband filtering method was used to remove unwanted patterns in diffraction. Meanwhile, we proposed beam recycling method to
further increase the output efficiency. In Chapter 4, we show our work on repurposing a commercial video projector as a phase-only SLM for research. Brief introduction of projectors is given. Phase measurements with a Linnik microscope interferometer were conducted on this homemade SLM. In the last chapter, conclusions of this thesis are included.

1.1 Introduction to a spatial light modulator (SLM)

SLM controls spatial variations on the properties of light. In the following context, we are going to stick to this definition and continue our discussion about the principles of amplitude and phase modulations on an SLM and their applications.

A plane wave is a homogeneous solution to free space Helmholtz equation\cite{16}. It has a simple form as

\begin{equation}
 f(\vec{r},t) = \tilde{A}(\vec{r},t)e^{i\phi(\vec{r},t)} \cdot \hat{u}
\end{equation}

Eq. (1) is the description of a field $f(\vec{r},t)$, which is a function of space and time. $\tilde{A}(\vec{r},t)$ describes the amplitude of the field and $\phi(\vec{r},t)$ carries the phase information. $\hat{u}$ denotes the polarization direction of the field. In most of the cases, the vector $\hat{u}$ denotes the polarization of the electric field, since many materials do not have a strong response to magnetic field. In the following subsections, the principles of amplitude and phase modulations are introduced.
1.1.1 Amplitude modulation

Amplitude modulation imposes variation on $\vec{A}(\vec{r}, t)$, while maintains the output phase unchanged. Mathematically, it can be understood as the incident wave multiplied by a real-valued attenuation function $M(\vec{r}, t)$.

$$g(\vec{r}, t) = M(\vec{r}, t) \cdot f(\vec{r}, t)$$

A typical use of amplitude modulation is using a SLM for display purpose, such as liquid crystal displays, projectors, and LED (light-emitting diode) displays, where light is subject to a spatially varying attenuation function. In angular spectrum theory,[17] the space and time modulated wavefront is no longer a single plane wave in free space, but can be expressed as a sum of a series of plane waves coming from different angles and of different wavelengths. Each plane wave solution satisfies the free-space Helmholtz equation and propagates individually. This process is described as diffraction and results can be predicted with different levels of accuracies when different approximations are used.

1.1.2 Phase modulation

Phase modulation is achieved by imposing phase retardance at different spatial location of the field. By changing $\phi(\vec{r}, t)$, it alters the shape of the wavefront in space. A classic example of phase modulation is plane wave focused to a point in space by a thin positive lens. When a collimated beam passes through the lens, each point of on the plane wave travels a different optical distance induced by the various thickness of the lens. An emerging wavefront at the back of the lens is thus
no longer a planar, but part of a spherical shell, with radius of $f$, the focal length of the spherical lens. For a positive lens, it delays the centre of the wavefront more and thus we have a converging wavefront – light focusing, as shown in Figure 1. An interesting property of a thin lens is the function of Fourier transform, in which the field at one focal length $f$ after the lens is exactly a scaled Fourier transform of the field emerges one $f$ before the lens[17]. This Fourier Transform property has been extremely useful in holography and optical information processing.

![Figure 1 Light focused by a thin positive lens[17].](image)

The phase of a signal is often expressed in the unit of radian. In optics, it is $2\pi$ times the ratio of OPL (optical path length) compared to the wavelength of the light (distance per cycle, or period)[18].

$$\phi = 2\pi \frac{OPL}{\lambda} \quad (3-1)$$

$$OPL = \int_{a}^{b} n(s)ds \quad (3-2)$$

$n(s)$ is the local refractive index of the medium and is a function of space. In an anisotropic medium, such as birefringence material, it is related to polarization and the incident angle in the
crystal coordinate, however, it is beyond the scope of the discussion. In an isotropic and homogeneous medium, the OPL is equal to \( n d \), where \( n \) is a constant refractive index. For a monochromatic wave, the wave repeats itself periodically. Therefore, we can wrap the phase to within \( 2\pi \), as shown in the Eq.(4). This property has been used in the design of diffractive optical elements (DOE) and wavefront reconstruction with SLMs.

\[
\phi'(\vec{r}) = \phi_0(\vec{r}) \ (mod \ 2\pi)
\]

(4)

### 1.2 Two types of SLMs

The most common types of SLMs are based on either LC (liquid crystal) or MEMS (Micro-Electro-Mechanical System). Depending on the design and material, both technologies are capable of amplitude or phase modulation.

#### 1.2.1 Liquid crystals and LCOS SLM

Liquid crystals are often used in phase SLMs, as they have crystal birefringence and the local permittivity \( \epsilon \) reacts to the local electric field rapidly, which results in changes of local refractive index. Hence, they can control the OPL of the light in time and space dynamically.

Historically, liquid crystal was accidently found by Austrian botanical physiologist Freidrich Reinitzer in 1888\(^{[19]}\), however, applications of liquid crystals in electro-optics emerged much later in 1960s. LC material experiences phase transition at different temperatures, from crystal solid at low temperature to isotropic liquid at high temperature. These phases also represent different degrees of positional and directional orders in the material (Figure 2)\(^{[20]}\). Among these phases,
smectic and nematic phases are often used in LC electro-optical devices. In nematic phase, LC molecules have low degrees of orders in/between layers and in orientation, while in smectic phase they have higher degrees of orders. Nematic LCs are often used in phase SLMs where continuous phase variations are desired. On the other hand, devices that use the ferroelectric property of SmC* LCs are capable of fast switching, though operation is limited only in binary phase mode (for example either at 0 or π phase).

Figure 2 Liquid crystal phase transition at various temperatures\textsuperscript{[20]}. When liquid crystal is used in a phase SLM, it is generally sandwiched between two transparent thin-film electrodes. They and can be further categorized into transmissive and reflective SLMs. Transmissive SLMs are easy to use which it can be inserted in the optical path without further modification of the system. However, due to the driver circuits and material absorption, transmissive SLMs have inheritably fill factors of less than one, as a result it suffers from low transmission efficiency. In contrast, reflective SLMs, especially LCOS (liquid crystal on silicon) SLMs, have higher efficiency because all the electrical structure is placed underneath of the reflective surface. A typical structure of an LCOS device is shown in Figure 3\textsuperscript{[21]}.  


Incident light passes through the cover glass, ITO (indium tin oxide) electrode, alignment layer, LC layer and another alignment layer in sequence, and then reaches the backplate which coated with aluminum. As a result, the reflected light passes these layers again and exits the device. The total reflectivity of an LCOS device is higher than 90% and due to the double pass structure, for a reflective SLM, it takes only half of the thickness of the LC layer on a transmissive SLM to delay the same amount of phase, resulting in a faster switching speed.

Furthermore, when thin layers of LC materials are used in a device, they can be arranged into different structures. Common structures include TN (twisted nematic), hybrid field effect, ECB (electrically controlled birefringence), SSFLC (surface-stabilized ferroelectric LC) and VAN (vertically aligned nematic), among which TN and VAN are good for display, but not suitable for phase modulation due to slow response time, small refractive index difference, and high threshold voltage\textsuperscript{[22]}. 

Figure 3 Schematic diagram of the cross section of a LCOS\textsuperscript{[21]}. 
1.2.2 Digital micromirror device (DMD)

While digital light processing, as known as DLP, is becoming a mainstream projection technology, research on the core component in a DLP system – DMD (digital micro-mirror device) – is also eye-catching. DMD is a MEMS (micro-opto-electromechanical system) based technology and was originally developed by Larry Hornbeck of Texas Instruments in 1997. Later, it was applied on projection system by Digital Projection Ltd in 1997[25–27]. They were both awarded Emmy Awards in 1998 for the DLP technology.

A DMD is a semi-static device, which uses technologies in solid-state physics and mechanics. It functions as a binary amplitude modulator by reflecting light selectively. When used in display applications, PWM (pulse-width modulation) technique is needed to attenuate light to different levels. There are millions of pixels on a DMD array. These pixels are micro Galvo mirrors which connect to the base via hinges and can swing from one side (+12°) to the other (−12°) with the control of the static electric field, shown in Figure 4. Except for being turned off, when all of them park at 0°, these mirrors won’t pause at other angles in normal situation.

Owe to the light weight and stiffness of the material, these pixels can complete a round trip, which
flips from one side to the other and restores, in less than 0.25 ms and resonates at over 4 kHz. In some high-end models, the frequency can go over 22 kHz, which provides much faster modulations compared to liquid crystal devices. Besides, a DMD is broadband applicable, since the reflectivity of the micromirrors is independent of wavelengths, polarizations and phases of the incident light as far as an appropriate mirror coating material is employed. While liquid crystal devices are sensitive to the working temperature, a DMD can sustain high working in extreme temperature condition, ranging from −40°C to 105°C[27], which makes DMD technologies very robust for applications involving wide working temperature range, incoherent illumination, fast switching or stable modulation.

An interesting type of applications uses the periodic geometry of the DMD[28]. When all the pixels are flipped to one side, the device essentially becomes a reflective blazed grating and can steer most of the energy into a specific diffraction order. The angular spacing between orders is governed by the grating equation[17].

\[ m\lambda = d\left(\sin\theta_i + \sin\theta_r\right) \]  

(5)

where \( \lambda \) is the wavelength of the incident light. \( \theta_i \) and \( \theta_r \) are incident angle and reflective angle, respectively. The DMD was illuminated with a 532 nm CW laser. At power-off state, the 0th order has most of the diffracted power. When all the mirrors are at 12°, light was diffracted into 12°, while the spacings between orders remain the same. Moreover, if we illuminate a DMD with a pulsed laser, we can take snapshots of these mirrors and freeze them in a specific angle between
−12° and 12°. Therefore, \( \theta_i \) is now a variable and so is the blazed angle – we can steer light into arbitrary diffraction orders.

1.3 Related applications

SLMs have been broadly applied to various fields, such as display, adaptive optics, holography, laser beam shaping and optical data processing. In this paper, we cover two major applications where SLMs are frequently used.

1.3.1 Digital holography with SLMs

Holography was proposed by Dennis Gabor in 1948\(^{[29]} \). It is a lensless imaging process which a wavefront can be recorded and reconstructed. Surprisingly, the initial motivations to develop holography were related to microscopy instead of the three-dimensional imaging and display trending these days.

In the process of wavefront recording, reference beam and signal beam are generally required. They can be expressed as the following correspondingly\(^{[17]} \)

\[
A(\vec{r}) = |A(\vec{r})| \exp[i\psi(\vec{r})] \quad (6-1)
\]

\[
a(\vec{r}) = |a(\vec{r})| \exp[i\phi(\vec{r})] \quad (6-2)
\]

The signal beam contains phase and amplitude information of the object to be recorded. The hologram, is the intensity of the sum of the fields and is expressed as
\[ I(\vec{r}) \propto |A(\vec{r})|^2 + |\alpha(\vec{r})|^2 + 2|A(\vec{r})||\alpha(\vec{r})| \cos[\psi(\vec{r}) - \phi(\vec{r})] \]  

(7)

The recording medium can respond linearly to the intensity of light. Suitable materials including photopolymers, dichromated gelatine, photorefractive materials. In digital holography, intensity is recorded with detector array and stored as digital image data. Transmittance of the exposed medium can be expressed as

\[ t_A(\vec{r}) = t_b + \beta'(|a|^2 + A^*a + Aa^*) \]  

(8)

where \( t_b \) is a uniform bias of the transmittance, \( \beta' \) is the responsivity slope.

In the process of wavefront reconstruction, both reference beam and signal beam are removed. A reconstruction beam illuminates the medium and reconstructs the object wavefront. Assuming the reconstruction beam \( B(\vec{r}) \) is the same as the reference beam \( A(\vec{r}) \), we can obtain the reconstructed field by multiplying \( B(\vec{r}) \) and \( t_A(\vec{r}) \).

\[ B(\vec{r})t_A(\vec{r}) = t_bB + \beta'aa^*B + \beta'A^*Ba + \beta'ABa^* \]  

(9)

If \( A = B \), the third term becomes \( \beta'|A|^2a \), which is a reconstructed object wavefront scaled with a constant. Since \( a \) is diverging, this wave forms a virtual image. However, if we illuminate the medium with \( B^* \), the conjugate of \( B \) and is equal to \( A^* \), the fourth term becomes \( \beta'|A|^2a^* \), which reconstructs the conjugate of \( a \) and forms a real image at the opposite direction.
The use of SLMs in digital holography provides huge benefits and conveniences. Computer-generated holograms (CGH) can be displayed on a SLM and reconstructed with optical setup in real time.

1.3.2 Beam steering with SLMs

Research on lidar or light detection and ranging systems has been growing as autonomous driving and robotics become popular. In a lidar system, laser beam steering is important as it is one of the major factors that limiting the speed and resolution of information acquisition. Mechanical beam steering methods have been used for broad spectrum applications, however, they tend to be heavy, bulky, and expensive, and thus is not suitable for many systems that have a small form factor. Smith et al. proposed a beam steering method with DMD, which completes light emitting and receiving with a single DMD, and can achieve 23k points acquisition per second while maintains a field of view (FOV) over 65°[28]. Another beam steering method uses holography which steers beams to arbitrary angle within spatial frequency limit. This limit is determined by the sampling theory and has a much narrower FOV compared to DMD scanning method. However, holographic beam steering is capable of random access and infinite angular resolution. A more detailed explanation is in section 4 in this paper.

1.4 Summary

In this chapter, we introduced the theories of amplitude modulation and phase modulation. Two types of spatial light modulators (SLM), liquid crystal SLM and DMD, are explained. While liquid crystal SLMs are capable of analogue phase modulation, it is generally slower and unstable. In
contrast, DMDs can modulate the amplitude of light at much higher frequencies and can work in extreme conditions, yet, it can only operate at binary modulation. We also introduced the principles of several applications where SLMs are often used. They will be further explained in the following chapters.
Chapter 2. LCOS Phase SLM in volume holographic data storage system

2.1 Volume holographic data storage

2.1.1 Technology overview

Information storage and reconstruction has always been a major research topic of holography. The capability of wavefront reconstruction allows this technique to store three-dimensional scene – a distinct feature compared to photography. The concepts of information storage by using holography for a data storage application were proposed by van Heerden in 1963. He estimated the storage density of holographic data storage is $V/\lambda^3$, where $V$ is the recording volume. Later, Leith and Upatnieks applied communication theory to holography. Leith and his colleagues demonstrated multiple image recording by rotation the recording medium. There are many advantages in volume holographic data storage system (HDSS) over bit-by-bit based data storages. Firstly, as a holography based imaging technique, HDSS is naturally a redundant storage system. The recording and reconstruction of holograms is a process of interference and diffraction. When a 2D hologram is being recorded, every point on object emits an expanded wavefront and it interferes with the reference beam. Thus, the interferogram for each object point smears across the recording medium, meaning that, we can reconstruct the object wavefront with any part of the hologram. As a result, deterioration of recording medium, such as surface scratch, dose not completely erase information. In volume holography, the interference not only occurs on the surface, but also extends to different depths of the medium, adding an additional degree of redundancy.
The second advantage is that HDSS uses volume holograms to storage data. Volume hologram or thick hologram has a low tolerance for reconstruction angle mismatch – angle offsets between the signal beam and the reconstruction beam. On a plane hologram or thin hologram, reconstruction beam can have a large angle mismatch. However, on a thick hologram, due to the thickness of the hologram, a more complicated scattering effect occurs as light interacts with the medium. This effect, Bragg selectivity, greatly limits the amount of angle mismatch\[32\]. When it occurs, the diffraction efficiency of that hologram reduces tremendously. Using this phenomenon, we can record multiple holograms with beams from different angles, which is called multiplexing of holograms, and they have low cross-talk. Generally, binary data are arranged into binary data pages. A signal beam carries the data page and interferences with the reference beam, leaving a volume hologram in the medium. We can multiplex multiple pages at the same location with various multiplexing techniques\[33\]. These pages multiplexed in one location together are called a book\[34\]. This data arrangement gives rise to the high data transfer rate of a HDSS system, since data are always read and written in pages.

Other than the advantages listed above, HDSS is capable of associative data retrieval\[1\]. In volume holography, if a reconstruction beam same as the signal beam is used, the reference beam wavefront can be reconstructed. In associative retrieval, searching for a data page can be done by illuminating the pages with part of the signal. It is a cross-correlation process and a strong signal returns if the data pages match.

Although such advantages are widely recognized, the development of holographic storage system is not easy. For almost half a century, academic and industrial research has been widely
undertaken. Many labs such as Bell Labs, IBM, RCA Laboratories, 3M, Hitachi, and NEC had tried to build and improve this technology, however, only few complete demonstrations have been made, since many new technologies are required, such as new recording media, new light sources, new detection devices and methods, and so on.

In HDSS, one important data multiplexing method is angular multiplexing. It records different data pages at different reference beam incident angles. Due to volume hologram Bragg selectivity, data pages can be read out with low cross-talk. However, due to angle degeneracy, the holograms can only be recorded within $180^\circ$. Half of the angle space is wasted and storage density is limited.

One solution was proposed by [35], in which eigenmode multiplexing was used in addition to angular multiplexing. Cross-talk of eigenmode multiplexing is also a factor of 2 lower than angular multiplexing. In that research, static phase plates have been used to generate Hermite-Gaussian modes. 2.5% readout cross-talk is obtained. However, mode switching requires mechanical movements. Accuracy and response time are greatly limited. Therefore, in this thesis, we are willing to demonstrate our work on using a low-cost projector SLM on the reference arm to realize eigenmode volume hologram multiplexing where no mechanical movement is required.

2.1.2 Explaining the system

From the view point of optical recording architecture, HDSS is an interferometer, in which the two interfering arms are called signal beam and reference beam. In the signal arm, a page composer is inserted to change the data to be written. Traditionally, it is an amplitude modulation device such as amplitude only LC-SLM or DMD. In the reference arm, some mechanisms are used to change
the properties of the beam, such as distribution of k-vectors, and wavelength, depending on the multiplexing methods being used. For example, a galvanometric mirror would be applied if angular multiplexing is used; a phase SLM would be used if cross-correlation based multiplexing techniques are used. The fields are Fourier transformed by microscopic objectives and intersect in the medium, forming volume holograms. In readout process, signal arm is turned off and a probe beam illuminates the target locations. Diffracted light of the data page is then collected by a sensor array.

2.1.3 Bragg selectivity and diffraction efficiency

The phenomenon of Bragg selectivity of volume hologram plays an important role in volume holography. In case for angle multiplexing, the Bragg selectivity is expressed as

\[ \eta = \frac{|E_d|^2}{|E_p|^2} = \left( \frac{\epsilon_1 k L}{2 \epsilon_0 \cos(\theta)} \right)^2 \text{sinc}^2 \left( \frac{2L(\Delta \theta) \sin(\theta)}{\lambda} \right) \]  

(10)

(\eta) is the diffraction efficiency of the holograms. Here \( \epsilon_0 \) is the dielectric constant of the material before exposure and \( \epsilon_1 \) is the variation of the dielectric constant in the exposed region (hologram). By Born’s approximation, \( \epsilon_1 \ll \epsilon_0 \). This theory is only valid in weak modulation and is violated for strong grating. \( \theta \) is the incident angle of the signal and reference beam, while \( \theta_p = \theta + \Delta \theta \) denotes the angle variation of the probe beam, where \( \Delta \theta \) is called the detuning angle. \( L \) is the thickness of the medium and \( k \) is the wavenumber. The diffraction efficiency is at its maximum when amount of detuning is zero, and it drops to its first zero as the angle increases, following the
sinc-squared function. More holograms can be written at these zero-efficiency angles to reduce inter-page cross-talk.

### 2.2 Multiplexing methods used in this research

In general, multiplexing techniques in volume holography can be classified into three categories: Bragg based, momentum based, and correlation based methods\textsuperscript{[36]}. In our research, we used angular multiplexing and eigenmode multiplexing, which are Bragg based methods.

#### 2.2.1 Angular multiplexing

As is introduced in chapter 2.1.3, angular multiplexing utilizes the Bragg selectivity of volume hologram. Hologram pages are recorded in the same location in the medium and orientated at a specific angle spacing.

![Figure 5](image)

Figure 5. An example of diffraction efficiency versus angle displacement of a volume hologram\textsuperscript{[33]}

The $|\text{sinc}^2(\cdot)|$ curve is obtained for $\lambda = 488$ nm, medium thickness $L = 1$ mm, and incident angle $\theta = 20^\circ$.

The angle spacing is the spacing between the zeros on the sinc-squared function. It is determined by the wavelength $\lambda$ of the incident light, the thickness of the hologram, $L$, and the recording
geometry. As L goes up, capacity goes up as well in theory, but with a ceiling as previously stated. However, due to angle degeneracy, angular multiplexing can only utilize an angle space of $\pi$.

2.2.2 Eigenmode multiplexing

Eigenmode multiplexing is effectively an angular multiplexing process where multiple beams interfere at multiple angles at the same time during recording and reconstruction. It is realized by modulating the phase of the reference beam. From the perspective of angular spectrum, variations of the field can be decomposed into plane waves at different angles. Each of the plane waves interferes with the signal beam and thus many grating are formed in exposure. In reconstruction, if the probe beam is modulated with the same phase code, the diffracted fields of these grating will interfere constructively and reconstruct the signal with high efficiency. If other phase codes are applied, deconstructive interference dominates and reduces the efficiency severely – no or small signal is retrieved. The quality of this selectivity largely depends on the orthogonality of the phase code imposed and the accuracy of phase modulation.

Reconstructed field by eigenmode multiplexing method is described as the cross-correlation function of the writing reference beam and reconstructing probe beam. The cross-correlation of the arbitrary complex field $h$ and $g$ in grating space can be expressed as following$^{[35]}$.

$$ (g \otimes h)(\vec{k}) = \int_{\mathbb{R}^3} g^*(\vec{k} - \vec{k})h(\vec{k})d\vec{k} \quad (11) $$

For orthogonal functions indexed by two mode numbers, the following relation is satisfied.
\[
\langle g_{n,m} | g_{p,q} \rangle (\vec{k}) = \int_{\mathbb{R}^3} g_{n,m}(\vec{k}) g_{p,q}^*(\vec{k}) d\vec{k} = \delta_{n,p} \delta_{m,q}
\]

(12)

where

\[
\delta_{n,m} = \begin{cases} 
0, & n \neq m \\
1, & n = m 
\end{cases}
\]

(13)

Hence, theoretically, the correlation coefficients between fields that are described by a collection of orthogonal functions will be zero and thus it is possible to multiplex holograms with orthogonal beams with low cross-talk.

2.3 Experiments

In our experiment, we recorded nine holograms in a single location with angular and eigenmode hybrid multiplexing. At the end of the experiment, we can read out different holograms by changing the angle of the incident beam, or by changing the phase displayed on the SLM. 38\% inter-page cross-talk was measured.

On the reference arm, a phase-only Liquid Crystal on Silicon (LCoS) SLM (0.7-inch SXGA+, JVC, Japan) extracted from a commercial projector (REALiS SX50, Canon) was incorporated with a 90° corner cube (Figure 7)\(^1\). The SLM has an 8-bit grey scale corresponds to 0 to \(\pi\) phase modulation at 532 nm (shown as inset in Figure 7) and the resolution of the SLM is 2500 pixels per inch. More details are explained in Chapter 4.

\(^1\) Information about this LCOS and projector is in Chapter 4 and Appendix A.
The SLM was placed outside the Rayleigh range of the incident beam to perform Fourier transform of the phase pattern on the SLM. On the SLM, the phase of the reflected light was modulated by the phase retardance of the pixel where the light hits. Grey levels $0 \sim 255$ are linearly mapped to $0 \sim \pi$ phase retardance. Grey level 0 (colour black) indicates no phase modulation on the corresponding pixels, while 255 (colour white) indicates $\pi$ phase retardance on the corresponding pixels. Phase detection result is shown in the inset of Figure 7. Fringes in the central region are shifted half wave, corresponding to the $\pi$ phase retardance of the SLM. Modulated reference beam interferes with the signal beam in a $10 \times 10 \times 20$ mm$^3$ Fe:LiNbO$_3$ crystal (Deltronic Crystal Industries). An iris was used to block unwanted light in the reference beam. A $\lambda/2$ plate converted the polarization of the object to that of the reference beams. In the reference path a $f = 50$ mm lens was inserted between the iris and the crystal to match the sizes of the object and reference beams in the crystal. The beam waist of the reference beam was located at the centre of the recording medium.

![Figure 6 A USAF target plate pattern](image)

This setup uses Fourier-plane recording geometry. On the signal arm, the Gaussian beam was expanded and illuminates a USAF target plate (Figure 6). A microscope objective (#80.3020, Rolyn Optics) was used to perform Fourier transform of the signal. Field of spatial frequencies was located at the beam waist of the transformed beam, intersecting the reference arm at the centre
of the crystal. An additional camera was placed after crystal to capture the signal and measure the normalized cross-talk of the experiment.

![Experimental setup](image)

**Figure 7.** Experimental setup
Inset: phase detection result

We started our experiment by generating Hermite-Gaussian modes with the phase-only SLM. Results are shown in Figure 8. The pattern in (a) was generated by a static phase plate and the pattern in (b) was generated by the SLM. By comparing the valley of the intensity profiles, the mode generated by the phase plate is closer to the ideal HG10 mode. The latter was converted by the SLM. The shallow valley in (b) indicates that there is a substantial mode cross-talk.
Figure 8. Comparison of phase plate and SLM HG$_{10}$ mode conversion results

(a) is the mode conversion result of static phase plate and (b) is that of the LCoS SLM. In terms of intensity profile, mode in (a) is closer to pure HG$_{10}$ mode. The shallow valley on the profile in (b) indicates that there is severe mode cross-talk.

This problem is often seen in inline holography wavefront reconstruction, in which the desired patterns overlap with the zero-frequency component. Besides, there is light reflected from other optical surfaces such as beam splitter, waveplates, and lenses. To improve purity of modes, in our experiments, we added a square-wave grating phase on top of the original phase patterns. From the perspective of angular spectrum theory, the eigenmode pattern is the spatial spectrum of the field, while the grating is a carrier wave. It moves the field spectrum to an off-axis angle, and thus separates the eigenmode pattern from the unwanted images. Figure 9 shows phase profiles on SLM and corresponding intensity profile. Three phase profiles, HG$_{00}$, HG$_{10}$ and HG$_{20}$ are displayed on SLM. For HG$_{20}$, the centre portion of SLM has a width d. The beam profile of the improved result is shown in (b).
In (a), the first row shows the phase patterns for different Hermite-Gaussian modes. The second row shows those with a grating phase added. The third row shows the mode conversion results. Colour red denotes the peak of the intensity. (b) shows an improved result with grating phase added.

As the grating period increases, diffraction efficiencies of $+1^\text{st}$ and $-1^\text{st}$ orders increase due to lower pixel cross-talk induced by liquid crystal fringe-field effect, however, the diffraction angle decreases. In our experiment, a grating period of 4 pixels (41.6 $\mu$m) produced 31% diffraction efficiency of the grating. Relevant work done by Márquez et al. shows that the low diffraction efficiency is due to the loss of phase and is related to the period of the grating$^{[37]}$. Mode conversion results are monitored by the beam profiler (WinCamD-UCD23, DataRay).

When generating HG$_{20}$ mode, the width of the central region was optimized to reduce cross-talk between modes. To determine the optimum width of this region, we evaluated cross talk as a function of the central width of the $\pi$ region that can yield the lowest cross-talk. Firstly, a hologram was written with HG$_{00}$ beam. Then, the hologram is constructed by HG$_{20}$ beams with a different
central region width. A CMOS camera (DCC1545M, Thorlabs) with a fixed exposure time is used to measure the diffracted power. Finally, we could plot a curve that indicates the setting where the least cross-talk occurs, as shown in Figure 10.

![Figure 10. Intensity curve of hologram written with HG00 beam and read with HG20 beam](image)

This curve was measured with increasing width. The minima of the curves are located at around 44 pixels; however, we can observe intensity drops as the width increases over 60 pixels.

Since the LiNbO3 is a volatile material, the reading process bleached the hologram gradually. We can expect a decrease in diffracted power and inaccurate reading. To address this data bias, measurement with reversed steps were conducted, shown in Figure 11.

![Figure 11. Reverse measurement with decreasing steps](image)

Local minima can be found at 44 pixels, which confirms the result in Figure 10.

Similarly, we wrote the hologram with HG10 and then read it by HG20 modes. The lowest cross-talk for both measurement occurs at width of 44 pixels (457.6 μm). This setting was used in our further recording experiments.
2.4 Experimental result analysis

In this experiment, a total of nine holograms are multiplexed by using three orthogonal modes at three different angles. Recording results are shown in Figure 12. In experiments, a 0.6° angle increment is used for angular multiplexing\cite{35}. The images in the dotted lines are the objects, indicating the locations.

As we can see in Figure 12, the implementation of SLM can still maintain a reasonable recording quality in the experiment where high frequencies can be captured and reconstructed. However, compared to eigenmode multiplexing with static phase plates, noticeable cross-talk between modes was observed\cite{38}.

The cross-talk was measured after all the pages were recorded. When the medium is illuminated with HG\textsubscript{20} mode at angle 0, ideally, only one hologram should be reconstructed. However, when cross-talk occurs, information on other pages is also detectable. Our measurement detects the amount of data and thus defines the amount of cross-talk. Cross-talk measurement results are shown in Table 1, where up to 38% cross-talk is observed. Besides, with SLM, eigenmode multiplexing cross-talk is more obvious than angular multiplexing cross-talk.
Figure 12. Nine holograms recorded and reconstructed with angular and eigenmode hybrid multiplexing. Corresponding original signals are placed as insets in the corners of images.

<table>
<thead>
<tr>
<th>Angle Multiplexing (Degree)</th>
<th>HG₀₀</th>
<th>HG₁₀</th>
<th>HG₂₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>0.6</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>1.2</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Table 1. Mode Cross-talk (Readout with HG₂₀ mode)

<table>
<thead>
<tr>
<th>Readout angle (degree)</th>
<th>HG₀₀</th>
<th>HG₁₀</th>
<th>HG₂₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>37.8</td>
<td>34.1</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
<td>26.2</td>
<td>26.8</td>
</tr>
<tr>
<td>1.2</td>
<td>1.2</td>
<td>21.9</td>
<td>23.9</td>
</tr>
</tbody>
</table>

From Eq. (12) we may infer that a lack of orthogonality between modes attributes to the high cross-talk. Also, the sizes of the reference beam and signal beam account for some cross-talk, since they are no longer the eigenfunctions to a defined problem. At the beam intersection point in the
medium, to capture most of the frequency information of the object, the reference beam should be slightly larger than the signal beam, but it shouldn’t be much larger considering the power density of the beams with given input power. In that case, if the HG$_{00}$ mode is well calibrated, as the mode number increases, the size of the reference beam will inevitably be even larger than the signal beam. The mismatch of the sizes will reduce the orthogonality of fields and thus the condition in Eq. (12) is no longer satisfied. Another factor is that the phase patterns are not calibrated and thus we expect that these eigenmodes are not completely orthogonal to each other. At last, according to [39], factors including loss of phase modulation depth, phase linearity and insufficient spatial resolution of the SLM can lead to phase distortion, which impairs the orthogonality of the modes. The fly-back phenomenon in liquid crystal pane can substantially distort the phase patterns. In other words, the panel is a low-pass filter where high frequency phase variations will not pass. The 31% diffraction efficiency (40.5% in theory) of the square-wave grating indicates that phase loss occurs. Simulations and measurements should be carried out to further validate the orthogonality of eigenmodes and quantify the cross-talk. Cavity eigenmode enhancement can be applied to lower the cross-talk.

2.5 Summary

In this chapter, research on dynamic reference beam modulation with phase-only LCoS SLM was demonstrated. A series of improvements, including reflection reduction by adding grating phase and phase pattern calibration, are brought in to enhance the performance of the SLM. Recording experiment with angular multiplexing and eigenmode multiplexing methods are conducted, recording nine holograms in total. On average, 38% mode cross-talk is observed. Despite the high
cross-talk, the implementation of SLM in reference beam phase encoding is considered feasible, given that a non-professional SLM and uncalibrated phase patterns are used. Further simulation and measurements should be carried out to address the cross-talk issue.
Chapter 3. Beam Steering with DMD

3.1 Beam steering methods

Over the years, beam steering technology has evolved a lot. Applications include laser printer, optical communication system, microscopes, laser processing, and a lidar. Such beam steering technologies are categorized into full-mechanical, limited-mechanical, and non-mechanical beam steering methods.

Mechanical beam steering methods use mirror to deflect beam to the desired angles. Common systems include Galvano mirrors, Risley prisms, rotating polygons and gratings\textsuperscript{[28]}. These methods are capable of fast steering. They tend to have high beam deflection efficiency, high power damage threshold over a broad spectrum. However, due to the large inertia of the components, these methods have in general poor random-access capability. Moreover, when mounted on moving platforms, such as vehicles or aircrafts, where immense vibration occurs, the performance of these methods can be greatly compromised.

Limited-mechanical steering mitigate the issues in full mechanical steering methods, yet, they didn’t truly solve the problems we mentioned above. The limited-mechanical methods introduce angle magnifying mechanisms. To increase the system stability, these methods limit the motions of the mechanical components, but magnify the small scan angles with afocal optics instead. Common systems include cascaded microlens arrays, or cascaded liquid crystal microlens arrays, flexure beam micromirror, and roving fovea. While small movements are enlarged, the movement errors are also magnified. Besides, the integration density is low on many systems.
Non-mechanical methods are getting increasing attentions nowadays, since many applications require the steering modules to be compact, low power consumption and light weighted such that they can be installed in robotic arms, vehicles, handheld devices and so on cost effectively. Conventional non-mechanical steering methods include acousto-optic deflector and electro-optic deflector. These methods are capable of fast switching and random-access. Since there is no moving part, these systems are very stable and immune to vibration. However, these systems have small field of view and induce optical frequency shift. Some operations at high-voltage and spread noise to the surrounding. Besides, they are not compact.

Recently research on phased array beam steering has gained many progresses. Phased array has been used in microwave radar systems for long. The array is formed by source clusters. Using the knowledge of wave interference, by tuning the phase delays between sources, one can precisely aim the location where the strongest constructive interference occurs. This technology is capable of fast switching and random access. It can sweep a large angle and can also scan in depth. However, phased array in optical regime is hard to achieve, because the wavelengths of light are many magnitudes smaller than those of microwave. The size of the sources as well as light guiding structures, therefore, must shrink as well as to meet the large sweep angle requirement. Shirasake et al. proposed VIPA, virtually imaged phased array, and achieved ~30° FOV[^40]. Yaacobi et al. achieved 1D steering with photonic phased array controlled by thermos-optic effect and achieved 51° FOV with continuous 100 kHz steering speed[^41]. Sun et al. created nanophotonic phased array (NPA) capable of 2D beam steering[^42]. These devices use CMOS process, which is compatible with the current semiconductor manufacturing technology. Although output power is still not high
enough for many applications, nanophotonic phased array is a promising beam steering method. As an extension of current LC-based beam steering technology Davis et al in Vescent Photonics demonstrated a new type of liquid crystal beam steering device which uses light in -plane propagation to deviate light to other angles\(^{[43]}\). However, the speed of modulation is greatly limited by the liquid crystal molecule time response.

Another novel beam scanning method uses DMDs. Smith and Hellman et al. demonstrated a single chip DMD beam steering method\(^{[11,29]}\). Different types of lidar systems based on the DMD scanning technique have been demonstrated based on the demo. As is introduced in chapter 1.2.2, the mirror array functions like a blazed grating with variable blazed angles. By precisely synchronizing the pulsed laser and the DMD frame, one can equivalently freeze the mirror array at a specific angle between \(-12^\circ\) and \(12^\circ\), and thus steering beams to different directions. Although many diffraction orders can be observed, as a blazed grating, most of the energy will fall on the blazed order and diffraction efficiency is as high as 90%. This method combines the advantages of DMD technology we mentioned previously and can output much higher power than phased array. Compared to conventional mechanical beam steering devices, DMD scanning devices are compact and power efficient. Cost can be greatly reduced with mass production.

Although a DMD scanning device can sweep beams over a large angle, the angular resolution is constrained by the DMD scanning frequency and the laser pulse repetition rate. In this chapter, we will introduce a holographic beam steering method that can further increase the angular resolution of the DMD beam scanning device.
3.2 Beam steering with binary amplitude gratings on a DMD

Essentially, beam steering with DMD holograms is the reconstruction of wavefronts by an amplitude hologram. A hologram is illuminated by an incident beam, which also is the reconstruction beam, the reconstructed wavefront would propagate to the desired direction and thus beam steering is achieved. To generate the holograms, we used a virtual hologram recording process in which we defined the reference wavefront and the signal wavefront in the computer program. The DMD is considered as a recording medium and placed in the interfering region. All parameters match the physical environment.

In our research, a DMD device (DLP3000, Texas Instruments) is used for hologram display. The dimensions of the DMD are labelled on Figure 13 (a). Configurations of the DLP3000 model are listed in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (diagonal)</td>
<td>7.62 mm</td>
</tr>
<tr>
<td>Dimensions (W × H)</td>
<td>6571.8 μm × 3699 μm</td>
</tr>
<tr>
<td>Resolution (W × H)</td>
<td>608 × 684</td>
</tr>
<tr>
<td>Micromirror pitch</td>
<td>7.6 μm</td>
</tr>
<tr>
<td>Micromirror tilt angle</td>
<td>±12°</td>
</tr>
<tr>
<td>Maximum FPS</td>
<td>4000 Hz</td>
</tr>
</tbody>
</table>

It is worth mentioning that the micromirrors are tiled with each square mirror rotated 45° (diamond shape). Therefore, a column of digital frame pixels is displayed by two columns, one blue column
and one red column, of micromirrors in a “zig-zag” sequence as labelled on Figure 13 (b). In such layout, the row pitch is half of the column pitch. The former is 5.4 μm and the latter is 10.8 μm.

Figure 13 Texas Instruments DLP3000 DMD dimensions.

and (b) are adapted from Fig. 6 in [45]. In this micromirror layout, the row pitch is half of the column pitch. The former is 5.4 μm, while the latter is 10.8 μm. The green “zig-zag” pixel chain denotes the micromirrors that used to display one image pixel column.

In our program, a cartesian coordinate is built with its origin at the central pixel of the DMD. The k-vectors of the signal beam and the reference beam are defined on this coordinate, shown as the following.

Figure 14 A Cartesian coordinate established on the DMD.

On this coordinate, the k-vectors of the reference beam and the signal beam are defined as
\[ \vec{k}_p = k_p \hat{z} \]  

(14–1)

\[ \vec{k}_s = k_s \left( \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z} \right) \]  

(14–2)

Two plane waves are thus defined with the two k-vectors. So long as the spatial coordinates of all the pixels are defined, the interferogram would be sampled by these pixels. Some examples are shown in Figure 15.

Figure 15 Holograms for various steer angles. The denser the fringes are, the larger the steer angle is. However, the grating frequency cannot exceed the sampling frequency of the DMD.

The maximum steer angle is limited by Nyquist-Shannon sampling theorem. At least two pixels are required to represent a varying signal. Therefore, the maximum spatial frequency is

\[ k_{\text{max}} = \frac{1}{2 \Delta x} \]  

(15)

By diffraction theory, it is known that

\[ k_{\text{max}} = \frac{x_{\text{max}}}{\lambda z} = \frac{\tan \theta_{\text{max}}}{\lambda} \approx \frac{\theta_{\text{max}}}{\lambda}, \quad \theta_{\text{max}} \text{ is small.} \]  

(16)
where \( \Delta x \) denotes the pixel pitch and \( \Delta x = 7.637 \ \mu m \) on this device. \( k_{max} \) is equal to \( 6.547 \times 10^4 \ \text{m}^{-1} \). Hence, when illuminated with 532 nm coherent light, \( \theta_{max} \) approximates \( \pm 2^\circ \), meaning that in our virtual recording process, the angle between the signal beam and the reference beam should be less than \( \theta_{max} \) to prevent undersampling. Otherwise, aliasing occurs.

### 3.2.1 Experiments

A test setup is built based on Figure 16. The DMD was illuminated with 532 nm laser. The beam was expanded and fully covered the DMD surface.

![Figure 16 DMD binary amplitude modulator test setup](image)

A test was carried out by displaying a binary amplitude hologram on the DMD. The hologram used can be found in the software from Holoeye SLMs. It is not designed for a DMD amplitude modulator. The ideal far field pattern should be a square. The test result is shown in Figure 17 (a). Multiple images were formed on the screen. The twin images are not easy to observe, since the conjugate image is diverging and projects a blurry background. Aliasing occurs where we can see patterns of diffraction orders overlapped. A zero-frequency term, or DC (direct current) term, can be seen spotted in the centre of the field.
In (a), arrow 1 and 2 indicate the image and the twin image respectively; arrow 3 indicates the aliasing phenomenon; arrow 4 indicates the DC component of the field; arrow 5 indicates the higher diffraction orders. In (b), arrow 1 indicates the desired image in the 0th order; arrow 2 and 3 indicate the image in adjacent order; arrow 4 indicates the DC component. Arrow 5-7 indicate the conjugates (twin images) of the images pointed by arrow 1-3.

In our experiment, we uploaded 96 holograms to the SRAM on the DMD to achieve high speed scanning. The desired pattern is pointed by arrow 1 on Figure 17 (b) and was moving from the left of the field to the right. The other patterns are the DC component and conjugate components of the field. Aliasing occurred as we can see the pattern of the adjacent orders locates closer to the DC term. They can be easily removed by limiting the steer angles. Since the reconstructed image is a plane wave, the twin image is therefore a plane wave and can be easily seen in the experiment.

3.2.2 Twin image removal and light recycling

To eliminate the unwanted components, an approach proposed in [46] is applied. Instead of letting the light propagate to infinite distance, a 4-f system was inserted in our system to perform spatial filtering. Since all the components are plane waves at different angles, they are focused to different
locations on the intermediate image. A spatial filter (band-pass filter) is then used to select the desired pattern.

Another issue in holographic beam steering is a low diffraction efficiency due to amplitude based modulation. The holograms displayed on the DMD are effectively Ronchi gratings and theoretically, the 0\textsuperscript{th} order occupies the highest diffraction efficiency, 25\%, while the desired pattern and its conjugate share 20.2\% of the incident light. However, in practise, the efficiency is much lower than 10.1\% because of the DMD fill factor is less than 1.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{DMD_array.png}
\caption{Drawing of a DMD array.}
\end{figure}

The fill factor is less than 1. A micromirror doesn’t span all the area defined by the pixel pitch.

Mathematically, the aperture function can be expressed as

\[
u_{\text{aperture}}(x, y) = \text{comb} \left( \frac{x}{L}, \frac{y}{L} \right) \ast \text{rect} \left( \frac{x}{d}, \frac{y}{d} \right) \cdot u_{\text{hologram}}(x, y) \cdot C_1, \quad d \leq L \tag{17}\]

All the constants are absorbed into \(C_1\). The fill factor is defined as

\[
\text{Fill factor} = \left( \frac{d}{L} \right)^2 \tag{18}
\]

It equals to 92\% on this model\textsuperscript{[45]}. The far field intensity distribution is
\[ I(\xi, \eta) = \left| F_2\{u_{aperture}\}\right|^2 = \left| \text{comb}(L\xi, L\eta) \cdot \text{sinc}(d\xi, d\eta) \otimes F_2\{u_{hologram}\} \cdot C_2\right|^2 \left| \frac{x}{\lambda z} \frac{y}{\lambda z} \right] (19) \]

All the constants are absorbed into \( C_2 \). \( F_2\{u_{hologram}\} \) is the 2D Fourier transform of the hologram, which yields the reconstruction image. By simply looking at the first two terms in Eq. (19), we can see that, if \( d = L \), fill factor equals 1 and

\[ \iint_{\xi \neq 0, \eta \neq 0} \left| \text{comb}(L\xi, L\eta) \cdot \text{sinc}(d\xi, d\eta) \right|^2 d\xi d\eta = 0 \] (20)

meaning that all the energy is in the 0th order. Otherwise, this integral is larger than 0, meaning that the energy leaks to other diffraction orders, which occurs in our experiment and substantially lowers the diffraction efficiency of the 0th order.

In our research, we proposed to recycle the twin image to increase the output efficiency. Since both the reconstruction image and its twin image are plane wave, we can fold the twin image to the same direction as the reconstruction image in Figure 19.
Figure 19 A 1D retroreflector.

(a) Reflection angles $\theta_i$ and $\theta_r$ are still accord with Snell’s law, but the incident plane and reflection plane are in symmetry of r axis. (b) shows the fine structure of the 1D retroreflector.

The twin image is at point symmetry to the desired image and they scan in opposite direction. Therefore, a 1D retroreflector is used to fold the beam in azimuthal plane and hence doubles the efficiency.

### 3.3 Steering beams with binary phase gratings on a DMD

Another solution to overcome the low diffraction efficiency is to use a phase hologram. As is mentioned in chapter 3.2.2, an ideal binary Ronchi grating can diffract 10.1% of the incident power to $\pm 1^{st}$ orders (20.2% in total), while 25% of the power remains in the $0^{th}$ order. 50% of the total power is absorbed by the grating. The low diffraction efficiency makes holograms less desirable in applications having low photon budgets, such as lidar systems.

A solution to this problem is to use phase holograms. Many have been using phase SLMs to steer beams in their research. Ideally, a binary phase grating can eliminate the $0^{th}$ order and direct 40.5% (81% in total) of the incident power into $\pm 1^{st}$ orders equally. The grating doesn’t absorb any power. As is mentioned in chapter 1.2.1, the fastest ferroelectric LC binary phase SLMs can
operate at several kilohertz, yet, they are expensive and the modulation speed is limited within kilohertz range, while the current fastest DMD can operate at 22 kHz. Several efforts have been made to convert a DMD into a phase modulator\textsuperscript{[31–34]}, however, these methods achieve phase modulation at the cost of diffraction efficiency. Among the efforts, Hoffmann et al. proposed an interesting system design in [51] and successfully achieved real binary phase modulation on a single DMD. 4 kHz binary phase modulation with 27% maximum diffraction efficiency is reported in their research. Hence, we are encouraged to implement similar systems in our research in beam steering with holograms.

### 3.3.1 DMD binary phase modulation

Hoffmann et al. proposed a symmetric system in [51]. Due to the pixels are at $\pm 12^\circ$, the beams deflected from the micromirrors are collected by two 4-$f$ systems placed at $24^\circ$ to the normal of the DMD, as shown in Figure 20 (a). Therefore, if a binary amplitude image is displayed on the DMD, the incoming light will be deflected to the left arm, if it hits an “on” pixel at $12^\circ$; or it will be deflected to the right arm, if it hits an “off” pixel at $-12^\circ$. The mirror in the left arm is attached to a PZT and is precisely controlled such that it introduces $\pi$ phase retardance between both arms. The phase modulated light is then imaged to the other half of the DMD.
Figure 20. DMD binary phase modulator.

(a) is a symmetric system shown in [51]. (b) is the modified setup used in our experiment. A telescope was installed for illumination control and modulated field relay (objects not to scale).

Examples of binary phase holograms are shown in Figure 21. Considering that the image from the left half of the DMD is flipped horizontally and vertically, and imaged to the right half of the DMD, the combined image is point symmetric. Therefore, we see a sharp cut in the holograms.
The bright and dark regions are of $\pi$ phase difference. These holograms are point symmetric due to the symmetric system layout.

### 3.3.2 Experiments and result analysis

A setup is built based on Figure 20 (b). In this setup, M1 and M2 are two first surface mirrors. M2 is mounted on a piezoelectric transducer (PZT, F4010885, Burleigh Instruments). L1 and L2 are two identical lenses ($f = 122 \, \text{mm}$, F/4.8). L3 and L4 together is an inverse telescope. The adjustable aperture stop is imaged by the telescope onto the DMD to counter diffraction effect. After beams exit both arms, they return to the DMD. The field on the DMD is then imaged by the telescope onto the 45° pickoff mirror and exit the system. In our current experiment, we inserted a 50/50 beam splitter between L4 and the DMD at 45° to monitor the DMD surface and the size of the aperture precisely with a camera (sensor: DCC1545M, Thorlabs; lens: $f = 35\, \text{mm}$, Nikon). This factor is considered in our loss analysis.

The challenge of building this system is aligning the 4-$f$ systems. The light coming from a micromirror on the DMD must be sent to the diagonal micromirrors without magnification. Misalignment will lead to wrong modulation and low power efficiency. In our experiment, we used Moiré fringes to aid the alignment process. In an ideal imaging condition where no aberration
occurs, defocus will cause image magnification and thus the Moiré patterns will be radially distributed; while image translation will cause Moiré fringe along one direction.

![Figure 22. Moiré fringes on the DMD panel](image)

Figure 22. Moiré fringes on the DMD panel

Figure 22 shows the best alignment result we have so far. The Moiré pattern cannot be eliminated due to aberration. Distortion may come from the uneven flatness of the glass window and the micromirror array, and/or aberrations in L1, L2, and mirrors.

A setup for diffraction efficiency measurement is built as Figure 23.

![Figure 23. Setup for diffraction efficiency measurement.](image)

Figure 23. Setup for diffraction efficiency measurement. The sensor (imaging or power detection) is placed at the focal length of L1. An iris is used to select one or more diffraction orders.

A sensor array (DCC1545M, Thorlabs) was used to capture the $0^{th}$ and $\pm 1^{st}$ orders, shown in Figure 24. They are, in indeed, the interferograms of two-beam interference. The unevenness shows that the wavefront curvatures of the beams are different.
Figure 24. Diffraction orders imaged by a sensor array. (a) to (c) are $+1^{st}$, $0^{th}$, and $-1^{st}$, respectively.

By tuning the PZT controller (Burleigh Instruments), we can change the relative phase between waves. In open-loop control, the phase shifts frequently, as shown in Figure 25. The intensities of the orders at different time shift rapidly.

![Image of diffraction orders](image)

<table>
<thead>
<tr>
<th></th>
<th>$+1^{st}$</th>
<th>$0^{th}$</th>
<th>$-1^{st}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>$t_2$</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>$t_3$</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 25. Intensity distributions of the orders at different time.

A MATLAB program is used to analyse the image sequence of the intensities and calculate the power ratio of each order with different window sizes based on Eq.(21). Results are shown in Table 3.
\[ Power \ ratio \ of \ m^{th} \ order = \frac{Power \ of \ m^{th} \ order}{\sum_{n=-1}^{+1} Power \ of \ m^{th} \ order} \] (21)

Table 3. Maximum Efficiencies of Each Orders at Different Window Sizes

<table>
<thead>
<tr>
<th>Window size (mm²)</th>
<th>0⁰</th>
<th>+1¹</th>
<th>-1¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.506</td>
<td>0.404</td>
<td>0.362</td>
<td>0.405</td>
</tr>
<tr>
<td>0.1584</td>
<td>0.405</td>
<td>0.399</td>
<td>0.378</td>
</tr>
<tr>
<td>0.0204</td>
<td>0.475</td>
<td>0.417</td>
<td>0.377</td>
</tr>
</tbody>
</table>

While in amplitude modulation, \(±1^{st}\) order each takes up around 22% of the power among the three orders, in the phase modulation mode we shown above, the maximum recorded power ratios of the \(+1^{st}\) orders are higher than 36%. It can reach 41.7% if a smaller aperture is used, yet, it is not completely phase modulation, since the ideal ratio is 50% for real phase modulation.

3.3.3 System loss analysis

The total measured efficiency of the system is 9.6% and it is measured with the beam splitter inserted in the path. Without the 50/50 beam splitter, the efficiency is doubled to 19.2%.

Table 4 shows our measurement of efficiencies of different parts of the system. The total efficiency estimated is close to the total measured. With this analysis, we will have a better knowledge of improving system performance.
Table 4. System Efficiency Break-down (50/50 beam splitter inserted)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenses only receive part of the light from the DMD</td>
<td>45.09%</td>
</tr>
<tr>
<td>Transmission of the lenses</td>
<td>72.14%</td>
</tr>
<tr>
<td>Mirrors only capture part of the light from the lenses</td>
<td>88.76%</td>
</tr>
<tr>
<td>Lenses only capture part of the wavefront from the mirrors</td>
<td>66.98%</td>
</tr>
<tr>
<td>Beam splitter</td>
<td>50%</td>
</tr>
<tr>
<td>Total estimated</td>
<td>8.32%</td>
</tr>
<tr>
<td>Total measured</td>
<td>9.6%</td>
</tr>
</tbody>
</table>

Using the diffraction efficiency mentioned in Table 3, the expected efficiency of the steered beam is around 4% (8% without beam splitter), which is much lower than 27% mention in [51]. It can be further improved from several aspects. First, the DMD used in their research has a larger pixel pitch, 13.68 μm, which is easier for system alignment. Second, for lens L1 and L2 in Figure 20, the F-number is f/3, while it is f/4.8 in our system and the light from the DMD and from the mirrors are not fully captured. Third, M1 and M2 are not large enough to capture all the spatial frequencies. Other factors include anti-reflection coatings, DMD flatness, and vibrations. At last, we can double the efficiency to 16% with light recycling method mentioned in section 3.2.2.

3.4 Summary

In this chapter, we introduced our research in beam steering with DMD amplitude holograms. A MATLAB program is used to simulate the holography recording process and generate the required amplitude holograms. Maximum steer angle approximates ±2°. A single-sideband method
proposed in [46] is implemented in our system to remove the unwanted diffraction patterns. We also proposed to recycle the twin image to double the output efficiency. To further improve the system functionality, a DMD binary phase modulator design from [51] is used. Total measured output efficiency in our system is around 8%. With light recycling method implemented, the efficiency is expected to be 16%.

3.5 Further research

In the future, we will incorporate this DMD binary phase modulator in the DMD lidar system, which will improve the system angular resolution by a factor of 48 with our current model of the DMD, or will provide two-dimensional scanning capability.

In Figure 20, L3 and L4 together make an inverse telescope. When light enters the system, this telescope magnifies the adjustable aperture stop and images it onto the DMD. As light exits the system, it de-magnifies and relays the field from DMD to M3, and at the same time, it magnifies the angles of the rays\[^{[18]}\]. With this property of geometric optics, we can further increase the FOV of the system several times. An amplitude mask can be placed on M3 for spatial filtering, shown as Figure 26. The magnification of the inverse telescope, solely, is the smaller the better, but not too small. As the field diverges immediately, it will be difficult to incorporate the modulator in a DMD lidar system.
Figure 26 Replace mirror M3 with a reflective spatial filter
Chapter 4. Low-cost phase-only SLM from a video projector

In our research, we investigated the possibility of assembling a low-cost LCOS SLM. Many professional SLMs from Holoeeye, Hamamatsu, and Meadowlark have good performance and high flexibility which allow the users to adjust the settings. However, these SLMs are generally very expensive and cost $20,000 to $30,000 on average. On the other hand, LCOS technology is becoming mature and can be found on many projection systems. There was no similar research on this area. In our research, we want to fill this gap and investigated the performance of these LCOS devices and it gives us ideas on what types of research can be done with these low-cost devices.

4.1 Making an inexpensive SLM from a projector

Combining the knowledges in chapter 1, it can be easily seen that, if we want to DIY a phase SLM, a 3-LCD projector is the best option. In our research, we purchased several 3-LCD projectors on eBay with around $60 each. Each of them came with 3 LCD panels inside, which gave us an enormous convenience in research.

In this section, we will introduce our work on making a low-cost SLM from a 3-LCD LCOS video projector. This process includes several steps. A detailed tutorial is posted on [52].
In our experiment, we used the same projector model Canon REALiS SX50 LCOS projector as the tutorial, shown in Figure 27. These projectors were bought on eBay with around $60/each. Three LCOS panels are used for R/G/B channels. Specifications of this model are listed as following.

Table 5. Canon Realis SX50 projector configurations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display device</td>
<td>JVC 0.7’ LCOS</td>
</tr>
<tr>
<td>Resolution</td>
<td>1400 × 1050 (SXGA+)</td>
</tr>
<tr>
<td>Projection lens</td>
<td>$f = 22.0 − 37.0$ mm, F1.85 − 2.5, $1.7 \times$ Zoom</td>
</tr>
<tr>
<td>Brightness</td>
<td>2500 ANSI Lumens</td>
</tr>
<tr>
<td>Lamp</td>
<td>200W NSH</td>
</tr>
<tr>
<td>Contrast ratio</td>
<td>1000:1</td>
</tr>
<tr>
<td>Uniformity</td>
<td>85%</td>
</tr>
</tbody>
</table>

A detailed description of procedures is attached in Appendix I. Nonetheless, we still want to briefly mention that, in the source chamber, there is a limit switch hidden near the lamp, which detects the integrity of the parts. It should be pressed to avoid system errors. Before pulling the lid off the bottom case, we should unplug the FPC (flexible printed circuit) cable from the motherboard. This cable connects the control panel on the lid and the motherboard. In SX50, the motherboard is
connected to the lamp ballast by two cable bundles. To fully disable the lamp without system errors, we unplugged the wire bundle, suspended those pins and connected three of them.

In terms of the LCOSs, they are not tuned for any wavelength and are interchangeable. In our experiment, we replaced it with another softer 150 mm FPC cable. The extended length and the softness of the cable allow us to place the LCOS further away from the projector, reducing the turbulence from the cooling fan, and isolate some vibration conducted via the FPC cable. Besides, to further reduce the vibration from the projector, we unplugged most of the fans, but the one closest to the ballast. Particularly, we detached the FPC cables of the other panels from the board (the system doesn’t check the existence of the LCOS drivers), since the processors on the drivers generate lots of heat and require circulating air to cool down.

Table 6. Canon SX50 Disassembling procedures

1. Remove the UHP lamp (not required).
2. Remove the upper half of the case.
3. Bypass lamp diagnosis signal from the ballast and test.
5. Detach all cables and wires from the motherboard.
6. Remove the motherboard.
7. Open the optical engine chamber and extract the ColorQuad.
8. Detach one of the LCOS panels and its driver.
9. Put all the parts back to the projector in a reversed sequence.
10. Leave the other two LCOS drivers unplugged if they are not used.
11. Leave only one fan running to reduce vibration.

Results of a simple holography experiment with this LCOS SLM is shown in Figure 28. Phase holograms are displayed on the LCOS and illuminated by a collimated 532nm laser. A positive
lens is then placed after the reflected field. A sensor array (DCC1545M, Thorlabs) is placed at the focal plane of the lens to acquire the far field patterns.

![Hologram reconstruction with the low-cost LCOS SLM.](image)

These are the far field patterns reconstructed from holograms in Holoeye software.

### 4.2 SLM testing with an interferometer

Although in previous analysis we estimated that these LCOS devices are capable of $0 \sim \pi$ phase retardance, a close inspection is necessary to know how the phase behaves across the panel. In this subsection, we show our experiment on testing the optical properties of this LCOS.

### 4.3 Experiment setup

First, we inspected the LCOS panel in a microscope. A result is shown in Figure 29. The electrodes are highly reflective and neatly arranged at the bottom. A Linnik microscope interferometer was built to test the phase of the LCOS.
Interferometer setup is shown as Figure 30. The system is built with Thorlabs cage system. Two identical 40X objectives were used in both arms. Light from a 532nm DPSS laser (Compass 315M, Coherent, Germany) was spatially filtered and collimated. In imaging mode, the LC layer is clearly imaged onto the sensor. In interferometer mode, OPD between the test arm and the reference arm is minimized.

Aside from measuring phase accuracy, we also did a test on phase stability. In this test, a grating pattern is displayed on the LCOS and diffracts the incident beam into multiple orders. A photodetector is then placed at the first order and measured the intensity of the order. Signal is monitored on an oscilloscope.
4.4 Results and analysis

In the phase accuracy measurement, an image with a white rectangle (grey level = 255, phase = \( \pi \)) on a black (grey level = 0, phase = 0) background with sharp boundary was displayed on the LCOS. Ideally, a shape boundary should be shown on the interferogram where a \( \pi \) phase jump could be observed. However, due to fringe-field effect, a phase gradient is observed (Figure 31).

The slope ran across three pixels. In display system, this phenomenon decreases the contrast and sharpness of the images. In the next chapter, we will see how it limits the performance of the device in other applications.

![Figure 31](image1)

Figure 31 Microscopy images of the LCOS panel.

(a) is the imaging result. The microscope was focused on the cover glass; (b) was measured at interferometer mode and a 2-pixel line was displayed. The phase transition takes up to 2 pixels; (c) shows the measurement result when a 2 \( \times \) 2 pixels square was displayed. The phase transition takes up to 2 pixels.

In the phase stability test, waveforms of the photodetector signal are shown in Figure 32. The test was performed on both our projector SLM and a Holoeye phase-only SLM (Pluto-2-NIR-002, Holoeye, Germany).
Figure 32 Phase stability test on the projector SLM and Holoeye SLM
(a) shows the waveform of the projector SLM diffracted power and (b) shows that of the Holoeye SLM. Unit of the vertical axis is 1V/div. These results are to show the phase dithering effect on liquid crystal devices. (a) and (b) are not comparable since the Holoeye SLM was not operated in the optimal configuration.

The projector SLM flickers at around 60 Hz and the Holoeye SLM flickers at higher frequency. In terms of phase stability, the projector SLM performs better in our test and is more stable, yet, be aware that this is not a serious comparison, since we were illuminating the Holoeye SLM, which was designed for near-infrared spectrum, with visible light. The phase error on the Holoeye SLM was thus enlarged.

4.5 Summary

Our experiments show that, although they have limited performance, these projectors can be a low-cost solution for research. The low-cost LCOS SLM is capable of maximum $\pi$ phase retardance at 532 nm. Fringe-field effect is observed, in which phase gradient takes 2-pixel area. Phase dithers at 60 Hz.
Chapter 5. Conclusions

In this thesis, we introduced our work on understanding spatial light modulators, especially amplitude modulation and phase modulation using liquid crystal SLMs and DMD SLMs. Modulation mechanisms and applications on volume holographic data storage and beam scanning were explained in detail.

In Chapter 2, we described our work on applying this low-cost liquid crystal SLM in a volume holographic data storage system (HDSS). Angular multiplexing and eigenmode multiplexing methods were used in our research. Nine hologram data pages were recorded in a single data book/location in the Fe$^{3+}$:LiNbO$_3$ crystal.

In Chapter 3, our research on holographic beam steering with DMD was elaborated. Two methods, amplitude modulation and phase modulation on a DMD, were explained. With Texas Instruments DLP3000 DMD illuminated by 532 nm laser, ±2° steer angle can be achieved. The fine beam steering along with programmable blazed grating enables a large FOV and fast beam steering by using single DMD. In both methods, a virtual holography recording simulation was used to generate the required holograms for beam steering. A single sideband spatial filtering method was used to eliminate unwanted diffraction patterns, and we proposed a twin image recycling method using 1D retroreflector to improve the total output efficiency. To further increase output efficiency, a DMD binary phase modulator was built and tested. Total efficiency of the steered beam is expected to be 4%.
In Chapter 4, we explained the amplitude modulation mechanism in a 3-LCD LCOS projector. An example of disassembling a Canon REALiS SX50 projector was described. We turned this projector into a phase SLM with limited functionality. A Linnik microscope interferometer was built and was used to test the phase accuracy of this low-cost SLM. $\pi$ phase retardance on this liquid crystal SLM was confirmed. Fringe-field effect was observed on this SLM, which acts as a low-pass device, smoothening the input phase profile. Phase stability of this SLM was measured. The phase was flickering at around 60 Hz.
APPENDIX A. PROCEDURES FOR MAKING A LOW-COST SLM

1. A brief introduction of projectors

Projectors are common optical instruments for large size displays and are often used for presentation, entertainment and education purposes.

Light source is a key factor in projection system. In the early generations of projectors, halogen lamps were used, yet, they only last approximately 70 hours\textsuperscript{[53]}. Although halogen lamps were cheaper, they were gradually replaced by metal-halide bulbs (MHL), which have better performance and longer lifetime even they were more expensive. MHL was invented in late 1960s. A combination of rare earth metal salts and mercury vapor is used to generate light. A MHL can last about 1,000 to 2,000 hours. However, the various metal halide additives used for improving the spectrum properties also decrease the luminance of these lamps\textsuperscript{[54]}. In 1995, Philips introduced the ultra-high-performance (UHP) lamp, which is also known as ultra-high-pressure lamp (up to 200 atm). It uses only mercury and has higher light efficiency, with a lifetime up to 4,000 hours. The use of mercury in these light source technology is an environment concern. In recent years, LED (light-emitting diode) technology becomes a better solution. LED sources generates much less heat and has much long lifetime over 20,000 hours. These advantages make LED a promising source for many portable projectors. On the other hand, laser as projector light source is becoming popular. Instead of using traditional lamps, a laser projector might use shorter wavelength laser to generate other longer wavelengths. Laser sources can be blue/violet laser diodes (LD), or DPSS (diode-pumped solid-state) lasers. It was made possible after 2014 Nobel Prize for Physics winner Shuji Nakamura, the inventor of the first blue LED and the first blue LD, made breakthrough in
gallium nitride (GaN) crystal development. Laser projector shows a better power efficiency and better display quality when compared to its predecessors. One of the drawbacks of laser projectors is laser speckle, which can be harmful to eyes and decrease image quality.

LCD is another factor that determines the quality of display. When liquid crystal was firstly applied to generate video images by John A. van Raalte in 1968, it was addressed by electron beams, which controls the reflective LC cell with electronic charge patterns. Later, concepts of liquid crystal cells as light valves were invented by Gene Dolgoff, but wasn’t realized until a better TFT (thin-film transistor) technology appeared. In chapter 1, we have briefly introduced the modulation mechanism of an LCD device. Liquid crystal has a slow response to the electric field addressed, therefore, sequential colour display is not practical. When used in a projector, there are three LCDs\(^1\) in total (each colour channel requires an LCD panel). Since liquid crystal devices are wavelength and polarization dependent, when used as a light valve, waveplates and polarizers are often used. As we will see in the next subsection, a system often called “light engine” is required for light splitting and merging. The qualities of these components are crucial for image quality. (Fringe-field effect, lower contrast, slow response, temperature) These factors lead the professional market favours DLP technology over LCD. However, A LCD projector doesn’t have moving part, which is easier to maintain. Compared to DLP projectors of the same level, LCD projectors are often cheaper, making it a better option in most situations where image quality requirement is not stringent.

\(^1\) 3LCD is often seen on projectors. It is a three LCD projection technology developed by Epson, Japan in 1980s and later was licensed to other companies.
2. Optical engine

An optical engine is the core of a projector, which generally includes an illumination system, a projection lens, display electronics and a cooling system. In this subsection, we will focus on the optical fundamentals of an optical engine, including colour splitting, polarization conversion, light modulation and colour combining.

In the illumination system, several integrator lenses (a.k.a. fly-eye lens) and condensing lenses are used to produce a maximized, uniform illumination. In some systems, cold mirrors are used to prevent the infrared spectrum of lamps from heating up the optics\textsuperscript{[21]}. This beam is then guided to the dichroic mirrors and PBSs (polarization beam splitters), which separate the white light into R/G/B components. Since liquid crystal modulators are polarization dependent, waveplates (quarter waveplates and half waveplates) are inserted in the optical path. These PBSs, waveplates, and LCDs are tuned for the corresponding channels. Depending on the design, various coatings are used and some components can be stacked to reduce the impacts of retro-reflections and maintain a small form-factor\textsuperscript{[3,4]}. Finally, the modulated monochromatic outputs from the three channels are combined with a dichroic prism and thrown to the screen by a projection lens\textsuperscript{[57]}. A drawing of an optical engine is shown below.
3. Amplitude modulation with liquid crystal on silicon (LCOS) devices

LCOS device doesn’t modulate the amplitude of the incident light directly. It modulates the phase of the incident beam and further changes the polarizations. Amplitude is modulated via Malus’s law and the process can be modelled with Jones calculus. In an ideal model, linear polarized light is incident on the LCOS. However, to avoid fringe-field effect in high resolution LCOS display, it is proven to be more efficient to use circular polarized light and an optical isolator model.\textsuperscript{[59]}

At first, the linear polarized incident light $u_0$ passes through a quarter-wave plate.

$$u_0 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad \text{(22)}$$
The beam exiting each channel is

\[ u'_0 = PLZ^{90°} \cdot QWP^{-45°} \cdot SLM^{45°}_\phi \cdot QWP^{45°} \cdot u_0 \]  \hspace{1cm} (23)

in which \( PLZ^\theta \) denotes a polarizer with transmission axis at \( \theta \) with the \( x \) axis.

\[ PLZ^{90°} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \]  \hspace{1cm} (24)

\( QWP^\theta \) denotes a quarter-wave plate with its slow axis at \( \theta \) with the \( x \) axis.

\[ QWP^\theta = R^{-\theta} \cdot \begin{bmatrix} 1 & 0 \\ 0 & j \end{bmatrix} \cdot R^\theta \]  \hspace{1cm} (25)

Where

\[ R^\theta = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \]  \hspace{1cm} (26)

\( SLM^\phi_\phi \) represents the LCOS panel and is expanded as the following.

\[ SLM^\theta_\phi = R^{-\theta} \cdot SLM^0_\phi \cdot R^\theta \]  \hspace{1cm} (27–1)

\[ SLM^0_\phi = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{bmatrix} \]  \hspace{1cm} (27–2)

Simulation result is shown below.
Figure 35 A simulation of modulated intensity versus LCOS phase retardance. The curve shows that $\pi$ phase retardance is enough to modulate the intensity. Nevertheless, in phase modulation mode, we are still able to modulate the phase of linear polarized light with one of the axes on the LCOS. In the following context, detailed disassembling procedures for Canon REALiS SX50 video projector are described sequentially.

To use a projector as an SLM, lamp removal is recommended, but not necessary. First, if we flip the projector upside down, we can spot a flat head screw at one corner. After unscrewing it and removing the lid, we can find a UHP lamp, and there is a metallic wire handle for lamp detachment. The lamp should be kept carefully after being pulled out, as it contains mercury, which would contaminate the environment if it was broken. If you are considering using this lamp again in the future, it should be stored in a clean condition, as any grease or scratch on the glass window would shorten the life and even cause explosion when the lamp is lit. There is a limit switch hidden near the lamp, which detects the integrity of the parts. If checked carefully, we will see a pillar protruding out of the lid. When placed in the right position, this pillar presses the limit switch, closing the protection circuit without receiving warning. After removing the lamp, we need to put the lid back and tighten the screw.
All the screws are located at the bottom of the case. To open the cover, insert a small screwdriver in the seam at the back of the projector. One might gently pry the case along the seam to pop out the top lid. There are some plastic clutches at the front near the projection lens. They won’t detach unless the rear is fully separated. Before pulling the lid off the bottom case, remember to unplug the FPC (flexible printed circuit) cable from the motherboard. This cable connects the control panel on the lid and the motherboard (Figure 37).

After removing the cover, the motherboard is exposed. All the other parts are located below the board, including the lamp ballast, the optical engine, several cooling fans, a speaker, and the projection lens. In SX50, the motherboard is connected to the lamp ballast by three cable bundles. Two are for power supply and the third (with only 4 wires) is for communication. When started up, the system will run a hardware self-check, which checks the system integrity, lamp condition,
and cooling system condition. To monitor the condition of the lamp, the lamp ballast monitor the current and voltage running through the lamp.

To light up a UHP lamp, an ignition module is required. At a cold start, to create a gas discharge, primary electrons are needed and can be generated either by applying high voltage (several kVs), or by shining UV radiation on tungsten electrodes, which is called a “UV enhancer” \cite{54}. For SX50, there are three optoelectronic isolators inside the lamp ballast, which isolate the digital electronics from the high-power circuits. One of these isolators sends lamp diagnosis signal to the motherboard. To have the projector running without being interrupted by the failure signal, we can simply unplug the wire bundle, suspending those pins and connecting three of them, shown as Figure 38.

![Figure 38 Wire bundles connecting the power supply and the motherboard](image)

Another step is to bypass the cooling fans. This step is not necessary, but in cases where vibration severely affects the experiment, removing some or all the fans can be useful. Each fan connects to the motherboard with 3 pins. The outer 2 are for a maximum 12V power supply. The middle pin sends real-time fan speed to the system and the latter adjust the voltage supplied to the fan. To bypass these fans, we can simply connect the middle pins to the ground of the motherboard (Figure 39). If the system can run without being interrupted by failure signal, the fan bypassing succeeds.
Figure 39 Ground contact and wiring

(a) shows the ground contact (circled) on the motherboard. (b) is the wiring for fans bypassing. The middle pin is connected to the ground.

On one side of the projector, there are several large capacitors. They can store enough power to keep the cooling system running for several minutes in case of sudden power lost, so that excessive heat and protect the electronics won’t damage the electronics. Besides, there is a socket for temperature sensor which we shouldn’t remove.

Three FPC cables are used to connect the LCOS drivers to the board and they should be detached from the board. To unplug the cables, unlock the socket by pushing out the base and pull out the FPC cables. After they are detached from the board, we can safely take away the board and expose the optical engine.
Figure 40 LCOS driver and motherboard

(a) is the LCOS panel; (b) is an LCOS driver. It connects the LCOS and the motherboard. (c) is the motherboard. A 200 mm FPC cable (white) replaced the original cable (gold).

The optical engine is sealed in a black chamber. By removing the screws, we can open the chamber and expose the ColorQuad prism assembly. Three panels are located on different sides of the ColorQuad and are tightly fixed on a metal frame. In our experiment, we only extracted one of the panels and leaving the others intact. The projector can still project tinted images with two panels, giving us convenience to adjust settings in the future – some image settings such as gamma, keystone and resolution adaption would induce errors in future experiments. Temperature can have an impact on the LC molecule. The LCOS chip is mounted on a heat sink with thermal grease to quicken heat dissipation in the chamber. Although the three panels are placed in different colour channels, the LCOS themselves are not tuned for any wavelength and are interchangeable, since adjustment can be done by changing the analogue signal levels electronically in the factory menu. After we obtain the LC panel, the rest would be putting the other parts back in the projector in a reversed sequence.

The cable that connects the LCOS driver and motherboard is a 40-pin FPC cable with gold plated copper conductors, shown in Figure 40. This cable is around 50 mm and is rigid. Air turbulence from the fans and mechanical vibration severely affect the LCOS panel. In our experiment, we
replaced it with another softer 200 mm FPC cable. The extended length and the softness of the cable allow us to place the LCOS further away from the projector, reducing the turbulence from the cooling fan, and isolate some vibration conducted via the FPC cable. Besides, to further reduce the vibration from the projector, we unplugged most of the fans, and particularly, we detached the FPC cables of the other panels from the board (the system doesn’t check the existence of the LCOS drivers), since the processors on the drivers generate lots of heat and require circulating air to cool down. However, we left the fan which is close to the ballast running to cool the power supply.

Canon SX50 Disassembling procedures (same as Table 6)

1. Remove the UHP lamp (not required).
2. Remove the upper half of the case.
3. Bypass lamp diagnosis signal from the ballast and test.
5. Detach all cables and wires from the motherboard.
6. Remove the motherboard.
7. Open the optical engine chamber and extract the ColorQuad.
8. Detach one of the LCOS panels and its driver.
9. Put all the parts back to the projector in a reversed sequence.
10. Leave the other two LCOS drivers unplugged if they are not used.
11. Leave only one fan running to reduce vibration.
APPENDIX B. SETUP PROCEDURES FOR DMD BINARY PHASE SLM

This appendix provides procedures for building a DMD binary phase modulator based on the design in [51]. Accuracy and quality of the system depend largely on the qualities of the components and the precisions of the instruments.

Table 7 Apparatuses for building a DMD Binary Phase SLM

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Laser source at visible wavelength × 1</td>
</tr>
<tr>
<td>2.</td>
<td>Spatial filter assembly × 1</td>
</tr>
<tr>
<td>3.</td>
<td>Collimation lens × 1</td>
</tr>
<tr>
<td>4.</td>
<td>Shear plate for wavefront quality measurement × 1</td>
</tr>
<tr>
<td>5.</td>
<td>3-axis linear translation stage × 2 or 1-axis linear translation stage × 6</td>
</tr>
<tr>
<td>6.</td>
<td>Precision rotation stage × 2</td>
</tr>
<tr>
<td>7.</td>
<td>First surface mirror with tip-tile adjustment × 1</td>
</tr>
<tr>
<td>8.</td>
<td>First surface mirror with tip-tilt adjustment on a piezo-electric transducer (PZT) and controller × 1</td>
</tr>
<tr>
<td>9.</td>
<td>Thorlabs optical cage system × 2</td>
</tr>
<tr>
<td>10.</td>
<td>Alignment target for Thorlabs cage system × 1</td>
</tr>
<tr>
<td>11.</td>
<td>DMD system mounted on a multi-axis stage (tip-tilt, rotation, translation) × 1</td>
</tr>
<tr>
<td>12.</td>
<td>Optical breadboard × 1</td>
</tr>
<tr>
<td>13.</td>
<td>Lenses that can be mounted on the cage system.</td>
</tr>
<tr>
<td>14.</td>
<td>A camera with a macro lens to inspect the DMD micromirror array.</td>
</tr>
</tbody>
</table>

**Beam collimation:** Before building the setup, it is vital to prepare the source well. A nice, clean collimated beam is very important for future system setup and testing. Therefore, a spatial filter assembly and a collimation lens are used. Beam quality is tested with the shear plate.
**DMD alignment**: After a collimated beam is obtained, we mount the DMD on an optical breadboard. In the future procedures, the body of the SLM will be installed on the board and it gives us convenience to transport the setup. After the board is fixed on the optical table, we can start aligning the DMD to the incident beam. When the DMD is turned off, reflected beam from the DMD surface should return to the source along the original path\(^1\). Since the DMD micromirror array is discrete, many diffraction orders can be seen and we should make sure it is the 0\(^{th}\) order reflected to the source. An alignment target/iris in the spatial filter assembly would be helpful.

**Symmetric arms alignment**: The next step is to align the symmetric arms. Using the left arm as example, it is essentially a folded 4-\(f\) system. Each arm is built with Thorlabs cage system and should be mounted on a complex-motion stage that is capable of 3-axis linear translation and rotation. Long range linear stages are preferred, since the stages are not aligned to the holes on the breadboard.

This step is for angle and position adjustment. It involves coarse alignment and fine adjustment. Since the mirrors on the DMD are at \(\pm 12^\circ\) in on/off mode, reflected beams are therefore at \(\pm 24^\circ\) to the normal of the DMD. This process is aided with Thorlabs alignment targets.

At the beginning of this step, we should turn on the DMD and set the DMD to display full white, which flips all the micromirrors to the left and deflects all the light to the left arm. The hollow alignment target should be placed in the entrance pupil, while the other with crosshair should be

---

\(^1\) The cover glass of the DMD also reflects part of the light to the source. However, the cover glass is not necessarily parallel to the micromirror array. It is important to make sure only the light from the micromirror array is reflected to the source. Luckily, the beam from the cover glass is much weaker than that from the micromirror array.
placed close to the mirror after the lens. Rotation of the arm determines the incident angle and thus the location of focus on the crosshair. Position of the arm determines the location of incident beam on the hollow target. Match the distance between the mirror and the lens to the focal length of the lens. When the arm is aligned to a correct incident angle and position, the beam that enters the arm should illuminate the centre of the hollow target, and then be focused onto the centre of the crosshair at the back\(^1\). To validate this result, we can simply remove the crosshair and place the hollow target at the back of the lens. If the system is aligned properly, the returning wave should illuminate the centre of the hollow target. By far, coarse alignment is accomplished.

In fine alignment, the distance between the mirror and the lens is precisely tuned. A beam splitter is placed in front of the DMD (make sure it is not in the path of the beam between the DMD and the lens)\(^2\). If the mirror is correctly placed at the focal length of the lens, the reflected beam from the DMD should still be collimated (check with the shear plate). At the end of this step, we should be able to align the collimation part of the 4-f system.

**Image alignment:** The next step is to align the imaging part of the 4-f system. This is done by inspecting the patterns on the DMD with a macro lens on a camera. In this step, we still need the beam splitter\(^3\). Since macro lens requires a shorter working distance, we will have to find an optimal focal length that gives us an acceptable image size that allows us to see the micromirror array clearly, while not blocking the light between the DMD and the lens in the arm. Meanwhile,

---

\(^1\) It would be more accurate and convenient to have some scales on the alignment targets.

\(^2\) In this experiment, a pellicle beam splitter is mostly preferred due to the limited space. Most importantly, a pellicle beam splitter can minimize the effect of multiple reflection.

\(^3\) In this step, a pellicle beam splitter or other beam splitter with 90% reflectivity will be very useful, since we only want to inspect the surface of the DMD.
the depth of focus is short. It is important to adjust the beam splitter to 45° to the normal of the DMD and the normal of the lens, to avoid defocus and uneven magnifications\(^1\).

To start image alignment, we start with a coarse checkerboard pattern, which only deflects part of the light to the left arm\(^2\). Adjusting the distance between the DMD and the lens would change the focus (sharpness) of the image\(^3\). Under coherent illumination, out of focus yields Fresnel diffraction pattern along the edges. At best focus, no edge diffraction should occur.

After the focus is found, adjust the tip-tilt of the mirror to align the image to the original pattern on the DMD. This alignment process can be repeated with checkboard patterns of different resolutions or with grating patterns of different periods for one direction alignments.

Repeat the same procedures on the other arm.

---

\(^1\) While aligning the beam splitter and the camera, an incoherent source is mostly preferred to avoid speckle noise in the image.

\(^2\) The patterns displayed on the DMD should be point symmetric along the centre of the

\(^3\) Make sure the lens and the mirror are coupled together on the cage system. Translation of the system is along the same angle, or along the axis of the 4-\(f\) system. No lateral translation should occur.
APPENDIX C. MATLAB PROGRAM FOR DMD HOLOGRAPHY

1. Main code, “DMD_Master.m”

% This program generates sequential amplitude patterns for DMDs. 
% Call Grating_angleScanning.m for angular beam steering 
% Call FZP_depthScanning.m for 3D point scanning.

% MKS units

%% 1-D x-scanning
close all
clear
clc

% Screen at 1m from DMD.
Hrange = 0.03;
Vrange = 0.005;
NH = 96;
NV = 1;

x = linspace(-Hrange/2, Hrange/2, NH);

if NV == 1
    y = Vrange;
else
    y = linspace(-Vrange/2, Vrange/2, NV);
end

[xa, ya] = meshgrid(x, y);

theta = atan(sqrt(xa.^2+ya.^2));
phi = (ya>=0).*atan(ya./xa) + (ya<0).*(atan(ya./xa)+pi);

% Output
interleave_mode = 0; % 0: Off; 1: On
symmetry_mode = 1; % 0: Off; 1: On
switch interleave_mode
    case 0
        for i = 1 : NH
            for j = 1: NV
                BiGRT = Grating_angleScanning(theta(j,i), phi(j,i));
                if symmetry_mode == 1
BiGRT(end:-1:1, end:-1:end/2+1) = BiGRT(1:end,1:end/2);
end
s = i+(j-1)*NH;
if s < 10
    imwrite(mat2gray(BiGRT), sprintf('.\angleSteering\grt_0%d.bmp', s));
else
    imwrite(mat2gray(BiGRT), sprintf('.\angleSteering\grt_%d.bmp', s));
end
end
end
case 1
for i = 1 : NH
    for j = 1: NV
        BiGRT = Grating_angleScanning(theta(j,i), phi(j,i));
        if symmetry_mode == 1
            BiGRT(end:-1:1, end:-1:end/2+1) = BiGRT(1:end,1:end/2);
        end
        s = (i+(j-1)*NH) * 2;
        if s < 10
            imwrite(mat2gray(BiGRT), sprintf('.\angleSteering\grt_0%d.bmp', s));
        else
            imwrite(mat2gray(BiGRT), sprintf('.\angleSteering\grt_%d.bmp', s));
        end
    end
end
darkI = zeros(size(BiGRT));
for s = 1 : 2: 95
    if s < 10
        imwrite(mat2gray(darkI), sprintf('.\angleSteering\grt_0%d.bmp', s));
    else
        imwrite(mat2gray(darkI), sprintf('.\angleSteering\grt_%d.bmp', s));
    end
end
2. 1-D grating generation code, “Grating_angleScanning.m”

% This program generates Fresnel zone patterns for DLP3000 DMDs.  
% DMD parameters:  
% H x V = 608 x 684  
% Pixel pitch = 10.8 um diagonal  
% Layout: 45\deg row interleaved  

% MKS units

function BiGRT = Grating_angleScanning(theta, phi)

% Define beam k-vector (spherical coordinate)  
% theta = 0.1; % Polar angle  
% phi = 0.1; % Azimuthal angle

nx = 0; % DMD surface normal  
ny = 0;  
nz = 1;  
kx = sin(theta)*cos(phi);  
ky = sin(theta)*sin(phi);  
kz = cos(theta);  
lbd = 532e-9; % wavelength  
k0 = 2*pi/lbd;

pw = @(x, y, z) exp(1j*k0*((kx-nx)*x+(ky-ny)*y+(kz-nz)*z));

% DMD parameters
pp = 10.8e-6;  
h = 608; %px  
v = 684;

w = [-h/2:-1, 1:h/2] * pp;  
h = [-v/2:-1, 1:v/2] * pp/2;  
[U, V] = meshgrid(w, h);  
U(2:2:end, :) = U(2:2:end, :) + pp/2; % Even-order rows displacement

GRT = angle(pw(U, V, 0)); % Phase grating  
BiGRT = (GRT <= 0); % Binary amplitude grating
APPENDIX D. MATLAB PROGRAM FOR DMD PHASE HOLOGRAPHY DIFFRACTION EFFICIENCY MEASUREMENT

close all
clear
clc

commandwindow
try
  load('config.mat');
  fprintf('Last data used: %s\n', file);
  gt = input('Use the last config? (Y/N)\n','s');
catch
  disp('Opening file...');
  [file,path] = uigetfile('*.'\ avi');
  gt = 'N';
end

if strcmp(gt,'N')
  disp('Opening file...');
  [file,path] = uigetfile('*.'\ avi');
end

v = VideoReader(fullfile(path,file));
newFrame = readFrame(v);
figure(1); imshow(255-newFrame); axis image;

if strcmp(gt,'N')
  figure(1)
  title('Please specify the center of each order from left to right.');
  [c, r] = ginput(3);
  title('Please specify the boundary of measurement by diagonal points.');
  [c2, r2] = ginput(2);
  cRange = round(max(c2)-min(c2));
  rRange = round(max(r2)-min(r2));
  fprintf('Width = %.2fum\n', cRange*5.2);
  fprintf('Height = %.2fum\n', rRange*5.2);
end
save('config.mat');

Tip = @(c,r) text(c,r-100,{1', '2', '3'},'Color', 'red', 'Fontsize', 15);
title('Click the order of which DE to be calculated.')
xCur, yCur = ginput(1);
dist = (c-xCur).^2 + (r-yCur).^2;
nOrder = dist==min(dist);

squarePlot = @(x0,y0,xR,yR) plot([x0-xR/2,x0+xR/2,x0-xR/2,x0-xR/2],[y0-yR/2,y0-yR/2,y0+yR/2,y0+yR/2,y0-yR/2],r,'LineWidth',1);
hold on; squarePlot(c(nOrder),r(nOrder),cRange,rRange); hold off

I = @(frame,i) mean(mean(mat2gray(frame(round(r(i)-rRange/2:r(i)+rRange/2),
     round(c(i)-cRange/2:c(i)+cRange/2)))));
I_DE = @(frame,n) I(frame, n)/sum(I(frame,1)+I(frame,2)+I(frame,3)); %
Calculate DE of a specified order.
I_max = I_DE(newFrame, nOrder);
title(sprintf('New max = %f',I_max));

td =
text(15,30,sprintf('Progress: %.2f%%',v.CurrentTime/v.Duration*100),'
Color','red','Fontsize',15);
i = 1;
while hasFrame(v)
    newFrame = readFrame(v);
    I_cache = I_DE(newFrame,nOrder);
    
    % Obtain DE
    for k = 1:3
        I_track(i,k) = I_DE(newFrame,k);
    end
    i = i+1;

    if I_cache > I_max
        I_max = I_cache;
imshow(newFrame)

        hold on;
squarePlot(c(nOrder),r(nOrder),cRange,rRange);
    Tip(c,r);
    hold off
    title(sprintf('New max = %f',I_max));
    drawnow
end
delete(td)
td =
text(15,30,sprintf('Progress: %.2f%%',v.CurrentTime/v.Duration*100 ),'Color','red','Fontsize',15);
end

title(sprintf('Done! Max DE = %f',I_max));

figure();
subplot(311);plot(I_track(:,1));
title('Power ratio of 0/+1/-1 order')
subplot(312);plot(I_track(:,2));
subplot(313);plot(I_track(:,3));

clear v; %Release video from Matlab
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