Improved Leaky-Mode Waveguide Spatial Light Modulators for Three Dimensional Displays

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Improved Leaky-Mode Waveguide Spatial Light Modulators for Three Dimensional Displays

Scott Alexander Gneiting

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

Improved Leaky-Mode Waveguide Spatial Light Modulators for Three Dimensional Displays

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Master of Science

This thesis improves on the design of the leaky-mode spatial light modulator, LMW-SLM, presented by Dr. Smalley [1]. Improvements include: input coupling gratings, a pulsed laser input, output coupling gratings, and a 3D printed adjustable module for the stabilization of critical alignments. First, input coupling gratings reduce the cost of the LMW-SLM from $500 to around $2, a drop in cost of over two orders of magnitude. This enables multiple modulators to be used in a single display and allows for an inexpensive modular design to be created. Second, a pulsed laser input allows for image creation without the use of a polygon for derotation. Removal of the polygon allows for direct viewing of the LMW-SLM output enabling near-eye and flat panel displays. Third, output coupling gratings allow for bottom exit devices that are essential for thin substrates and flat panel displays. Fourth, the 3D printed module allows for the critical alignments of the LMW-SLM to become permanent. This in turns allows for transportation of the created displays without a trained technician by abstracting away the complexities of the device. The resulting changes simplify hardware, reduce cost, and enable the LMW-SLM to be modularized and the resulting 3D displays to be transportable.

These improvements are made possible by the addition of a one new mask step during fabrication, a simple circuit design, and a 3D printed module designed in SOLIDWORKS. Included in this thesis as attachments are the MATLAB, Eagle, and SOLIDWORKS files used to create the improved LMW-SLM.

Keywords: LMW-SLM, leaky-mode, holography, BYU
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NOMENCLATURE

\( A_m(y) \) Amplitudes of the \( m \)th guided mode as a function of position
\( A_0(y) \) Expansion coefficient of the incident guided mode light as a function of position
\( \alpha_\nu \) Radiation decay coefficient for the \( \nu \)th radiation mode
\( \beta_0 \) Propagation constant of the incident guided mode
\( c \) Speed of light in a vacuum in meters per second
\( C_T \) Total Capacitance of an IDT
\( C_n \) Capacitance of the \( n \)th finger pair of an IDT
\( D \) Coefficient of diffusion of the proton exchange melt
\( d \) Distance or depth
\( d_1 \) Distance beyond the focal plane used for calculating Depth of Field
\( d_2 \) Distance before the focal plane used for calculating Depth of Field
\( d_s \) Depth of the substrate
\( d_w \) Depth of the waveguide
\( f \) focal length
\( f_0 \) Center frequency of an IDT
\( f_a \) Frequency of the input RF signal
\( G_L \) IDT transducer admittance
\( \gamma_\nu \) Angle of the radiation into the substrate
\( j \) The imaginary number
\( k \) Wavenumber of a given electromagnetic wave
\( k_i \) Wavenumber of the incident wave
\( k_r \) Wavenumber of the reflected wave
\( k_t \) Wavenumber of the transmitted wave
\( k_0 \) Propagation constant in free space
\( k^2 \) Electromechanical coupling constant for a given direction
\( K_a \) Momentum of the SAW
\( K_{\nu 0} \) Coupling coefficients between guided and leaky-modes
\( L \) Interaction length of the LMW-SLM
\( L_{\text{max}} \) Maximum interaction length capable of exiting the end of the LMW-SLM
\( L_n \) The length of the \( n \)th grating finger in the IDT
\( L_{sn} \) The width of the \( n \)th grating finger in the IDT
\( \Lambda \) Spatial period of a grating or interference pattern
\( \lambda \) Wavelength of an electromagnetic wave
\( m \) Mode number
\( n \) Refractive index of a material
\( n_1 \) Refractive index of material one
\( n_2 \) Refractive index of material two
\( n_s \) Refractive index of the substrate
\( \eta \) Mode conversion efficiency
\( P \) Power of an Electromagnetic Wave
\( \rho \) Density of the material
\( \phi \) Phase measured in radians
\( \phi_1 \)  Maximum phase offset
\( \Delta \phi \)  Relative change in phase
\( \phi_a \)  Applied electrical potential
\( Q_L \)  Load quality factor of an IDT
\( r_p \)  Radius of the average adult pupil
\( r_n \)  Transformer ratio of the circuit equivalent model of the IDT
\( S_i \)  Distance from the lens of the eye to the focal plane of the eye
\( S_o \)  Distance from an object to the eye
\( t \)  Time in seconds
\( \theta \)  Angle in degrees
\( \theta_c \)  Critical angle at a material interface
\( \theta_i \)  Angle of incidence
\( \theta_r \)  Angle of reflection
\( \theta_t \)  Angle of transmission
\( \theta_m \)  Angle of a given mode
\( \theta_{\text{max}} \)  Maximum output angle achievable by the LMW-SLM
\( \theta_n \)  Acoustic transit angle
\( V_a \) or \( v \)  Velocity of the SAW
\( w_n \)  Width of the overlap region in IDT fingers
\( \omega \)  Angular frequency of an electromagnetic wave in radian per second
\( x, y, z \)  Positions
\( \Delta x \)  Positional shift at the image plane
\( Z_0 \)  Mechanical impedance of the substrate on which the IDT is fabricated

**Operators, Functions, and Sets**

\( \mathfrak{F}\{\} \)  Fourier transform operator
\( J_m \)  First kind of Bessel function of order \( m \)
\( K() \)  Jacobian complete elliptic integral of the first kind
\( \mathbb{Z} \)  Set of all integer values

**Matrices, Tensors, Vectors, and Coefficients**

\( d \)  Piezoelectric tensor for a material
\( E \)  Column vector of applied electrical fields to a material
\( S \)  Column vector of strains in a material
\( \bar{E} \)  Electric field of an electromagnetic wave
\( \bar{E}_0 \)  Amplitude and Phase of an electromagnetic wave
\( \bar{E}_i \)  Electric field of the incident wave
\( \bar{E}_r \)  Electric field of the reflected wave
\( \bar{E}_t \)  Electric field of the transmitted wave
\( \bar{k} \)  Wave vector of a given electromagnetic wave
\( \hat{n} \)  Surface normal vector
\( \bar{r} \)  Position vector
\( c_{ijkl} \)  Coefficients of elastic stiffness in a constant electric field
\( e_{ijk} \)  Piezoelectric coefficients
\( \epsilon_{ik} \)  Dielectric permittivity coefficients for a constant strain
\[ u_k \quad \text{Components of mechanical displacement} \]
CHAPTER 1. INTRODUCTION

1.1 Pursuing Inexpensive 3D Displays

Although much work has been accomplished in the area of 3D displays, an inexpensive commercial display capable of true 3D has not yet reached consumers. True-to-life 3D displays, such as the Mark II at MIT, tend to be large and prohibitively expensive in much the same way as the very first computers. Cheap displays, such as the Google Cardboard, tend to sacrifice capabilities and rely on only a few of the 3D cues in order create a "3D feel." Unfortunately, the side effects of relying on the viewer’s brain to make up the difference can include nausea, fatigue, and strain. Leaky-Mode Waveguide Spatial Light Modulators (LMW-SLMs) may be the key to bridging the gap between true 3D function and cost. Due to simple, planar fabrication on common materials, the LMW-SLM is inexpensive to produce. One chip costing $2. On the other hand the LMW-SLM is a holographic device capable of producing all three of the primary 3D cues. Much work has been done by Dr. Smalley and his team on using the LMW-SLM for economical holographic video.

This thesis improves on the design of the LMW-SLM presented by Dr. Smalley [1]. Improvements include input coupling gratings, a pulsed laser input, output coupling gratings, and a 3D printed adjustable module for the stabilization of critical alignments. First, input coupling gratings reduce the cost of using the LMW-SLM from $500 to around $2, a drop in cost of over two orders of magnitude. This allows multiple modulators to be used in a single display and allows for an inexpensive modular design. Second, a pulsed laser input permits image creation without the use of a polygon for derotation. Removal of the polygon allows for direct viewing of the LMW-SLM output enabling near-eye and flat panel displays. Third, output coupling gratings creates bottom exit devices that are essential for thin substrates.
and flat panel displays. Fourth, the 3D printed module maintains the critical alignments of the LMW-SLM, producing a transportable display without a trained technician. The resulting changes simplify hardware, reduce cost, enable modularization of the LMW-SLM, and create a transportable 3D display.

These improvements are made possible by the addition of one new mask step during fabrication, a simple circuit design, and a 3D printed module designed in Solidworks. Included in this thesis as attachments are some of the Matlab, and Eagle files used to create the improved LMW-SLM. The Electro-Holography Lab at BYU can, at their discretion, supply all files with any updates.

1.2 Contribution of this Work

This work combines and builds upon my other publications to present a form factor of the LMW-SLM that is capable of being incorporated into flat panel and near eye displays. It frees the user of the LMW-SLM from the use of derotation optics, allows for bottom exit viewing, and enabled arrays of modulators that could be implemented into a pixelated flat screen design. This work, however, is meant to furnish the tools necessary for others to create such a design. No attempt at any holistic holographic display system is included.

This work builds upon my other publications. A complete list of my publications is as follows:

Current Publications


Pending

1. Backside Emission Leaky-Mode Modulator. To be submitted to Optics Express June 30th.


1.3 Overview of the Text

This thesis is organized as follows: Chapter 2 compares the LMW-SLM to other 3D display technologies and explains its importance in the field of 3D displays, Chapter 3 explains the important theoretical elements necessary to understand LMW-SLMs, Chapter 4 documents the critical design choices made in improving the LMW-SLM, Chapter 5 discusses fabrication processes, Chapter 6 provides results, and Chapter 7 concludes and presents future work.
CHAPTER 2. BACKGROUND

2.1 Understanding True 3D

The human brain is an incredibly elastic organ capable of quickly translating a pair of two-dimensional views provided by the eyes into a 3D model of the world. In order to accomplish this, the brain relies heavily on 3D cues. Many pictorial cues are present in 2D displays such as shading, size comparisons, and shape. However the 3D cues of occlusion, parallax, and accommodation are the elusive cues that must be mastered to create a true 3D display. Each of the three 3D cues are represented in Figure 2.1 Each will be discussed in the paragraphs that follow.

The first cue, occlusion, or the covering of one object by another, helps to establish depth even at great distances. As one object blocks the view of another, the mind automatically recognizes that the now invisible object is behind the visible one. To prove this look out your window. The window is closer than the scene that can be seen through it. It follows that the frame of the window blocks, or occludes, your view of the outside world. If this cue is removed, the result is a scene where every object is always visible, creating a world that appears to be filled with semi-transparent, ghost objects.

This also occurs at much greater distances: buildings block what lies beyond them and the clouds block our view of the sun. At such large distances, occlusion is the only of the three cues that the mind uses to establish depth. Thus, it is possible to create a true-to-life display that appears 3D using only occlusion. While a simple flat-screen television would do the job, that display would only remain effective when displaying objects at near true-to-life sizes on a distant screen.
Figure 2.1: Representations of the three-dimensional cues that the brain uses to create a 3D understanding of the world. Unfortunately, since this is a 2D sheet of paper, only 2D representations are possible. A) Occlusion: The yellow sphere blocks parts of the other spheres from view. Which parts are blocked, changes with viewing angle. B) Parallax: the slight difference in position between the two eyes creates two slightly different perspectives of the line of spheres. C) Accommodation: as focus changes from the yellow sphere in the front to the black sphere in the back, the objects not at the focus blur.

The second cue, parallax, describes the difference between two view angles. This cue becomes more prominent as objects become closer. In artistic terms, each eye has its own perspective. Trees on the horizon look the same when viewed from one eye or the other; however objects nearby change perspective slightly between eyes. Take a look at the person next to you. From directly in front, the human face looks symmetric. However just slightly to the side the profile of the nose breaks the symmetry. Since the eyes are separated by 61 mm on average, when viewing a nearby person each eye sees a slightly different image. For a display showing nearby objects, a lack of parallax breaks the 3D "feel".
It is hard to pin down the exact distance at which parallax becomes necessary\cite{7}. For an object directly in front of one eye, the perceived angular offset to the other eye is

\[
\tan(\theta) = \left( \frac{0.061m}{S_o} \right),
\]  

(2.1)

where \( \theta \) is the perceived angle and \( S_o \) is the distance to the object being viewed in meters. This angular shift passes through the lens system of the eye to become positional shift, see Figure \ref{fig:2.2} If the eye is modeled as a single variable focal length lens, with a flat imaging plane at a distance of 17mm\cite{8}, and using the ray that passes through the center of the lens and thereby does not deviate, then by the law of similar triangles
\[
\left( \frac{0.061m}{S_o} \right) = \left( \frac{\Delta x}{0.017m} \right) \tag{2.2}
\]
\[
\Delta x = \left( \frac{1037}{S_o} \right), \tag{2.3}
\]

where \( \Delta x \) is the relative distance that the object has been shifted at the receptors in the eye in units of microns, \( \mu m \). To give some intuition, a human rod cell is roughly \( 2 \mu m \) in diameter and the diameter of a human cone cell varies from \( 0.5 \mu m \) to \( 4.0 \mu m \). If the cells are spaced by their smallest dimensions then at a distance of \( 51.85m \) the object has shifted 10 rod cells and 40 cone cells, which may or may not be noticeable. At a distance of \( 10.37m \), however, the relative shift is equivalent to 50 rod cells or 200 cone cells. A 200 pixel shift in an image is quite noticeable. A 3D display used for objects closer than \( 10m \) must demonstrate parallax if it is going to produce true-to-life 3D images.

The third cue, accommodation, arises from the physical nature of the human eye. The eye, like every optic system, has a limited depth-of-field. Therefore, when two objects cannot be brought into focus at the same time, the viewer immediately knows that they lie at different distances. Added to this optical phenomenon, are the physical simulations that accompany the change in focus. In order to bring an object into focus, the eye contracts an annular muscle that changes the curvature of a lens located inside the eyeball. This small force, almost imperceptible to the conscious mind, assists the brain in placing the distance to the object.

Want proof? Hold a pencil at arms length, close one eye, and then focus on the tip of the pencil. The wall across the room will go out of focus. You may also feel the muscular change in your eye. These two sensations are accommodation.

The single lens representation presented earlier is useful here for developing a mathematical intuition of accommodation through a depth-of-field analysis.
Figure 2.3: A conceptual drawing of depth of focus. Light enters the pupil of the human eye and focuses down onto a single receptor, in this case a rod. Important distances are labeled.

A human eye in daylight has a pupil size of about 3mm\cite{10}. The most extreme light rays enter at the outer edge of the pupil, a distance of half the diameter of the pupil. Assuming a perfect lens, a point on the object focuses to a single point on the image plane. Another object point, at a different distance, loses focus when its rays spill unto adjacent cones, see Figure 2.3. If the point focuses after the image plane, then law of similar triangles states

\[
\frac{r_p}{1700 + d_1} = \frac{0.25}{d_1},
\]

where \(d_1\) is equal to the distance beyond the focal plane, \(r_p\) is the pupil radius and all units are in microns. For a 3mm diameter pupil, \(d_1 = 2.834\mu m\). Similarly, if the point focuses before the image plane

\[
\frac{r_p}{1700 - d_2} = \frac{0.25}{d_2},
\]

where \(d_2\) is the distance before the focal plane. Under the circumstances described, \(d_2 = 2.833\mu m\).

Image focal distances can be converted into object focal distances by means of the thin lens equation. The thin lens equation is
\[
\frac{1}{S_o} + \frac{1}{S_i} = \frac{1}{f},
\]

(2.6)

where \(S_o\) is the distance from the object to the eye, \(S_i\) is the distance to the focal plane, \(f\) is the focal length required to bring the object into focus. Equation 2.6 can be used to find the depth-of-field. First the required focal length to bring the first object point into focus is determined given that \(S_i = 17mm\). That focal length is then used to find the corresponding image points for \(S_i + d_1\) and \(S_i - d_2\).

Here are some examples to help with intuition. To bring an object at 50\(m\) into focus requires focal length of 16.994\(mm\) and objects between 91.2\(m\) and 32.7\(m\) are still in focus. An object at 10\(m\) requires a focal length of 16.971\(mm\) and objects between 11.0\(m\) and 9.1\(m\) are still in focus. An object at 2.5\(m\) requires a focal length of 16.885\(mm\) and objects between 2.56\(m\) and 2.44\(m\) are still in focus. An object at 50\(cm\) requires a focal length of 16.441\(mm\) and objects between 50.2\(cm\) and 49.8\(cm\) are still in focus.

When an object is near enough to touch, the depth-of-field is less than 5\(mm\). A true-to-life 3D display at this distance must show similar blurring as the viewer changes focus.

To review, there are a trio of 3D cues that must be present in a true-to-life 3D display. Occlusion is the covering of one object by another, its effects are always present for opaque objects no matter the distance. Parallax, or different perspectives at different locations, begins to play a role at distances in the 10s of meters. Accommodation, the focusing of the eye both optically and physically, effects objects even closer still. A nearby 3D display requires all three 3D cues to create a true-to-life virtual object.

### 2.2 The Search for a True 3D Display

With an understanding of the 3D cues established, it is easier to discuss the quality of current 3D technologies. Four technologies will be discussed in this section, starting from the most basic and moving to the more complex 3D displays.
2.2.1 Binocular Disparity

One common 3D approach is the implementation of binocular disparity in the images presented to each eye. One example of this is the common "3D" movie experience. The viewer puts on a pair of polarizing glasses which provide each eye with a slightly different image by means of polarization filtering. Removing the glasses exposes both images to each eye. The result is the blurry image familiar to 3D movie connoisseurs.

This solution relies entirely on binocular parallax to create the "3D" experience. This means that a 3D movie is missing parts of the other two 3D cues. Since all of the images shown are on the flat plane of the movie screen, there can be no sense of true accommodation. The producer decides which objects are in focus at any given time and the viewer cannot change that focus. Occlusion also is only partially present. Since only one object exists at any given point on the screen, there can be no covering of an object by another. Put another way, moving around in the theater does not shift the objects in the image relative to each other, with some objects covering other ones. This occlusion, which naturally appears with motion parallax, is not present. Instead, the movie is rendered with a chosen perspective, and all covered surfaces are deleted in a process called culling. With only two of the 3D cues partially present, the system relies heavily on the viewer’s brain to make up the difference. For some, such as myself, this leads to headaches and eye fatigue.

Of course, binocular disparity as a means to create 3D images is not limited to the movie theater. It appears in 3D phone applications such as Google Cardboard, and virtual reality applications. While its simplicity is appealing, the lack of the cue of accommodation means this type of display falls short.

2.2.2 Holographic Displays

While binocular disparity falls short of true 3D, holographic image creation contains all the 3D cues. Parallax and occlusion are created during the render process. First the desired scene is modelled in a virtual 3D space using CAD software. Each desired view is rendered.
Figure 2.4: Diagram of holographic image creation. Two distinct points, P1 and P2, are created by two superimposed holographic chirps. Blanking in the hologram for P2 creates occlusion at view point V1. Relative positions of the points vary from V1 to V2 creating parallax. Accommodation arises from the different distances created for each point.

As each view is faithfully displayed, parallax is created. The information contained in all views for a given 3D point is then encoded into a holographic image. Occlusion is created by blanking the regions of the hologram responsible for objects that cannot be seen. The resulting holograms for all 3D points are then superimposed upon each other to create the final hologram. Accommodation is created by varying the focal distance of given image points. Figure 2.4 demonstrates how holography can create all three 3D cues.

Thus a true holographic display requires wavefront control. Accommodation is created by diverging or focusing the light. Parallax is created by varying the angular output contained across the display. Occlusion is created by choosing which views contain which 3D points.
2.2.3 The LCoS SLM

A Liquid Crystal on Silicon spatial light modulator (LCoS SLM), one method for producing the wavefront control required for accommodation, is the most common SLM used in current holographic 3D displays. It relies on liquid crystals to delay discrete portions of the light that pass through it. This relative delay can simulate the effects of a negative or positive lens, as well as a large range of less common wavefronts. If the LCoS SLM is reflective, the distance travelled by the light is doubled and therefore the requirements necessary to achieve the maximum relative phase modulation, $2\pi$, are halved.

Three problems arise when using a LCoS SLM. Figure 2.5 shows a typical output of a LCoS display. The first problem the user of the LCoS SLM faces is the unwanted zero-order light that passes through the system unchanged. No SLM is perfectly efficient, and the LCoS SLM presents no simple way of removing this unwanted, undiffracted light.

The second problem is the limited resolution, which leads to low diffraction angles. As an example I will use HoloEye, a company that specializes in LCoS SLMs. The smallest pixel pitch, or diagonal distance across one pixel, available from HoloEye is $4.5\, \mu m$ [11]. If the pixel is square then each side is $2.12\, \mu m$ long. Through principles described in Chapter 3, at the maximum frequency, one pixel on and one off, the output angle of the device at $635\, nm$ is $7.2$ degrees. Since a binary grating like the one just described causes unwanted diffracted light more pixels are often used to create more complex grating designs, thus decreasing the maximum output angle of the LCoS SLM.

The third problem that plagues the LCoS SLM when used as a holographic display tool is pixelization effects. The example LCoS SLM mentioned above has a fill factor of $92\%$. This means that between each cell in the display is $4.1\%$ gap. This creates an unwanted and ever present diffraction pattern at $14.5$ degrees that must be dealt with. The undesirable resolution and pixelization artifacts of LCoS make it a poor choice for displaying a true 3D image, as complicated and costly optical systems must be designed to remove them. However, until recently few alternatives have been available.
2.2.4 Nanophotonic Phased Arrays

One way to overcome the resolution and pixelization artifacts of the LCoS display is to shrink the optical elements even further. This is the approach taken by nanophotonic phased arrays. These displays produce the desired wavefronts of light by using tightly packed light emitters while controlling the phase of the output light.

Such displays are capable of producing all of the required 3D cues\[12\]. However, like all antenna arrays, Nyquist sampling of the antenna plane requires placements of antennas within half wavelength distances. In the optical regime, this results in around a quarter million independently-addressed but parallely-driven emitters within a single square millimeter. Such drive requirements quickly saturate available bandwidth from modern computers. Add to this the complexities of delivering the optical and electrical signals to each emitter and such challenges make large displays difficult to create. At least for now, nanophotonic phased arrays are not a viable solution for a true 3D display.
2.2.5 The LMW-SLM

Holographic manipulation of plane waves provides another solution to generating all the required 3D cues. Since holography is a diffraction-driven process, it too requires features on the order of a wavelength. Direct implementation, with sub-micron holographic pixels, would suffer from the same limitations as nanophotonic phased array technologies. However, it is possible to encode an entire line of holographic information (termed a hololine) into a single surface acoustic wave (SAW) created by an interdigital transducer (IDT). This is the fundamental principle behind the leaky-mode waveguide spatial light modulator or LMW-SLM. If used directly the two dimensional phased array would be replaced by the one dimensional IDT array for hololine generation, thereby square rooting the number of required drive signals to roughly 500 per square millimeter. Since each drive signal requires \(70\,MHz\) of bandwidth, each square millimeter of this display would require a \(35\,GHz\) signal. Such an implementation is beyond common consumer computers, although a specialty machine could be created to drive this 3D Display.

A display supercomputer is not necessary however, as an entire image can be generated by a single channel on the LMW-SLM if vertical parallax is sacrificed. Vertical parallax is the change in the image as the viewer moves up and down. Horizontal parallax is still maintained, as well as occlusion and accommodation. The reason vertical parallax is able to be removed without much detriment to the 3D nature of the display is because the human eyes are offset horizontally and not vertically. Thus the loss of vertical parallax will not be perceived by a seated or stationary viewer or even when moving side to side. Instead only a squatting or jumping viewer is able to notice the lack of vertical changes.

Removing vertical parallax allows the hololines to be stacked vertically over a period of time. If the refresh rate of the entire screen is faster than sampling rate of the human eye, above about 60 frames per second, then the entire image appears to be continuously visible due to the persistence of vision of the user [13]. This technique, called progressive scanning, is common among modern monitors. By allowing this minor degradation in the 3D nature
of the display, it is possible to create a 3D display with occlusion, horizontal parallax, and accommodation, that requires a single 70MHz drive signal and can be run with hardware available today[14].

Dr. Daniel Smalley, in his research with Massachusetts Institute of Technology (MIT) and Brigham Young University (BYU), has created a 3D monitor using this scanned SAW approach [1]. His monitor relies on a LMW-SLM capable of 20 degrees of diffraction to red light, 638 nm. With scanning optics, it is capable of 30 fps refresh rates, has 30 degrees of encoded angular output, and a display size of 4 cm by 12 cm. The design is scalable and image size is currently limited by the parabolic reflecting optic used as the output. His goal is to see holographic video monitors become a standard way to view 3D data.

Despite his holographic video monitor design being an order of magnitude less expensive than previous work done by MIT, the LMW-SLM still had serious limitations. One, it required an expensive rutile prism to couple into the waveguide; two, it was impossible to transport without losing critical alignment; three, it had a limited exit aperture decreasing the usable length of hololine that could be produced; and four, it required a derotation polygon plus scanning mirror assembly with precise phase matching between the rotation of the mirror and the radio frequency, RF, input signal.

2.3 Improvements to the LMW-SLM

This thesis builds upon Smalley’s work and presents solutions to each of the aforementioned challenges in previous designs. An input coupling grating, adding only a few fabrication steps and essentially no cost to the $2 LMW-SLM, is introduced to remove the need for the $500 coupling prism. This reduction in cost allows for the use of multiple modulators within a single monitor and the creation of a modular design which can be easily stabilized for transport. Output coupling gratings are added to remove the dependence of the exit aperture on the thickness of the crystal used to create the modulator. Finally, providing
pulsed laser illumination for the LMW-SLM removes the need to derotate the holographic output.

These improvements indicate the possibility of the LMW-SLM as a flat screen technology with horizontal parallax only. Input and output coupling gratings allow for a side-lit, parallel-illumination scheme that can be scaled to the required display size. Vertical deflection, required for full-parallax large-area displays, is currently being by Smalley’s team.
CHAPTER 3. PRINCIPLES OF LMW-SLM

3.1 Fundamental Principles of LMW-SLMs

The LMW-SLM is a combination of two powerful technologies: optical waveguides and surface acoustic modulators. Each in turn are explained in this chapter. The essential principles of optical waveguides are discussed including: the waveguiding conditions, the rise of discrete guided modes, and the presence of leaky modes. The basics of surface acoustic waves (SAWs) and how they are created are also presented. The intent of this chapter is to provide the reader with the theoretical tools necessary to understand the function of the LMW-SLM.

3.2 Interfaces and Diffraction

This section derives the Law of the Conservation of Momentum at a material interface. This is used to explain the Laws of Reflection and Refraction. Conservation of Momentum is then used to derive the diffraction equation.

3.2.1 Waveguiding and the Conservation of Momentum

At any interface between two dielectric lossless materials, there exists the chance that some power of an incident wave, a vector quantity denoted here as $\vec{E}_i$, is reflected from the surface into a wave $\vec{E}_r$, and some is transmitted into a wave $\vec{E}_t$. For convenience and without loss of generality, all waves will be treated as plane waves, where $\omega$ is the angular frequency, $t$ is time, $\vec{k}$ is the wave vector, and $\vec{r}$ is the position vector. The angle that the wave is incident on the material is denoted as $\theta_i$. In the paragraphs to follow, the reflected and transmitted angles, $\theta_r$ and $\theta_t$ respectively, are mathematically derived. Figure 3.1 shows in more detail the interface described.
Figure 3.1: Diagram of the reflection and refraction of a plane wave at a dielectric interface of two materials. Dashed parallel lines represent infinite plane fronts while solid arrows denote the direction of propagation. The relationship $n_2 > n_1$ is shown.

\[
\bar{E}_i(r, t) = \bar{E}_{i0} \ast \exp[j(\omega t - \bar{k}_i \cdot \bar{r})] \quad \text{where} \quad \bar{k}_i = n_1 \frac{w_i}{c} [\hat{\imath} \cos(\theta_i) + \hat{x} \sin(\theta_i)] \tag{3.1}
\]

\[
\bar{E}_r(r, t) = \bar{E}_{r0} \ast \exp[j(\omega t - \bar{k}_r \cdot \bar{r})] \quad \text{where} \quad \bar{k}_r = n_1 \frac{w_r}{c} [\hat{\imath} \cos(\theta_r) + \hat{x} \sin(\theta_r)] \tag{3.2}
\]

\[
\bar{E}_t(r, t) = \bar{E}_{t0} \ast \exp[j(\omega t - \bar{k}_t \cdot \bar{r})] \quad \text{where} \quad \bar{k}_t = n_2 \frac{w_t}{c} [\hat{\imath} \cos(\theta_t) + \hat{x} \sin(\theta_t)] \tag{3.3}
\]

Equations 3.1 through 3.3 shows the mathematical representations of the three plane waves at the interface, where $\bar{E}_0$ is the amplitude and phase at the origin and the letter subscript indicates the respective wave, $n$ is the refractive index, $c$ is the speed of light in a vacuum, and $j$ is the imaginary number.

Since the dielectric material boundary does not have an electromagnetic source, the sum of the electrical fields in one material must be equal to the sum of the electric fields in the other to satisfy the Law of the Conservation of Power. This is mathematically represented by

\[
\hat{n} \times \bar{E}_i(r, t)|_{z=0} + \hat{n} \times \bar{E}_r(r, t)|_{z=0} = \hat{n} \times \bar{E}_t(r, t)|_{z=0}; \tag{3.4}
\]
where \( \hat{n} \) is the surface normal. Equation [3.4] is true for every moment in time, \( t \), and every position, \( \vec{r} \). This can only occur if the arguments of the exponents are the same for each electric field. Applying this condition simplifies the equation to

\[
\omega_i t - \vec{k}_i \cdot \vec{r}|_{z=0} = \omega_r t - \vec{k}_r \cdot \vec{r}|_{z=0} = \omega_t t - \vec{k}_t \cdot \vec{r}|_{z=0}.
\] (3.5)

The time, \( t \), is the same in each argument, thus the \( \omega \) multiplier on \( t \) must be the same for all fields, \( \omega_i = \omega_r = \omega_t = \omega \). With this change to Equation [3.5] the time components cancel. The result is the law of the Conservation of Momentum at a material boundary or

\[
|\vec{k}_i \cdot \vec{r}|_{z=0} = |\vec{k}_r \cdot \vec{r}|_{z=0} = |\vec{k}_t \cdot \vec{r}|_{z=0}.
\] (3.6)

Both laws governing the angular component of the light leaving a material interface quickly fall out of Equation [3.6]. The Law of Reflection is obtained by replacing the position vector, \( \vec{r} \), in Equation [3.6] with its Cartesian equivalent, \( x\hat{x} + y\hat{y} + z\hat{z} \), and simplifying for only the incident and reflected waves. The steps are show Equations [3.7] through [3.10]:

\[
|n_1 \frac{w}{c} (\hat{z} \cos \theta_i + \hat{x} \sin \theta_i) \cdot (x\hat{x} + y\hat{y} + z\hat{z})|_{z=0} = |n_1 \frac{w}{c} (\hat{z} \cos \theta_r + \hat{x} \sin \theta_r) \cdot (x\hat{x} + y\hat{y} + z\hat{z})|_{z=0}
\] (3.7)

\[
|(\hat{z} \cos \theta_i + \hat{x} x \sin \theta_i)|_{z=0} = |(\hat{z} \cos \theta_r + \hat{x} x \sin \theta_r)|_{z=0}
\] (3.8)

\[
|x \sin \theta_i| = |x \sin \theta_r|
\] (3.9)

\[
\theta_i = -\theta_r.
\] (3.10)
Figure 3.2: A K-Space diagram of a dielectric interface showing the incident, reflected, and transmitted rays. It should be noted that the components of each ray that lies in the direction of the material interface are equal. This diagram is consistent with the example shown in Figure 3.1 where \( n_2 > n_1 \). Since momentum is conserved along the boundary, \( \theta_t < \theta_i \). The diagram makes the region of TIR visually clear.

Considering the incident wave and the transmitted wave only, Equation 3.6 produces Snell's Law of Refraction. The steps are shown in Equations 3.11 through 3.14:

\[
|n_1 \frac{w}{c}(\hat{z} \cos \theta_i + \hat{x} \sin \theta_i) \cdot (x\hat{x} + y\hat{y} + z\hat{z})|_{z=0} = |n_2 \frac{w}{c}(\hat{z} \cos \theta_t + \hat{x} \sin \theta_t) \cdot (x\hat{x} + y\hat{y} + z\hat{z})|_{z=0}
\]  
(3.11)

\[
|n_1 (\hat{z} \cos \theta_i + \hat{x} \sin \theta_i)|_{z=0} = |n_2 (\hat{z} \cos \theta_t + \hat{x} \sin \theta_t)|_{z=0}
\]  
(3.12)

\[
\hat{x} n_1 \sin \theta_i = \hat{x} n_2 \sin \theta_t
\]  
(3.13)

\[
n_1 \sin \theta_i = n_2 \sin \theta_t.
\]  
(3.14)

Visually, the Conservation of Momentum at a material boundary can be shown by a K-Space diagram, such as Figure 3.2. All light is shown as vectors whose length is proportional to the magnitude of \( \hat{k} \) in Equations 3.1 through 3.3.
3.2.2 Momentum of a Diffraction Grating

The previous section assumes that the boundary at the material interface is flat. While useful to simplify the mathematics, this assumption is not correct in the case of a Diffraction Grating. In this section, the momentum gained from a sinusoidal periodic phase structure at the material interface is derived following the approach by Goodman [15]. The binary etched gratings used as couplers in this thesis can then be analyzed from a superposition of harmonic sinusoids.
The setup shown in Figure 3.3 is of a normal incidence beam hitting a sinusoidal phase grating of period \( \Lambda \). The phase change of a sinusoidal grating is

\[
\Delta \phi(x) = \exp \left[ j \frac{\phi_1 \sin(2\pi x)}{2} \right], \quad (3.15)
\]

where \( \phi_1 \) is the maximum phase offset, \( x \) is the position on the grating, and \( \Delta \phi \) is the change in phase. It should be noted that there is no change in \( y \) and therefore the \( y \) term is suppressed.

Normal incidence removes any momentum effects from the material differences leaving only momentum effects from surface perturbations. Using the thin grating approximation, the phase just after the surface is

\[
\bar{E}_i(z, t) = \bar{E}_{i0} \ast \exp \left[ j(\omega t - kz + \frac{\phi_1 \sin(2\pi x)}{2}) \right]. \quad (3.16)
\]

Because the phase of a normal incident plane wave is constant across a surface and absolute phase is not relevant to diffraction phenomenon, we can choose an initial phase such that \( kz = 0 \). Time dependence can then be suppressed using the principle of superposition, creating the simplified phasor equation

\[
\bar{E}_i(r) = \bar{E}_{i0} \ast \exp \left[ j \frac{\phi_1 \sin(2\pi x)}{2} \right]. \quad (3.17)
\]

Applying the principle of Fraunhofer diffraction, the far-field effects are the Fourier transform of the near-field. At this point it is useful to use the mathematical identity

\[
\exp \left[ j \frac{\phi_1 \sin(2\pi x)}{2} \right] = \sum_{m=-\infty}^{\infty} J_m(\phi_1/2) \ast \exp \left[ j \frac{2\pi mx}{\Lambda} \right] \quad (3.18)
\]

to simplify the Fourier transform of Equation 3.17, where \( J_m \) is the first kind of Bessel function of order \( m \). The completed Fourier transform is
\[ \mathcal{F} \{ \vec{E}_t(z) \} = \mathcal{F} \left\{ \vec{E}_{i0} * \exp \left[ j \frac{\phi_1 \sin(2\pi x)}{\Lambda} \right] \right\} = \vec{E}_{i0} * \sum_{m=-\infty}^{\infty} J_m \left( \frac{\phi_1}{2} \right) \delta \left( \frac{x}{\lambda z} - \frac{m}{\Lambda}, \frac{y}{\lambda z} \right), \]

where \( \mathcal{F} \) is the Fourier transform operator and \( z \) is the distance of the electric field beyond the diffraction grating.

Equation 3.19 is composed of an infinite train of delta functions with unique scaling factors. Since understanding angular momentum is the goal, all amplitude information can be discarded leaving

\[ \mathcal{F} \{ \vec{E}_t(z) \} \propto \sum_{m=-\infty}^{\infty} \delta \left( \frac{x}{\lambda z} - \frac{m}{\Lambda}, \frac{y}{\lambda z} \right). \] (3.20)

Only the \( x \) direction contains periodic information, therefore for this derivation the \( y \) component can be suppressed. The delta function is an infinite spike when the argument is zero; thus the locations of optical output can be found by setting the argument equal to zero and then simplifying or

\[ \frac{x}{\lambda z} - \frac{m}{\Lambda} = 0 \quad \text{where} \quad m \in \mathbb{Z} \] (3.21)

\[ \frac{x}{z} = m \frac{\lambda}{\Lambda} \quad \text{where} \quad m \in \mathbb{Z}, \] (3.22)

in which \( \mathbb{Z} \) denotes the set of all integer values.

The left side of Equation 3.22 is a vector \((x, z)\) pointing out of the interface. By substituting first for angle and then momentum, Equation 3.22 becomes the diffraction equation for normal incidence

\[ \vec{k}_g = m \frac{\lambda}{\Lambda} \quad \text{where} \quad m \in \mathbb{Z}. \] (3.23)

Combining Equation 3.6 with Equation 3.23 yields
Figure 3.4: The K-Space representation of the added momentum of a grating. Only the positive grating mode orders are shown. The power distribution and the shape of the modes are determined by the grating geometry.

\[ |\vec{k}_i \cdot \vec{r}|_{z=0} + |\vec{k}_g| = |\vec{k}_r \cdot \vec{r}|_{z=0} = |\vec{k}_t \cdot \vec{r}|_{z=0}, \]  

Equation 3.24 which describes the effect of a grating on any angle of incident light. Equation 3.24 is the wave vector form of the grating equation. Figure 3.4 shows the effect of the grating equation in K-Space.

A more common form is

\[ \sin \theta_i + \frac{m \lambda}{A} = \sin \theta_t \quad \text{where} \quad m \in \mathbb{Z}. \]  

Equation 3.25 the reflected wave is not considered. Also, the grating is assumed thin so that the light ends in the same material that is started in, usually air.

It should be noted that when creating binary grating from a superposition of harmonic sinusoids, the momentum equation does not change. This is because the smallest period already includes all the positions that will be attributed to $2 \Lambda$, $3 \Lambda$ and so on.
3.3 Optical Waveguides

A waveguide, in the simplest definition, is a structure that directs a wave along a specific path through the use of physical boundaries. In the case of a LMW-SLM the wave of interest is light. As the light hits the boundaries of the waveguide, changes in the material properties cause some of the light to reflect back into the material. If the geometry is correct, the reflected light then travels to the other side of the guiding material and is reflected back at this boundary as well. With each bounce the light is redirected into the material and thus guided down a path that the designer can designate. Long distances can be achieved if the loss at each boundary is negligible.

This section addresses the role of total internal reflection (TIR) in waveguides, mathematically describes a waveguide mode, explains leaky-mode waveguides, and covers how light enters the waveguide at angles sufficient for TIR.

3.3.1 TIR

As described in Section 3.2.1, without the presence of surface perturbations in the waveguide, and due to the Law of Conservation of Momentum, the wavevectors of the incident and reflected waves must be equal. If the waveguide is modeled as a dielectric slab waveguide with the material boundaries in the $yz$ plane and propagation of the wave in the $xz$ plane, then this relationship can be written as

$$|\vec{k}_i \cdot \vec{r}| = |\vec{k}_r \cdot \vec{r}| = k \cdot \vec{r},$$

where $\vec{k}$ is the wavevector, $\vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$ is the position vector, $k$ is the wavenumber, and the subscripts $i$ and $r$ denote the incident and reflected waves respectively. It is important to note that reflection at a boundary does not change the amplitude of the wavevector, known as the wave number, but only the direction. The wavenumber is related to the wavelength by
Figure 3.5: K-Space diagram of the waveguiding condition. There is no angle in material 1 that can carry the angular momentum of the guided wave in material 2. Thus all power is reflected at the material surface.

\[ k = \frac{2\pi}{\lambda}, \quad (3.27) \]

where \( \lambda \) is the wavelength in the material. Remember that \( \vec{k}_i \cdot \vec{r} \) is part of the exponent of a phasor and as such represents an accrual of phase. When traveling in the direction of the wave, \( \hat{r} = \hat{k} \), and at a distance of \( r = \lambda \) from the initial point, the wave has gained \( 2\pi \) phase and has returned to the value where it initially started in the periodic wave. In other words \( f(k\lambda) = f(0) \). This is the mathematical definition of the intuitive term wavelength.

Inside a lossless waveguide the light is contained through total internal reflection, TIR. TIR occurs when the light incident on the material boundary has more momentum than can be supported by the lower index material (see Figure 3.5). Since no light can be transmitted into the second material, all of the light is reflected back into the first material. This only occurs at high incidence angles.
3.3.2 Waveguide Modes

In a lossless material, a TIR waveguide can guide the light indefinitely. While the first bounce sends the wave in a different direction than it started with, the second bounce returns the wave to its initial direction, and the pattern repeats.

If the light source is coherent, then every second bounce of the wave must be in phase in to not cause destructive interference. Accrued interference over multiple bounces will quickly block the light from transferring its power down the waveguide.

Anytime the bounces of light are in phase and can travel down the waveguide is called a mode. Figure 3.6 shows the phase accrual down a waveguide at two different angles. The
in-phase angle is a mode for this waveguide. The condition for being in phase can be written as

\[ \Delta \phi = 2\pi m = k * r = \frac{2\pi}{\lambda} \sin(\theta_m) d_w, \]

where \( m \) is the mode number, \( \Delta \phi \) is the change in phase after transversing the thickness of the waveguide to the second bounce, \( \theta_m \) is the angle of travel with respect to a ray parallel to the edges of the waveguide and \( d_w \) is the depth of the waveguide. Solving (3.28) for \( \theta_m \) results in

\[ \theta_m = \arcsin \left( m \frac{\lambda}{d_w} \right). \]

Equation (3.29) gives the angles for discrete modes inside the waveguide. It also shows how the number of modes and the internal angle of travel are governed by both the thickness of the waveguide and the wavelength of light used inside the waveguide.

The arcsin is undefined when the argument is greater than one. Therefore the highest mode order is

\[ m_{\text{max}} = \left\lfloor \frac{d_w}{\lambda} \right\rfloor. \]

### 3.4 Leaky Modes

Due to the anisotropic nature of the crystal, waveguides made in proton exchanged, x-cut lithium niobate are polarization specific. As the Hydrogen atoms replace the Lithium atoms during the proton exchange process, the index of refraction of the extraordinary axis of the crystal increases, creating the region of high index required for the TIR [16]. Interestingly, the index of the ordinary axis decreases. Thus polarized light oriented along the extraordinary axis, TE light, is the only light that can be guided because only this orientation "sees" a
waveguide. The light enters a particular mode depending on the coupler design and the illumination angle.

Once in a mode, if unaffected by any other source, the light will stay in that mode until the waveguide ends. There are, however, many sources of momentum that can transition light from one mode into another mode or even help it escape from the waveguide. One example visible in dilute proton exchanged lithium niobate, is scattering, a random process that knocks the light both into other modes and out of the substrate. This light lost to the substrate appears as a streak emanating from the surface of the waveguide. This unbroken line across the surface of the substrate, called the characteristic streak in a LMW-SLM, indicates that light is travelling down the waveguide and is helpful in recognizing correct alignment.

A temporally-changing, holographic gratings in the form of SAWs provides another source of added momentum. These gratings actually do double duty. First, the induced stress in the crystal acts similarly to a wave plate, rotating the polarization and allowing the TM light produced to exit the substrate. Second, the grating patterns add momentum to the mode thereby changing the angle of the output light. The polarization rotation provides an easy mechanism to filter the desired modulated light from the unmodulated light while the diffraction makes the light shapeable and steerable.

The mechanism by which the leaky mode transition occurs deserves special attention as it is the fundamental principle behind the leaky-mode modulator. However, the derivation of the phenomenon is quite complex and so only a summary is provided here. For a more complete discussion of the leaky-mode phenomenon, see the work done by Matteo which was used as a pattern for the next section [2].

3.4.1 Angular Selection Through SAWs

SAWs in piezoelectric materials such as lithium niobate are governed by the following electro-mechanical wave equations:
\begin{align}
    c_{ijkl} \frac{\partial^2 u_k}{\partial x_i \partial x_l} + e_{ijk} \frac{\partial^2 \phi_a}{\partial x_i \partial x_k} &= \frac{\rho}{\partial t^2} \\
    e_{ikl} \frac{\partial^2 u_k}{\partial x_i \partial x_l} - \epsilon_{ik} \frac{\partial^2 \phi_a}{\partial x_i \partial x_k} &= 0 \quad \text{where } i, j, k, l = 1, 2, 3. \tag{3.31}
\end{align}

In these coupled second-order differential equations, $u_k$ are the components of mechanical displacement, $\phi_a$ is the electrical potential, $\rho$ is the density of the material, $c_{ijkl}$ are the coefficients of elastic stiffness in a constant electric field, $e_{ijk}$ are the piezoelectric coefficients, and $\epsilon_{ik}$ are the dielectric permittivity coefficients for a constant strain. The variables $x$ and $t$ denote space and time coordinates respectively. The crystal is oriented in such a way that the light is propagating in the $y$ direction of an $x$-cut lithium niobate crystal.

A solution can be found by plane wave decomposition that compares the incident modes to each of the other guided and radiation modes. The following assumptions greatly simplify the decomposition: the spatial change in amplitudes of the guided modes ($A_m(y)$) are small, the interaction lengths are larger than the free space wavelength, and the momentum of the leaky wave can be supported by the substrate material or

\begin{equation}
    \beta_0 - K_a <= n_s k_0. \tag{3.33}
\end{equation}

In equation (3.33) $\beta_0$ is the propagation constant of the incident guided mode, $K_a$ is the momentum of the SAW, $n_s$ is the index of refraction of the substrate, and $k_0$ is the propagation constant of the incident wave in free space. The momentum of the SAW can be calculated by

\begin{equation}
    K_a = \frac{2\pi}{V_a} f_a, \tag{3.34}
\end{equation}

where $V_a = 3906\text{m/s}$ is the velocity of the SAW and $f_a$ is the frequency of the input RF signal.
Since guided-to-guided coupling is negligible in practical cases and using a counter propagating SAW, the solution to Equation 3.32 becomes

\[ \frac{\delta A_n(y)}{\delta y} = -A_0(y)\alpha_\nu, \]  

where \( A_0(y) \) is the expansion coefficient of the incident guided mode light as a function of position \( y \) describing the field contained within the waveguide and \( \alpha_\nu \) is the radiation decay coefficient for the \( \nu \)th radiation mode. The radiation decay coefficient can be calculated by

\[ \alpha_\nu = |K_{\nu 0}^{-1}|^2 \pi \cot \gamma_\nu, \]  

where \( K_{\nu 0} \) are the coupling coefficients between guided and leaky-modes and \( \gamma_\nu \) is the angle of the radiation into the substrate.

The result of Equation 3.36 is that the amplitude of the guided wave, \( A_0 \), decays exponentially as it leaks into a continuum of radiation modes or

\[ A_0(y) = \exp[-\alpha_\nu y]. \]  

The power \( P \) at any given location in the mode is

\[ P(y) = \exp[-2\alpha_\nu y]. \]  

The mode conversion efficiency, \( \eta \), over the entire interaction length \( L \) is

\[ \eta = \{1 - \exp[-2\alpha_\nu L]\} \times 100\%. \]  

The Equations 3.36 through 3.39 taken together show exponential energy transfer from the guided mode into the radiation modes that meet the phase matching condition

\[ \beta_\nu = \beta_0 - K_a. \]
This condition is remarkably similar to the holographic grating phase matching condition of Equation 3.24 with the mode order $m = -1$.

The output angle, $\gamma$ of the leaky mode is related to the momentum by

$$k_0 n_s \cos \gamma = K_a = \frac{2\pi}{V_a} f_a.$$  \hspace{1cm} (3.41)

Therefore, a desired output angle can be encoded into the momentum of the SAW by selecting the appropriate frequency.

### 3.4.2 Production of SAWs

In order to understand the physical creation of the SAW, it is helpful to simplify the coupled second-order differential equations of 3.32, focusing only on the results of the piezoelectric effect in the substrate. According to Chang Liu[17] the piezoelectric tensor for x-cut lithium niobate is

$$d = \begin{bmatrix}
0 & 0 & 0 & 0 & 68 & -42 \\
-21 & 21 & 0 & 68 & 0 & 0 \\
-1 & -1 & 6 & 0 & 0 & 0
\end{bmatrix} \frac{pC}{N}.$$  \hspace{1cm} (3.42)

The mechanical strain caused by an electrical field can be given by

$$S = d' \times E,$$  \hspace{1cm} (3.43)

where $S = \begin{bmatrix}s_1 & s_2 & s_3 & s_4 & s_5 & s_6 \end{bmatrix}'$ is a column vector of strains, the subscripts 1-3 are tensile strains and 4-6 are rotational strains, $d$ is the piezoelectric tensor shown in Equation 3.42 and $E = \begin{bmatrix}E_x & E_y & E_z \end{bmatrix}'$ is a column vector of electrical fields.

The IDTs are aligned with the waveguides and the fingers of the ITDs run in the $z$ direction of the crystal. Therefore, the applied electric fields caused by voltage differences
across the IDT fingers, lie in the y direction of the crystal. Ignoring fringe effects and analyzing only one pair of fingers, the electric field vector is completely in the y direction or

\[ \mathbf{E} = \begin{bmatrix} 0 & E_y & 0 \end{bmatrix}^T. \] (3.44)

By substituting back into Equation 3.43 the mechanical strain can be calculated as

\[
\begin{bmatrix}
  s_1 \\
  s_2 \\
  s_3 \\
  s_4 \\
  s_5 \\
  s_6
\end{bmatrix} = \begin{bmatrix}
  0 & -21 & -1 \\
  0 & 21 & -1 \\
  0 & 0 & 6 \\
  0 & 68 & 0 \\
  68 & 0 & 0 \\
  -42 & 0 & 0
\end{bmatrix} \frac{pC}{N} \begin{bmatrix}
  0 \\
  E_y \\
  0
\end{bmatrix} = E_y \begin{bmatrix}
  -21 \\
  21 \\
  68 \\
  0 \\
  0 \\
  0
\end{bmatrix} \frac{pC}{N}. \] (3.45)

The results of Equation 3.45 shows the deformation of the crystal lattice induced by a single finger pair. The component \( s_1 < 0 \) corresponds to a compression of the crystal in the x direction, which is vertically in x-cut lithium niobate. The component \( s_2 > 0 \) corresponds to an expansion of the crystal in the y direction. The component \( s_4 > 0 \) corresponds to a counter-clockwise rotation about the x-axis of the crystal. A representative diagram of this process is shown in Figure 3.7.

The next pair over has the direction of the field reversed, causing expansion in x, compression in y, and clockwise rotation around the x-axis. The rotations cancel and the end result is a compression wave that, once created, travels along the surface of the substrate by the elasticity of the crystal lattice. The finger spacing determines the wavelength and frequency of the SAW in the crystal. Since LMW-SLM are relatively large bandwidth devices, the IDT is usually chirped across the usable frequency range to provide the proper finger periods for every desired frequency.
Figure 3.7: Diagram of the production of a SAW. Red indicates a positive voltage, white a negative voltage, and black no voltage. Deflections are exaggerated. A) Without any voltage applied, the electrodes rest on a flat substrate. B) When the first voltage is applied to the electrodes, positive fields compress the substrate vertically and stretch it horizontally; negative fields do the opposite. C) Half a period later the compression is reversed. As time passes the wave travels across the surface of the substrate.
CHAPTER 4. DESIGN

4.1 Overcoming Previous Limitations of the LMW-SLM

As mentioned in Chapter 2, previous instantiations of the LMW-SLM relied on a rutile prism for coupling into the waveguide, had an aperture defined by the width of the substrate, required derotational optics, and possessed alignments that were difficult to maintain during transport. This chapter discusses the design choices made to overcome these challenges.

4.2 Input Coupling Gratings

LMW-SLMs rely on proton exchanged waveguides diffused into LiNbO3. In the diffusion region, the crystal lattice structure has been disrupted by H\textsuperscript{+} ions impeding the motion of light and increasing the refractive index of that region. This waveguide can have indexes of refraction, \( n \), as high as 2.3. The core of the waveguide, another name for the high index region, works to guide the light through TIR at the low index boundary, or cladding. Maxwells equations describe the equal relationship between the parallel components of the electric field at a planar interface. This is often written in the form of Snells Law of Refraction shown in Equation 4.1, where \( \theta \) is the angle within that material.

\[
n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (4.1)
\]

When \( n_1 \) is greater than \( n_2 \), there exist angles inside material one that do not map to real angles inside material two. This is easily shown in a k-space diagram, such as Figure 3.5 in Chapter 3, which uses the idea of conservation of momentum parallel to the boundary to map angles from one medium to another. While this phenomenon is important for guiding light within the waveguide, it creates a problem for light trying to enter the waveguide. Without
another source of momentum it is impossible from the lower index material to enter the TIR region of the higher index material.

There are many ways of coupling, or achieving the momentum necessary for entering the TIR region of a waveguide. End coupling, tapered waveguide coupling, prism coupling, and grating coupling are a few common techniques for light to enter a waveguide. Each will be considered in turn.

4.2.1 End Coupling

End coupling is one of the simplest forms of free-space coupling into a waveguide. All it requires is that the light be incident upon a perpendicular surface of the guiding material. Usually, a lens is used to focus the light down into a spot roughly the size of the small guiding core, see Figure 4.1. Because the surface of the core is perpendicular to the light propagation, $\theta_1 = 0$. By Snell’s Law, it follows that $\theta_2 = 0$ regardless of the indexes of refraction of the material. This method is tolerant to small deviations from perpendicular, commonly created by slight misalignments and fabrication tolerances, although such deviations will require an angular offset in order to correct for the errors.

The simplicity of this design is appealing as it requires only a well-polished edge and a lens to couple into the waveguide. However, due to the small waveguide cross section of the LMW-SLM, it has a waveguide depth of 1 – 2$\mu$m depth, aligning the focused beam to the core can be tedious. Unfortunately, end coupling also launches a large amount of light towards the viewer making it a poor coupling design. A larger, cleaner approach is preferred.

4.2.2 Tapered Waveguides

A tapered core allows for a larger entrance area while maintaining the final waveguide dimensions. Figure 4.2 shows how a typical tapered waveguide operates. The entrance pupil of the tapered waveguide is made large enough for easy alignment. The dimensions of the
Figure 4.1: Diagram of End Coupling. End Coupling is the simplest form of waveguide coupling. The laser light is focused by a lens and then aligned to the waveguide core at the desired mode angle.

core are slowly decreased until the desired core dimensions are achieved. As a general rule, the shallower the taper angle, the more efficient the coupling becomes.

The tapered waveguide is appealing because of its larger entrance size. Unfortunately, approximating a two-dimensional taper in proton exchanged lithium niobate is extremely complex, requiring many mask steps to produce a stepwise approximation. A one dimensional taper is the most that can practically be done, which does not improve the thickness of the $1 - 2\mu m$ target.

4.2.3 Prism Coupling

Prism couplers combine end coupling with optical tunneling to provide the needed momentum for light to enter the waveguide. A material with a refractive index higher than the
core of the waveguide is polished into a right triangle such that light entering the prism at the desired mode angle encounters a perpendicular face. The light then enters the high index material in the same manner as in end coupling and begins to propagate through the high index prism. The light then totally internally reflects off the bottom surface of the prism and continues on its way.

Light is never completely contained by any material. Even at a TIR boundary, the electromagnetic waves exist in both materials; however, in the material in which the waves do not propagate, the amplitude of the waves decay exponentially as the waves moves away from the surface. These non-propagating waves are called evanescent waves. By inducing large evanescent waves at a boundary, it is possible to induce electromagnetic fields in a
Figure 4.3: Diagram of Prism Coupling. Prism Coupling provides a larger area for coupling by entering the side of the core rather than the end by means of optical tunneling. Due to horizontal symmetry, exact placement is no longer necessary. These benefits come at the added expense of the coupling prism and the required clamping mechanism.

material that is located a few microns away from the boundary. If the light can propagate in this separate material, it will, appearing to ignore the physical gap (see Figure 4.3). This is called optical tunneling. The closer the two materials are, the more light will optically tunnel through the gap and the more efficient the coupling. One benefit of prism coupling is that it changes the coupling surface from one that is perpendicular to the waveguide to one that is parallel to the waveguide, allowing for larger area illumination and easier alignment.

The previous design of the LMW-SLM used a rutile prism to couple into its waveguides. Rutile has a high index of refraction, 2.91 for extraordinary axis and 2.61 for the ordinary axis \[18\]. This is well above the 2.3 of proton exchanged lithium niobate. This greater index also magnifies the angular input and decreases the needed angular rotation during
alignment. Unfortunately, it also costs more than one hundred times the fabrication cost of the modulating chip on which it was placed and requires bulky clamping mechanisms to secure it. A cheaper, less bulky coupler is needed.

4.2.4 Grating Coupling

A grating coupler uses the principle of diffraction to match the free-space wave to the waveguided mode. Light intersecting the grating diffracts according to the Momentum Grating Equation, Equation 3.24. This means that the designer can specify an input angle, desired mode angle, and wavelength of light; then design a grating with the correct period to match the input light to the waveguiding mode. The shape of the grating coupler determines the distribution of power into the various modes created by the grating. The geometry of the grating coupler also allows for the shaping of input light to better match the waveguiding condition. Well-designed grating couplers can easily achieve above 90% efficiencies[19].

Using an input grating coupler provides the same parallel entry as a prism coupler for large area illumination, requires only one mask to fabricate (adding almost no cost), and allows for the use of a one dimensional tapered waveguide to increase the power density of the guided light. For these reasons I choose to implement a grating input coupler to improve the LMW-SLM. As absolute efficiency of the LMW-SLM is not the highest priority, I use only a simple uniform etched grating. The resultant losses in coupled power into the waveguide can be overcome by increasing the input laser power.

The desired mode has an internal angle that varies between $5 - 7^\circ$ as the light varies from 460 – 635 nm. To only create one grating coupler, I design my input coupling gratings for the middle wavelength, green at 532 nm. With the output angle and wavelength set, entrance angle is tied to grating period. High entrance angles require small period gratings, which are difficult to fabricate. Low instance angles stretch the size of the required grating, which can harm efficiency. An internal entrance angle of $20^\circ$ proved to be effective, see Figure 4.4.
Figure 4.4: Diagram of Grating Coupling. Grating Coupling provides the side access possible with a prism coupler without the added expense. A one dimensional tapered waveguide can be included to increase the coupling area without adding complexity during fabrication. Well-designed prism couplers can be over 90% efficient.

The LMW-SLM waveguide is asymmetric: the top cladding layer is air, \( n = 1 \), and the bottom cladding is pure lithium niobate, \( n = 2.2 \). This presents two alternatives for coupling into the waveguide. The wavenumber inside the substrate is much closer to the wavenumber inside the waveguide, so by choosing bottom-entry, the momentum required for input coupling is greatly reduced. This in turn increases the grating period making the grating easier to fabricate. In LMW-SLM devices, top entry requires a period size of 0.4\( \mu m \) while bottom entry needs only a period of 6\( \mu m \). Therefore a bottom entry design was used[4].

One final decision has to be made in the fabrication of the input coupling grating: fabrication order. The input coupling grating requires a hard mask, exposing only those parts of the sample where the grating is to be etch. All other parts of the sample must be covered.
Etching the input coupling grating after proton exchange would make use of the added etch rate caused by the disruption of the crystal lattice in the proton exchanged region\cite{20}. Such an approach requires a fresh deposition of aluminum on the sample for the RIE process that must be removed after the etching is done. However, the input coupling gratings always lie in the regions on the device that are proton exchanged. Therefore I decided to etch the input coupling gratings first, after the very first aluminum deposition, and then re-etch the aluminum to also define the proton exchange region, thus reducing the fabrication steps by one aluminum deposition.

As RIE etching of the input coupling gratings change the surface profile of the lithium niobate, this does have an effect on the profile of the waveguide in the input coupling region. However, the diffuse nature of the proton exchange process helps to smooth the effect of this non-uniformity and the resulting input coupling grating has proven effective.

### 4.3 Output Coupling Gratings

No matter what method is used to enter the waveguide, once inside, the light continues in the waveguide until the waveguide ends, the power is attenuated, or the light is knock out of the waveguide by some redirecting force. In the case of the LMW-SLM, the light is diffracted into substrate by a periodic change in the surface structure and the refracted index induced by SAWs. From there it is deflected into a range of angles from just off collinear to the waveguide to roughly 10 degrees downward into the substrate. As the light exits the substrate, the refractive index difference between air and lithium niobate multiplies that angular deflection, by roughly two times, according to Snells Law of Refraction.

In order to have a continuous sweep of angles, all the modulated light has to undergo the same angular offsets, if there are any in the system. This means that if any light reflects off the bottom of the substrate, then it cannot be used in the same system as light that does not reflect. In the previous design the light exited the end of the sample. Thus, with a given
substrate thickness, $d_s$, and a maximum output angle, $\theta_{\text{max}}$, the continuous angle condition sets the interaction distance, $L_{\text{max}}$, for the SAW according to

$$L_{\text{max}} = \frac{d_s}{\tan \theta_{\text{max}}}. \quad (4.2)$$

Large interaction lengths are desirable as they improve the resolution of the output points. Unfortunately, thick lithium niobate is expensive. However avoiding this expense limited the possible interaction distances. Also, exiting the end of the sample allows only for co-planar outputs, which would not be ideal for large panel displays. A bottom exiting solution would be desirable for such displays to allow for holographic panels created using planar fabrication methods.

The light that hits the bottom substrate does so at a glancing angle, at least about 80 degrees, well above the critical angle, 27.04 degrees, found by rearranging Snell’s Law and setting the output angle $\theta_1 = 90$ degrees

$$\theta_c = \arcsin \left( \frac{n_1}{n_2} \right). \quad (4.3)$$

Any angle larger than the critical angle, $\theta_c$ in Equation (4.3) is totally internally reflected. Added momentum is needed for the light to escape the bottom of the substrate.

Most of the coupling methods listed in Section 4.2 could be used. End coupling would require pits in the substrate to be fabricated to allow the light to escape. Prism coupling could also allow the light to escape and change its angular offset. Either of these approaches could then be enhanced by a mirror attached to the substrate to increase the angular shift. However, in both cases the fabrication and complexity are prohibitive. Once again, a grating coupler proves an elegant solution. Unlike input coupling gratings, however, there is no asymmetry that can be used to increase the grating feature sizes. Therefore the grating period must be 400 nm rather than the more desirable 6 $\mu$m.
Figure 4.5: Diagram of the interference lithography setup used to make output coupling gratings. The Lloyd’s Mirror creates interference by using the principle of the division of wavefront. By changing the angle of the mirror setup, $\theta$, the user changes the angle of interference between the two beams. This in turn sets the period of the pattern produced.

In my research, all designs with features greater than 1$\mu m$ are patterned using a $\mu$PG 101 Heidelberg to directly write the photoresist. This allows for ease in design modifications as new parameters are tested. This approach would be replaced by common photo-lithographic mask processes upon mass production. However, the Heidelberg’s resolution of 1$\mu m$ is not sufficient for output coupling grating fabrication. Instead, I chose to use interference lithography by means of a Lloyd’s Mirror. This allowed for quick implementation and full wafer exposures while maintaining grating quality.

The setup, which follows, is shown in Figure 4.5. A 325$nm$ laser is redirected by a mirror into a 10$mm$ focal length IR lens. A 20$\mu m$ pinhole placed in the focal plane spatially filters the beam. The beam expands as it travels until it fills the mirror-sample setup that makes up the Lloyd’s mirror. The light intensity at the mirror is 14.8$\mu W/cm^2$.

The period of lines produced by interfering the two wavefronts can be calculated as

$$\Lambda = \frac{\lambda}{2 \sin(\theta)},$$

(4.4)
where $\Lambda$ is the period of the interference pattern, $\lambda$ is the wavelength of the incident beam, and $\theta$ is the offset angle from the surface normal of the exposed sample. For a 400 nm grating with 325 nm laser, an angle of $28.36^\circ$ is required. While the small wavelength incident light is helpful in creating small feature gratings, it is outside the sensitivity range for the s1805 resist that I use. This necessitates a 2.5 minute exposure on an optics table to eliminate vibrations while patterning.

Photoresist is extremely sensitive to etching, while lithium niobate is not. This difference in etch rates makes direct etching of lithium niobate difficult. Silicon nitride provides an etchable layer that is hard enough to withstand the pressures exerted on the device during use and is readily applied in BYU’s cleanroom. For this reason a 200 nm layer of silicon nitride is deposited before the photoresist is applied. Unfortunately, silicon nitride, with a refractive index of 2.1 when prepared with a composition heavy in silicon, is not a higher than the index of refraction of lithium niobate, 2.2. Thus, this output grating coupler relies on evanescent fields which severely diminishes its coupling efficiency. In the future a hard mask process should replace this one, directly etching into the surface of the lithium niobate.

### 4.4 Pulsed Laser Driver

The LMW-SLM uses SAWs to encode the holographic information into the surface of the waveguide. The SAWs are launched from an IDT and travel across the surface to the desired location. One unfortunate side effect of this method of holographic encoding is that the desired holographic pattern must pass through every location before the desired location as well as every location afterward. The result is a physical shift or blurring. If a single frequency pulse is launched out of the IDT that covers only one hundredth of the output length, that small output dot is smeared into the area that would be illuminated by CW input of the same frequency.

One way to overcome this limitation is by passing the output through a lens, which changes the translation into a rotation, and then a counter-rotating mirror located at the
focal plane to remove the rotation. By rotating at half the rate of the natural image rotation of the device, the mirror maintains a fixed output, derotating the image. The original image can then be obtained again by passing the image through another lens.

There are three challenges to this approach for large scale displays. First is timing. The rotating mirror at the focal plane must be matched perfectly in order to maintain the image. Errors in matching the mirror to the LMW-SLM result in flickers in the image. Since the mirror is a spinning polygon mirror with a large amount of energy, a rather slow phase lock loop must be used. Second is scaling. Increasing either the number of hololines output by the LMW-SLM or the angular content of the output display requires an increase in the size of mirror used to derotate the image. Currently that mirror is a spinning polygon, which scaled to a full room display would be large. Third is application. Not many people are comfortable with a metal disk spinning at 1000s of rotations per minute resting just in front of their head, as would be required for a near eye implementation of this display. Not only is it noisy and potentially dangerous if dislodged, but like any rotating mass, it would resist the natural motions of the human head. Flat screen technologies also prove difficult as each channel would require its own personal derotation lens-mirror-lens setup. Another solution is preferred in such cases.

Pulsing the input laser provides an elegant solution to the problem of derotation. Pulsing is a temporal solution and derotation is a temporal problem. By emitting a short pulse from the laser when the data has arrived in the proper position, the SAW encoded hologram does not have time to move along the surface to create blurring. One drawback to this pulsed driver method is the loss of the arbitrarily long hololines that could be created by direct derotation. However, the removal of aperture limited interaction regions offset this loss.

The length of the light pulse can be calculated as follows. The SAW produced in a LMW-SLM is slow when compared to light, travelling at only $3903 m/s$ [21]. This means that for the LMW-SLMs current interaction length of 6mm, it takes 1.54μs for a SAW to travel from the IDT to the end of the interaction zone. To reduce the image blur to less
than 7 percent the original blur, a pulse of 100ns is required. Further reductions in image blur simply require shorter pulses. If the image is to retain its brightness then the power of the pulse must increase by the inverse of the pulse percentage. This is done by increasing the laser power or by increasing the RF driving signal power to the IDT. If still more light is required, the efficiency of the LMW-SLM can be increased by optimization of the input coupling grating as well as optimization and direct etching of the output coupling grating. Figure 4.6 compares the old derotation approach with the pulsed laser driver.

As a proof-of-concept design, I created a pulsed laser driver for LMW-SLMs. It creates, on the falling edge of an input signal, an electrical pulse with a variable pulse duration ranging from 30ns to 330ns which is used to drive an inexpensive laser diode. This circuit does not exemplify the desired end goal method for driving the LMW-SLM.

The pulsed laser driver design is as follows. An input signal is delayed, inverted, and NANDed with the original signal to create a falling edge detector. The resulting pulse is inverted and amplified to provide the gate voltage of a N-MOSFET in saturation, thereby directly controlling the allowed current flow through that MOSFET. The laser is then attached to the high voltage and current regulated to ground through the saturated MOSFET. Both the pulse duration and the gate voltage can be changed by modifying potentiometers, one that is part of the RC constant of the delay line and the other in the gain of the amplifier. The circuit’s schematic is shown in Figure 4.7.

Simplicity was a key goal of this proof-of-concept design. Therefore the circuit uses the 2106 series MOSFETs, rated for 8ns rise and fall times for both the P and N types, since they were readily available. A 3906 BJT in a common emitter configuration provides the amplification. An electrolytic capacitor is used to stabilize the Vcc voltage with respect to ground. The circuit is designed to drive a laser diode using a 5V Vcc. Any laser diode could be supported by modifying the Vcc voltage and transistors used. Current pulse duration limitations can be overcome by decreasing the delay line RC constant and the response times of the MOSFETS used. The result is a simple, tunable pulse driver for a laser diode.
Figure 4.6: Comparison between the systems of polygon derotation and the pulsed laser input. A) A CW laser input is passed through the LMW-SLM. A lens changes the natural linear motion into angular motion which is removed by the spinning polygon mirror. The final lens finishes the telescope and transforms the image back to the original LMW-SLM output. B) The pulsed laser input removes the need for derotation as the SAW does not have time to move. No other optics are required.
Figure 4.7: The pulsed laser driver schematic. The driver inverts and delays a copy of the incoming signal, NANDs that copy with the original, amplifies the result, and uses that amplified signal to set the current flow through a MOSFET in saturation.

4.5 3D Printed Alignment Module

The previous instantiation of the full color Holovideo Monitor’s Optics Deck effectively produced 30 fps holographic video; however it was bulky, difficult to align, and impossible to transport. Much of this difficulty arose from the precise angular input required to enter the desired waveguide mode. The modulator used a prism coupler that was pressed into the surface of the device by a clamping mechanism. Angular selectivity was created by linear beam offsets from the optical axis of the focusing lens. Figure 4.8 shows a picture of the previous design.

All optics were aligned and then held in place by hand tightened set screws. During transport these screws would loosen and critical alignments would be lost. One of the benefits of this optical breadboard design was the ease of modification. A holomonitor optic deck could be made using any SLM, not only LMW-SLM. With improvements to the LMW-SLM, however, this capability became less important. With the inclusion of input coupling
The old alignment apparatus: a) as viewed from the side, b) as viewed from above. Each laser was simultaneously coupled into a single channel. The angle of entry was controlled by position on the focusing lens. A dedicated linear alignment stage and mirror were carefully manipulated until alignment was achieved. The XYZR stage on which the LMW-SLM and prism coupler mounted is not shown.

gratings it also became possible to add multiple modulators to the same monitor without significantly increasing its cost. With these considerations in mind, a new modular design for the housing of LMW-SLMs has been investigated.

4.5.1 Modular Design Housing Considerations

The modular design is meant to be inexpensive, rigid, and yet easy to modify. Once aligned, it should completely stable. The whole module should be inexpensive enough to be replaced with another, possibly updated, design as necessary. Only the modulated light should escape the module, thereby limiting the scattered and unwanted light added to the
optical system. The modular design needs to be easy to align and able to adjust to different input requirements as LMW-SLM designs continue to change.

3D printed plastic fulfills these requirements, being very easy to modify, with less than a day required to completely change the housing design. In thicknesses exceeding 3mm, it is rigid enough to retain its shape under reasonable stress. Resin is relatively inexpensive, a full modular design requires about 120\text{mL} of resin costing roughly $15. Finally, printed plastics can be designed using 3D CAD software that allows for preassembled testing of designs.

The design itself requires an XYZ translation stage as well as a rotational stage for the process of alignment. Once aligned, a mirror must be added to direct the final output of the module either through the front or out one of the two sides. Multiple designs were tested for ease of alignment and ability to be secured. The final design is shown in Figure 4.9.

For stability, the translational stage is divided into two parts. The first is a two sled combination to provide XZ control. The inner sled is supported by two flanges that run the length of the sled in the Z direction. These flanges have a tapered edge to reduce friction during alignment while maintaining contact with the outer sled. In this inner sled is mounted the laser, with access to the laser driver from the top. The outer sled runs along three flanges similar in shape to the inner sled and provides translation in X. Both sleds use a set screw and counter-spring combination to select the location of the sled. In order to reach the set screw of the inner sled, a groove is placed in the back of the housing in the X direction.

The second translational component is paired with the rotational control. This is possible since the axis of revolution is parallel to the translation of this stage, uncoupling the two. The axis of rotation is designed to land on the center of the input grating, making the alignment in X also rotationally invariant. The Y axis sled is designed as an "I", where the vertical section holds the LMW-SLM and the horizontal sections provide the runners for the track. It also relies on a set screw and counter-spring system for placement.

Rotational control is achieved by spinning the entire rotational stand to the desired angle. The stage has roughly 10 degrees rotation either side of the expected input angle, although
Figure 4.9: Rendered views of the modular design for alignment of LMW-SLMs. Shown are the following: A) the LMW-SLM in the Y translational sled, B) outer housing with top suppressed, C) the Z translational sled with laser and focusing lens, D) X translational sled, E) Y translational tower attached to the large rotational insert, and F) small rotational input for the final redirecting mirror.
in practice only about 3 degrees are necessary. A cap, located on the top of this rotational slot ensures the entire rotational insert cannot lift out of the modular housing. For finer rotational control, a slot designed for an extender bar is located on one side of the insert.

The mirror also must rotate and be aligned to the output of the device. Therefore a simple rotational tower, an insert similar to the larger rotational insert already described, is located in the larger rotational component. Since the output angles do not vary greatly, the rotational tower is placed as near the exit aperture as possible. This relative location is fixed even as the entire rotational insert moves, allowing this component to always remain aligned. Unfortunately, this relationship does create an X translational variation in the location of the output beam when directed forward, and a Z translational variation in the location of the output beam when directed to the side. This variation caused by variable input angles can be corrected by proper placement of the entire modulator in the optics deck.

Once assembled, the 3D printed alignment module has proven to be robust to physical impacts. During transport from BYU to MIT, it maintained the critical alignments of the device. For instructions on assembly and alignment see Section 5.2.

4.6 Other Design Considerations

Two key optimization parameters for the design of the LMW-SLM have not yet been mentioned: the depth of the waveguide and the shape of the IDT. Waveguide depth determines the angular spread, number of modes, and can impact the efficiency of the guided-to-leaky-mode transition. The shape of the ITD determines the efficiency of the RF-to-SAW conversion and the shape of the launched SAW. The effects of waveguide depth will be considered first.

4.6.1 Optimizing Waveguide Depth

As stated in Section 3.3.2, waveguide depth directly controls the number of modes and their angles by Equation 3.29. Graphically this is shown in 4.10. The zero-order mode is
Figure 4.10: The effect of both waveguide depth and wavelength on mode angles. The zero order mode is not shown. As the waveguide depth increases the number of modes increases. The represented wavelengths are as follows: **Blue** = 480nm, **Green** = 532nm, **Red** = 635nm. The critical angle for the waveguide to substrate boundary is shown as a horizontal black dashed line. Solid lines represent odd modes while dashed lines are even modes. Mode numbers are counted per color from left to right.

always parallel with the edges of the waveguide, at 0°. Increasing waveguide depth shifts all other modes toward parallel and can introduce higher order modes. Decreasing wavelength increases the total number of modes and their respective angles of travel. When designing a LMW-SLM, first choose the desired number of modes for the largest wavelength to be used. Then choose the appropriate waveguide depth.

Figure 4.11 illustrates the effect of changes in the depth of the proton exchanged waveguide. Increased depth tends to decrease the overall bandwidth of the LMW-SLM as well as increase the overall efficiency. It also causes a shift in the RF center frequency of the LMW-SLM. Since SAW frequency maps to output angle in the LMW-SLM, a 1µm waveguide is
used to maximize angular output[5]. Although this shallow waveguide is less efficient, this loss in efficiency allows for longer SAW interaction regions and larger hololines. The result is a higher numerical aperture and a tighter focus. Any loss in total output power can be overcome by increasing the light inside the waveguide.

The depth of dilute proton exchanged waveguides in lithium niobate can be designed according to

$$d_w = 2\sqrt{(Dt)}, \quad (4.5)$$

where $d_w$ is the depth of the waveguide, $t$ is the exchange time in hours, and $D$ is the coefficient of diffusion of the proton exchange melt. Once the $D$ of a particular melt is determined, any depth of the waveguide can be created. Although only one test is required
to calculated $D$, if the time of exchange is known and the depth is measured, I suggest multiple runs to remove sensitivity to measurement errors.

### 4.6.2 IDT Analysis

A simple chirped IDT has both electrical and acoustical components. Each finger pair on the IDT adds capacitance to the entire system and modifies the frequency response and coupling efficiency of the IDT. The filter’s frequency response determines the sensitivity of the IDT to a given RF signal. The physical aperture defines the diffraction pattern of the produced SAW. A detailed analysis of design parameters for the simple chirped, dispersive, and apodized IDT is given by Smith [22].

Smith analyzes the IDT by replacing each finger of the IDT with the equivalent circuit shown in Figure 4.12A. The capacitance of the $n$th finger pair, $C_n$, is given by

$$C_n = \frac{w_n \sqrt{\varepsilon_{11} \varepsilon_{33}}}{2} \frac{K(q_n)}{K'(q_n)}$$  \hspace{1cm} (4.6)
where \( w \) is the width of the region in which the fingers overlap, \( \epsilon_{11} \) and \( \epsilon_{33} \) are dielectric tensor components of the substrate, and \( K \) is the Jacobian complete elliptic integral of the first kind with

\[
q_n = \sin \left( \frac{\pi L_{sn}}{2L_n} \right) \tag{4.7}
\]

\[
q'_n = \sqrt{1 - q_n^2}. \tag{4.8}
\]

Both \( L_n \) and \( L_{sn} \) are lengths defined by the electrode spacing and can be seen in Figure 4.12B. The total capacitance of the IDT is \( C_T = \sum C_n \).

The acoustic transit angle \( \theta_n \) is found using the velocity of the SAW, \( v \) by

\[
\theta_n = \frac{\pi}{2} \frac{2fL_n}{v}. \tag{4.9}
\]

The transformer ratio \( r_n \) is given by

\[
r_n = (-1)^n \sqrt{(2f_rC nk^2 Z_0)} \frac{K(2^{-1/2})}{K(q_n)} , \tag{4.10}
\]

where \( k^2 \) is the surface-wave electromechanical coupling constant and \( Z_0 \) is the mechanical impedance of the substrate.

Analysis of an IDT is then accomplished by arraying the circuit models for the individual finger pairs and solving for the admittance coefficients.

It is important to note that the admittance coefficients, \( Y_{ij} \), relate to the electrical current or particle velocity, \( I_i \), and the voltage or acoustic force, \( E_i \), on each port by

\[
I_i = \sum_{j=1}^{3} Y_{ij}E_j \quad \text{where} \quad i = 1, 2, 3. \tag{4.11}
\]
4.6.3 IDT Design

A general design procedure follows. First, choose a desired load quality factor $Q_L$, center frequency $f_0$, and transducer admittance $G_L$. This sets the required total capacitance by

$$C_T = \frac{Q_L G_L}{2\pi f_0}.$$  \hspace{1cm} (4.12)

Second, choose a desired transfer function in the frequency domain using the form

$$H(f) = E(f) \exp[j\Phi(f)].$$  \hspace{1cm} (4.13)

Perform the Fourier transform to obtain the desired impulse response

$$h(t) = e(t) \exp[j\phi(t)].$$  \hspace{1cm} (4.14)

The positioning of each electrode can then be found by

$$\phi(t_n) + \arctan\left(\frac{Q_L e(t_n)\phi(t_n)}{2\pi f_0 e(t_n) + Q_L \delta e(t_n)/\delta t}\right) = n\pi \quad \text{where} \quad n = 1, 2, 3..., N.$$  \hspace{1cm} (4.15)

If aperture weighting is desired, then it can be solved for by

$$w_n = A \left(\frac{f_n}{f_0}\right)^{-3} K(q_n)K(q'_n) \left\{\left[e(t_n) + \frac{Q_L}{2\pi f_0} \frac{\delta e(t_n)}{\delta t}\right]^2 + \left[\frac{Q_L}{2\pi f_0} e(t_n)\phi(t_n)\right]^2\right\},$$  \hspace{1cm} (4.16)

where $A$ is a constant found after the fact to ensure the proper total capacitance. With the finger spacing and finger overlap determined, the IDT is ready for fabrication and testing.
CHAPTER 5. FABRICATION

This chapter is written with practical application in mind, designed to be a reference for those seeking only to duplicate the results of this thesis without giving a full understanding of the principles behind the technology. The three sections following describe the recipe used to create the improved LMW-SLM, the assembly and alignment process of the 3D printed module, and the assembly and function of the pulsed laser driver.

5.1 Improved LMW-SLM: Fabrication

5.1.1 Input Coupling Gratings

The LMW-SLM is fabricated on a clean sample of x-cut lithium niobate substrate. The first step to fabricating a LMW-SLM is to etch the input coupling gratings with a reactive ion etch, RIE, using a hard mask of aluminum. Figure 5.1 illustrates the procedure listed below:

1. Evaporate 600nm of aluminum onto the wafer to serve as a hard mask for both the input coupling gratings and the waveguides.

2. Spin a thin layer of appropriate positive resist, such as S1805.

3. Pattern the resist to expose the input coupling gratings and alignment marks for future masks. Orient the gratings so that input light will be traveling in the y-direction of the crystal.

4. Wet etch the aluminum in an aluminum etchant solution heated to 60°C until the substrate is exposed in the patterned regions. This should take approximately 30 seconds.
Figure 5.1: Fabrication steps for the current input coupling grating. The sub-figures are as follows: A) initial substrate, B) aluminum deposition, C) photoresist application, D) patterned resist, E) aluminum wet etch to create hard mask, F) RIE of the substrate, and G) intermediate cleaning for next process.

5. RIE the wafer in a $100 \text{mTorr}$ mixture of $2.2 \text{SCCM} \text{ Ar}$ and $100 \text{SCCM CF}_4$ with a power level of $300 \text{W}$ for 56 minutes.

6. Strip the photoresist from the substrate using Acetone and IPA.

7. Clean the wafer in Nanostrip.

5.1.2 Waveguides

After patterning the input coupling gratings, waveguides are created in a dilute proton exchanged melt of 100:1 Benzoic Acid and Lithium Benzoate by weight. Figure 5.2 illustrates the procedure listed below:

...
Figure 5.2: Fabrication steps for the current waveguides. The sub-figures are as follows: A) a clean etched sample, B) photoresist application, C) patterned resist, D) aluminum wet etch to create hard mask, E) dilute proton exchange, F) photoresist removal, G) wet etch to remove aluminum.

1. Spin a thin layer of positive resist.

2. Pattern the resist to expose the waveguide regions. Orient the waveguides in the y-direction of the crystal and align the pattern to the marks created with the input coupling gratings. Do not expose the area that will be used for the IDT.

3. Wet etch the aluminum that remains from the previous deposition in an aluminum etchant solution heated to 60°C until the substrate is exposed in the patterned regions. This should take approximately 30 seconds.

4. Submerge the wafer in the acid melt for 3 hours. Anneal the sample for 45 minutes at 375°C. Strip the photoresist from the substrate using Acetone and IPA.
Figure 5.3: Fabrication steps for the current interdigital transducers. The sub-figures are as follows: A) clean sample with input coupling grating and waveguides, B) aluminum deposition, C) photoresist application, D) patterned resist, E) aluminum wet etch to create transducers, F) photoresist removal.

5. Strip the aluminum hard mask using aluminum etchant.

6. Clean the wafer in Nanostrip.

5.1.3 Interdigital Transducers

With both the input coupling gratings and waveguides in place, it is time to fabricate the IDTs. The IDTs are patterned from a clean layer of aluminum deposited on the top of the substrate. Figure 5.3 illustrates the procedure listed below:

1. Evaporate 200 nm of aluminum onto the wafer. This layer will serve as the electrodes of the IDTs.

2. Spin a thin layer of positive resist.

3. Pattern the resist, exposing everything but IDTs. The IDTs should be placed at the end of the waveguide prepared to launch counter-propagating SAWs.
4. Wet etch the aluminum in an aluminum etchant solution heated to 60°C until the substrate is clear and only the IDT fingers remain. This should take approximately 10 seconds.

5. Strip the photoresist from the substrate using Acetone and IPA.

6. Clean the wafer in Nanostrip.

5.1.4 Output Coupling Gratings

The final step is to etch the output coupling gratings. Due to the fine feature size required, around 200nm, interference lithography is required at the patterning step. The slow etch rate of lithium niobate compared to photoresist in standard the RIE processes makes direct
etching of the pattern impossible. Instead, the output coupling gratings are made in a thin film of silicon nitride. Once this is done, the LMW-SLM is complete and ready for packaging. Figure 5.4 illustrates the procedure listed below:

1. Spin a thin layer of resist on the top surface of the substrate. This acts as a protective layer.

2. Set the protective resist by preforming a hard bake for 10 minutes at 100°C in an oven.

3. Using a PECVD process, deposit 200nm of silicon rich silicon nitride onto the bottom surface of the substrate. The higher the index of refraction the better.

4. Spin a thin layer of appropriate positive resist on the bottom surface of the substrate.

5. Expose the resist to the interference pattern. Use an 80mW laser with a 305nm wavelength and an exposure time of 2.5 minutes.

6. Develop the pattern in the resist.

7. RIE the bottom surface of the wafer in a 100mTorr mixture of 3.1SCCM O₂ and 25SCCM CF₄ with a power level of 100W for 2 minutes.

8. Do a final clean of the wafer using Acetone to remove the photoresist, Nanostrip to remove the organics, and IPA to clean off any chemical residues.

5.2 3D Printed Alignment Module: Assembly and Alignment

The 3D Printed Alignment Module allows for 4 Degrees of Freedom during the alignment of the LMW-SLM including: an XYZ translational stage and one rotational stage. There is also rotational stage for a small output mirror to direct the module’s final output in the correct direction. The steps to proper assembly and alignment are outlined in this section. Before assembly begins all set screw holes should be tapped for an 8-32 thread. Glue needs only to cure stiff, hot glue or superglue are sufficient.
5.2.1 Assembling the Laser XZ Translation Stage

For this step, the following components are needed (see Figure 5.5):

- (1) Module Base
- (1) Z Translational Sled
- (1) X Translational Sled
- (1) Lens Adapter Cap
- (1) 15mm Lens
- (1) Laser Diode (Either Pulsed or CW)
- (3) 8-32 Set Screws 1/2 inch in length and hex-key
- (4) Springs, #460 from Century Spring
- Linear polarizer
- Spring steel or other sturdy thin wire
- Superglue

The assembly is as follows:

1. Insert and remove the X Translational Sled into the Module Base repeatedly until the motion becomes smooth. Tolerances on parts are intentionally tight so this self-smoothing can occur. Likewise, smooth the Z Translational Sled with respect to the X Translational Sled.

2. Insert the Laser Diode into the Z Translational Sled. Guides are provided to help estimate orientation.

3. Using a polarizer, rotate the Laser Diode until TE illumination is achieved.
4. Tighten the set screw to hold the diode in place.

5. Glue the **Lens** to the **Lens Adapter Cap**.

6. Glue the **Lens Adapter Cap** to the **Laser Diode**.

7. Glue the **Laser Diode** into place without gluing the set screw.

8. Insert two springs into the **X Translational Sled** and secure them on the inside edge with pieces of spring steel long enough to hang out beyond the plastic.

9. Insert the **Z Translational Sled** all the way into the **X Translational Sled**.

10. Insert the remaining two springs into the **Z Translational Sled** and secure them on both sides with pieces of spring steel long enough to hang out beyond the plastic.

11. Insert the set screw used to position the **Z Translational Sled**.

12. Insert the **X Translational Sled** into the **Module Base**, attach the two springs with pieces of spring steel, and insert the set screw. The final result is shown in Figure 5.6.
5.2.2 Mounting the improved LMW-SLM

For this step, the following components are needed (see Figure 5.7):

- (1) The 10mm by 15mm by 1mm LMW-SLM
- (1) Y Translational Sled Insert
- (1) Y Translational Sled
- (1) RF Breakout Board

The assembly is as follows:

1. Mount the LMW-SLM on the Y Translational Sled Insert so that the input coupling grating is on the top and the 10mm side of the crystal nearest the input
Figure 5.7: Required parts for mounting the improved LMW-SLM.

coupling grating is flush to the side nearest the cross bar on the **Y Translational Sled Insert**. Secure this in place with super glue. The center of the grating should be located 1\text{mm} from the nearest 10\text{mm} side of the crystal.

2. Mount, with superglue, the **RF Breakout Board** on top of the **Y Translational Sled Insert** using the rails provided. Trim all excess rail.

3. Wirebond the **LMW-SLM** to the **RF Breakout Board**.

4. Insert the **Y Translational Sled Insert** into the **Y Translational Sled** so that the input side is flush and the slanted edge of the cross bar aligns.

5. Glue the **Y Translational Sled Insert** in place with superglue. The final result is shown in Figure 5.8.
5.2.3 Assembling the Rotation Stage

For this step, the following components are needed (see Figure 5.9):

- (1) Assembled Y Translational Sled with LMW-SLM
- (1) Large Rotational Stage
- (1) Assembled Module Base with Translational Sleds
- (1) 8-32 Set Screw 1/2 inch in length and hex-key
- (2) Springs, #460 from Century Spring
- Spring steel or other sturdy thin wire
The assembly is as follows:

1. Smooth the track for the Y Translational Sled by inserting and removing it from the Large Rotational Stage. Finish with the Y Translational Sled inserted completely into the Large Rotational Stage.

2. Insert the two springs into the top of the Large Rotational Stage and secure them with spring steel on the bottom of the upper cross bar of the Y Translational Sled and the top of the tower on the Large Rotational Stage.

3. Insert the set screw.

4. Insert the entire Large Rotational Stage Assembly into the Module Base Assembly and work the plastic until smooth. A hole is provided in the Large Rotational Stage for a hex key that can be used for leverage. The final result is shown in Figure 5.10.
5.2.4 Alignment

The alignment process, best taught in person, relies on the skill of the aligner to recognize the characteristic signs of proper leaky-mode coupling. Although a paper list is poor substitute, the steps below provide a guide for alignment. Alignment should be done as one continuous process for if unsecured by glue, small shifts over time will remove all critical alignments. A more detailed alignment procedure can be found in my work in JOVE [3].

1. Begin by turning on the laser.

2. Position the **Y-Stage** so that the channel desired is in line with the laser.

3. Position the **X-Stage** so that the laser is passing through the center of the input coupling grating.

4. Position the **Z-Stage** so that the laser is focusing on the input coupling grating. It may be helpful to remove the Large Rotation Stage Assembly temporarily to roughly
position the focal point of the laser in free space by passing a card or piece of white paper through the beam.

5. Slowly rotate the **Large Rotation Stage** until the characteristic streak is achieved (see Figure 5.11). Be sure that during rotation the laser continues to pass through the center of the input coupling grating. If the rotation stage is loose, it may be helpful to attach the **Large Rotation Stage** to the **Module Base** with a spring between the two pegs provided. One is located near the axis of rotation of the **Large Rotation Stage** and the other is nearby on the surface of the **Module Base**.

6. Apply an RF input signal into the breakout board. At this point, polarization rotated modulated light should be seen at the designed RF frequencies. Do fine adjustments to maximize the desired output light.

7. Once the desired levels are achieved, glue all components in place in the following order: the **Large Rotational Stage**, the **Z-Stage**, the **Y-Stage**, and finally the **X-Stage**. Avoid gluing the springs, set screws, and spring steel pins. Instead glue plastic to plastic.

8. Once glue sets, remove all possible hardware components (springs, set screws, and spring steel pins) and added additional glue if required. **Note**: If carefully assembled, all hardware components should be accessible for removal.

9. The **Small Rotational Tower Insert** can be used to select the final output angle of the light.

10. Cover the entire module with the appropriate lid and insert the polarizer over the exit aperture. If more precise light blocking is required, a knife-edge light block can be added immediately after the end of the LMW-SLM. The module is now ready for transportation and simple plug in use.
Figure 5.11: An image of the Characteristic Streak. In this image light travels from right to left. The bar of light on the right hand side of the image is the edge of the substrate, the bright dot in that bar is the entry point of the laser beam, the small illuminated square is the input coupling grating, and the streak of light leaving the grating is the Characteristic Streak. It is important to note that there are blobs of light on the back plane of the sample, seen in this image as above the Characteristic Streak. It is possible to confuse the presence of these blobs of light as the Characteristic Streak, however these blobs are neither as uniform or a narrow as the Characteristic Streak nor are they angularly selective.

5.3 Pulsed Laser Driver: Assembly and Testing

The Pulsed Laser Driver explained in this section is designed to fill the need for pulsed lasers diodes during preliminary testing of the properties of derotation by pulsed illumination and is not intended to be implemented as the final design. The Pulsed Laser Driver pulses by changing the gate voltage of a saturated MOSFET. The laser is either completely off or running at some set current level. Unfortunately, this solution may decrease the working lifetime of the laser diode. Future investigations should replace this simple circuit with an optically pulsed approach such as a Mach-Zehnder interferometer.

The parts list is as follows:

- (3) VP2106 P-Channel Enhancement-Mode Vertical DMOS FET
- (2) VN2106 N-Channel Enhancement-Mode Vertical DMOS FET
• (1) 2N3906 General Purpose Transistor
• (1) 100pF Capacitor
• (1) 100Ω Resistor
• (1) 10Ω Resistor
• (1) 1kΩ Potentiometer
• (1) 100Ω Potentiometer
• (3) Single signal test points
• (1) 3 port connector
• (1) 2 port connector

The Pulsed Laser Driver is soldered together following the circuit diagram shown in Figure 4.7 using common soldering techniques. Figure 5.12 shows the initial board and the populated board.

Testing is done without a laser diode attached. Inputs are routed as follows: 5V is supplied to the Vcc line indicated by the + symbol, ground is tied to the − symbol, S indicates the location of the input signal. Any input frequency below 5MHz may be used in testing. For the purpose of the initial test, use 100kHz.

Test each of the three test points using an oscilloscope with two inputs: one to measure the input signal and the other to probe the desired test point. The signal at first test point is an inverted copy of the original with a slight delay, around 100ns. If the unit is correctly assembled, this delay should be adjustable by the first potentiometer. The second test point shows the result of the NAND operation. The signal should be nominally on with a dip at the falling edge of the input signal. The duration of this dip is determined by the delay and is thereby controllable by the same potentiometer. The final test point shows the voltage supplied to the saturated N-Channel MOSFET that is used to regulate the current through
Figure 5.12: The pulsed laser driver before and after assembly. Upper: The assembled pulsed laser driver board as seen from the top. Lower: The unpopulated board as seen from below. Since the opposite sides of the two boards are show, the layouts are mirrored vertically.

the laser diode. It should show a pulse that is nominally off with a duration controlled by the first potentiometer and an amplitude determined by the second potentiometer. If all test points are correct, the driver is ready to be attached to a laser diode.
CHAPTER 6. RESULTS

6.1 An Improved LMW-SLM

The changes to the LMW-SLM design described in Chapter 4 created a device that is cheaper, easier to use, and more versatile than before. This chapter focuses on describing the effects of these changes in detail.

6.1.1 Results of the Input Coupling Gratings

The inclusion of input coupling gratings to the LMW-SLM has two important effects. First, it drops the cost of the LMW-SLM by 2 orders of magnitude. Second, it shrinks the size of the supporting hardware, eliminating the need for any clamping mechanism to hold the coupling prism. As a result of these changes, future generation holovideo monitors can employ multiple LMW-SLMs without significant added cost, allowing for the simpler module design with dedicated single color channels described in 6.1.4. Each module can be prealigned and quickly replaced as improvements are made, creating a ”plug and play” feel to the LMW-SLM. This in turn allows for inventors and designers with limited knowledge about the intricacies of the LMW-SLM to use this device in future prototypes.

Input coupling gratings improved total power output of our modulators from 14\(\mu W\) to 70\(\mu W\). The results of a simple efficiency comparison between prism coupling and grating input coupling are shown in Table 6.1. The power measurement was taken after a 1\(mm\) long proton exchanged waveguide. The best grating produced to date has a period of 6\(\mu m\), a depth of 362\(nm\), a fill factor of 50\%, and an efficiency of 15.1\%. This represents an improvement of about 7 times that measured from prism coupling.
6.1.2 Results of the Output Coupling Gratings

The silicon nitride output coupling grating described in this thesis serves as a proof of concept prototype, proving the ability to couple out of the bottom of the LMW-SLM (see Figure 6.1). The efficiency of the silicon nitride output coupling grating is very poor due to the index of refraction mismatch between silicon-rich silicon nitride. The highest index of refraction nitride created during my experimentation was 2.1, still much lower than lithium niobate at 2.2. Since the incident light strikes the bottom surface at well beyond the critical angle, the silicon nitride output coupling grating relies on evanescent coupling into the grating region. Direct surface etching is necessary before a grating output coupler can be used in a display.

6.1.3 Results of the Pulsed Laser Driver

The pulsed laser driver gives the user control over the amplitude and duration of a laser pulse triggered by a falling edge. The values used in the schematic included in Appendix A give a usable pulse range from $30\,\text{ns}$ to $330\,\text{ns}$ with an amplitude ranging from $0\,\text{V}$ to $5\,\text{V}$. Figure 6.2 shows three pulses, the green signals, produced by the pulsed laser driver.

A pulsed laser input into the LMW-SLM removes the need for derotation and allows the user to view the output of the LMW-SLM directly. Using this driver, a near-eye display prototype was created as a proof of concept. Figure 6.3 shows discrete lines as output from the LMW-SLM. The near eye display prototype did not use any derotation optic to stabilize the image.

Table 6.1: Comparison of Efficiency between Prism and Grating Input Couplers

<table>
<thead>
<tr>
<th>Coupler</th>
<th>Laser Power</th>
<th>Waveguide Power</th>
<th>Background Power</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prism Coupler</td>
<td>2820µW</td>
<td>52.2µW</td>
<td>0.4µW</td>
<td>2.1%</td>
</tr>
<tr>
<td>Grating Coupler</td>
<td>2820µW</td>
<td>467.8µW</td>
<td>42.4µW</td>
<td>15.1%</td>
</tr>
</tbody>
</table>
Figure 6.1: A) Photograph of the output of a silicon nitride output coupling grating. Coupling efficiency is low due to the index of refraction mismatch between silicon nitride and lithium niobate. However, the silicon nitride output coupling grating serves as a proof of concept showing that bottom output coupling, necessary for flat screen displays, is possible using the LMW-SLM. B) A later cleaner output coupling grating. The dashed line was added to show the laser flight path.

Figure 6.2: Three pulses created by the pulsed laser driver as seen on an oscilloscope. Shown is the ability to vary the pulse amplitude as well as the pulse length. The yellow signal is the input square wave created by a signal generator. The green signal is the voltage applied to the gate of saturated N MOSFET used to limit the current through the laser diode. The voltage is measured at test point 3 (TP3).
6.1.4 Results of the 3D Printed Alignment Module

The 3D printed alignment module provides a simple way to align the LMW-SLM by decoupling the X translational stage from the rotational stage. After alignment has been achieved, all parts can be secured in place by glue or epoxy. This enables the alignment to be maintained throughout the lifetime of the LMW-SLM.

The new modular design has been tested in both the holovideo monitor and in a newly created near eye display. In both cases it has successfully created holographic output. The entire module housing uses 120mL of resin costing roughly $15, making possible the inclusion of multiple independent LMW-SLM chips in one display[4]. A new design for the holovideo monitor’s optics deck, now with three independent LMW-SLMs, one for each color, is shown in Figure 6.4. At the time of this document, only the red channel has been assembled. A color cube is used to combine the color outputs.

Figure 6.5 compares the output image from a monochrome holovideo monitor using the LMW-SLM modular design to the input image. The monitor reproduces the input image
correctly; however, the illumination across the entire output area is nonuniform, creating an extra bright region above the bear’s nose and a dim region near the bird’s beak. Poor overall uniformity of output is not a result of poor alignment, but rather a lack of calibration of the RF input signal for the particular LMW-SLM design. The LMW-SLM naturally varies across its sweep and must be measured and adjusted to correct this output variation. This monitor has successfully been shipped to MIT from BYU and arrived in working condition with no technical assistance required.

A near eye display prototype has also been created. The near eye display is a similar concept to the holovideo monitor. Since only a small scanned aperture is required to fill the human eye, the extensive optical deck of the holovideo monitor could be collapsed down to a modular LMW-SLM and a single galvanometer. The second prototype of the entire display is shown in Figure 6.6. This prototype was shipped to DAQRI in Los Angeles, CA and is functioning there. The previous prototype did not yet employ the pulsed laser driver, relying
Figure 6.5: Comparison between the output of LMW-SLM module design when inserted into a holovideo monitor, top, and the input image, bottom. Calibration of the RF input signal can remove the non-uniform illumination of the output region, which leads to degradation in the image along the edges. However, the image proves the alignment capabilities of the new modular design. This monitor was shipped to MIT and is now functioning there, proving the stability of the alignment even during transport.

on an Arduino controlled system with CW illumination. It produced the images found in Figure 6.7.
Figure 6.6: A near eye display prototype. Shown are A) the pulsed driver board, B) the XZ translational sleds, C) laser and focusing lens, D) rotational insert and the tower for the Y translational sled, E) Y translational sled, modulator, and polarizer, and F) the steering galvanometer.

Figure 6.7: Input images, bottom, and output images, top, of a near eye display prototype. CW illumination was used, leading to the blurring shown.
CHAPTER 7. CONCLUSION AND FUTURE WORK

7.1 Conclusion

The LMW-SLM is a versatile device suited for holographic video output. It has the ability to create holographic images in full color with a single scanned 200 MHz channel. The addition of input grating couplers replaces the expensive prism coupler used previously and drops the cost of a single modulator from around $500 to $2. Input coupling gratings also reduce the size of the overall system by removing the need for bulky clamping hardware to hold the prism in place. Output coupling gratings remove the dependency of the LMW-SLM hololine on the thickness of the sample and allow for a perpendicular output suitable for planar displays. A pulsed laser input makes such a planar display possible by removing the need of a derotation optic and allowing the user to view the LMW-SLM output directly. Finally, the modular design provides a secure housing that is easy to align and maintains the critical alignments previously lost during transport. All of these improvements prepare the LMW-SLM for use in a wide range of holographic displays from flat panel to near eye displays.

7.2 Future Work

The work described in this thesis should be seen only as a starting point for the continued improvement of the LMW-SLM. Each of the added features can be optimized, and in many cases replaced, with more efficient solutions. I cover a few of those possible improvements in the paragraphs to come.

First, the input coupling grating is currently this grating is a simple symmetric binary grating etched into the surface of the waveguide. Efficiency could be greatly improved
by optimizing the coupling design for mode shape. The focusing sub-wavelength grating couplers described in [23] suggest one possible approach. In the 1500nm regime Wang et. al. achieved an insertion loss below 5dB with a simulated loss of 2dB. This could be combined with binary approximations of a blazed grating to improve input coupling efficiency further.

Second, the output coupling grating could benefit both from similar geometric optimizations applied to the input coupling grating as well as the creation of a hard mask process to etch the output coupling gratings directly into the surface of the lithium niobate. Although the hard mask could be designed using liftoff, liftoff procedures are limited by about half the thickness of the resist used to create the desired pattern and leave poor side walls. Lecestre reports a mask made by electroplating of nickel with near perfect vertical sidewalls and an aspect ratio of 1:1 [24]. Nickel provides a selectivity of 6 to 1 with lithium niobate and has an etch rate of 6nm/min. As such, an electroplated nickel mask appears to be a promising hard mask for output coupling gratings.

Third, the simple edge detector circuit of the pulsed laser driver cannot guarantee constant power output from the laser during the laser pulse, or even consistent power output from pulse to pulse as heat changes the resistance of the laser diode over time. A simple solution to this problem is to return to a CW laser input that can be regulated for consistency and then optically modulate the input of the LMW-SLM itself using a Mach-Zehnder interferometer. Chen proposes a bent Mach-Zehnder design with one arm longer than the other that could be used to create a system that is nominally off [25]. A more classic approach with equal length arms could be used in tight geometries.

Fourth, while free-space alignment with the 3D printed alignment module is straightforward, free-space methods are generally not compact. With the inclusion of an optimized input grating coupler, it becomes reasonable to design for a polarization-maintaining fiber-coupled laser output that could be directly coupled into the waveguide. Alignment of such a device could be accomplished once and cemented into place, creating a flexible and compact solution. If interchangeability is required, a self-aligning connector designed for temporary
alignments could be pursued. Such a solution would greatly reduce the footprint of the optical components required for the LMW-SLM. That reduction is essential for use in small displays such as the head-mounted, near-eye display.

A list of possible improvements to the LMW-SLM would not be complete without a brief mention into the many other integrated optic tools available to devices made in lithium niobate. First, the high electro optic coefficient of lithium niobate that makes Mack-Zehnder interferometers possible could also be employed to scan the output of the LMW-SLM in two dimensions by adding a phase offset to adjacent channels before the holographic encoded SAW knocks the trapped light out of the waveguide[26]. Second, frequency doubling of laser inputs would allow for the complete suppression of unguided light, while polarization rotation would remove the unmodulated guided light. Such frequency doubling has been shown for 410\textit{nm}, 542\textit{nm}, and 686\textit{nm} [27][28]. Finally, on-chip laser sources would greatly reduce the challenge of optical alignment. An end fire optical pumping laser is used in [28] to simultaneously create red, green, and blue laser lines in doped lithium niobate. Combining all of these future improvements would create a frequency-multiplexed, full color device capable of steering light in two dimensions with the unwanted light filtered out. Such a device would provide the holographic pixel required for a flat screen display, making large holographic displays a possibility.

I now extend the challenge to those who come after me to continue the improvement of the LMW-SLM and its surrounding systems until it becomes a standard way to view 3D data. Near-eye and flat-screen systems can be designed. Different form factors and display features can be added to the existing holovideo monitor. The functionality of the LMW-SLM can be expanded. Pick a challenge and overcome it.
REFERENCES


APPENDIX A. MATLAB AND EAGLE PREPARATION FILES

I chose to use the Heidelberg exposure for files in the .DXF file format. The photoresist used for all exposures is s1805. The Matlab code to create the holochip is as follows. For the current DXF_Library files contact the Electro-Holography Group at BYU.

This appendix presents first the Matlab code to create a holochip, then the resulting holochip DXF files, and finally the Eagle files for the pulsed laser driver.

1 clear all;
2 %--------------------------------------------------------------------------------------
3 % This writes three files that will be used on the Heidelberg to make the
4 % standard holochip device. It assumes s1805 a positive resist.
5 %
6 % The first file exposes the input gratings and alignemtn marks for RIE
7 % etching. The second file exposes the waveguides for dilute proton
8 % exchange. The third file exposes all but the transducers and grinding
9 % marker for an aluminum etch. To do this it must use the XOR option on the
10 % Heidelberg before exposure.
11 %
12 % The end result should look something like this:
13 %--------------------------------------------------------------------------------------
14 % | |
15 % | G>---------T |
16 % | |
17 % | G>---------T | x is horizontal
18 % | + 0 | y is vertical
19 % | G>---------T | 0 is the origin of all files
20 % | | + is the other alignment mark
21 % | G>---------T |
% All distances are in um. All files place the origin in the center of the sample.

User Parameters

label = 'HoloChip';

Device Dimensions – This will define your exposed sample area

finalXDimension = 8e3;  % longer side
finalYDimension = 5e3;  % shorter side

Label and Alignment Parameters

labelHeight = 500;
lineThick = 10;
markSize = 10;

Holochip Parameters

numChannels = 5;  % Number of transducers
channelSpacing = 500;  % Space between channels
channelWidth = 100;  % Width of the channel
channelCenter2Center = channelSpacing+channelWidth;
lambda0 = 0.638;  % Wavelength in um

Transducer Parameters

startf = 400;  % Transducer Chirp Start Frequency
stopf = 600;  % Transducer Chirp Stop Frequency
transducerX = 800;  % Length of the Transducer
busWidth = (channelSpacing−channelWidth)/2;  % Transducer bus width
outputDistance = 500;  % Transducer distance from the end of the sample
55 \textit{% Input Coupling Gratings}
56 \texttt{polishLineX =200; \% mark where to stop polishing}
57 \texttt{insetDistance = 1e3; \% distance right of polish line to center of grating}
58 \texttt{gratingSize = 400; \% side dimension of square input coupling grating}
59 \texttt{gratingPeriod = 6; \% period of the grating}
60 \texttt{HornCouplerEntryWidth = 1.5*channelWidth; \% Y diminsion of the initial opening of the Horn coupler}
61 \texttt{FF = .5; \% Grating Fill Factor}
62
63 \textit{% DFX Constants}
64 \texttt{linecolour = 7; \% Black}
65 \texttt{linetype = 1; \% Continuous}
66 \texttt{unitBox = [ [0,0]; [0,1]; [1,1]; [1,0]; [0,0]]; \% starts BL and moves CW}
67
68 \textit{% Enter Library Folder}
69 \texttt{oldPath = cd(’./DXF_Library’);}
70
71 \textit{% File 1 - Input Gating Coupler}
72 \textit{% This file draws what will be removed.}
73 \textit{% Create DXF File.}
74 \texttt{filename1 = strcat(label,’.Gratings.dxf’);}
75 \texttt{[fid, err] = DXF.start(filename1,1); \% The 1 signifies a scaling factor of one.}
76 \textit{In other words the units are in \textit{um}.}
77
78 \textit{% Place Center Alignment Marks}
79 \texttt{xStart = [0,-finalXDimension/2+insetDistance]; \% Lower left corner}
80 \texttt{yStart = [0,0]; \% Lower left corner}
81 \texttt{for i=1:length(xStart)}
82 \texttt{P = markSize*unitBox; \% Create One rectangle}
83 \texttt{DXF.poly(fid, xStart(i)+P(:,1), yStart(i)+P(:,2), size(P,1), linecolour,}
84 \texttt{linetype); \% Draw upper right Rectangle}
85 \texttt{DXF.poly(fid, xStart(i)-P(:,1), yStart(i)-P(:,2), size(P,1), linecolour,}
86 \texttt{linetype); \% Draw lower left Rectangle}
end

clear('P','xStart','yStart');

% Calculate Grating Positions, offset if odd
totalGratingSize = gratingSize+(numChannels-1)*channelCenter2Center;
if mod(numChannels,2)==1 % Odd
    channelOffset = channelCenter2Center/2;
else
    channelOffset = 0;
end

% Place Grating
xStart = -finalXDimension/2+insetDistance-gratingSize/2;
for i = 1:numChannels
    yStart = channelCenter2Center*(i-1)+gratingSize-totalGratingSize/2+
              channelOffset;
    DXF_grating( fid, xStart, yStart, gratingSize, gratingSize, gratingPeriod,
                                      90, FF );
end

clear('xStart','yStart');

% Close first file
DXF_end(fid);

%% File 2 - Waveguides
% This file draws what will be removed.
% Create DXF File.
filename2 = strcat(label,'_Waveguides.dxf');
[fid, err] = DXF_start(filename2,1); % The 1 signifies a scaling factor of one.  
    In other words the units are in um.

% Place Center Alignment Marks
xStart = [0,-finalXDimension/2+insetDistance]; % Lower left corner
114 % yStart = [0,0]; % Lower left corner
115 % for i=1:length(xStart)
116 % P = markSize*unitBox; % Create One rectangle
117 % DXF_poly(fid, xStart(i)+P(:,1), yStart(i)+P(:,2), size(P,1), linecolour, linetype); % Draw upper right Rectangle
118 % DXF_poly(fid, xStart(i)-P(:,1), yStart(i)-P(:,2), size(P,1), linecolour, linetype); % Draw lower left Rectangle
119 % end
120 % clear ('P', 'xStart', 'yStart');
121
122 % Draw Input Coupling Pad
123 couplingPadX = insetDistance+gratingSize/2;
124 Y = finalYDimension;
125 P = unitBox.*repmat([couplingPadX,Y],[5,1]);
126 DXF_poly(fid,P(:,1)-finalXDimension/2,P(:,2)-finalYDimension/2,size(P,1), linecolour,linetype);
127
128 % Determine waveguide starting position
129 totalWaveguideWidth = channelOffset-channelWidth-(numChannels-1)*channelCenter2Center;
130
131 % Draw Waveguides
132 for i = 1:numChannels
133 % Add Horn Coupler
134 xStart = couplingPadX-finalXDimension/2;
135 yStart = channelCenter2Center*(i-1)-(numChannels-1)/2*channelCenter2Center+channelOffset;
136 hornCouplerLength = DXF_Horn_Coupler( fid, xStart, yStart, HornCouplerEntryWidth, channelWidth, lambda0);
137 clear ('P', 'xStart');
138
139 % Long Rectangular Portion
140 xStart = -finalXDimension/2+couplingPadX+hornCouplerLength;
straightWaveguideLength = finalXDimension/2-transducerX-outputDistance-
xStart;
P = [[0, -channelWidth/2]; [0, channelWidth/2]; [straightWaveguideLength,
channelWidth/2]; [straightWaveguideLength, -channelWidth/2]; [0, -
channelWidth/2]];
DXF.poly(fid, xStart+P(:,1), yStart+P(:,2), size(P,1), linecolour, linetype);
% Draw upper right Rectangle

clear('P','xStart');
end

% Close second file
DXF.end(fid);

%% File 3 - Transducers
% This file needs to be XORed before exposure.
% Create DXF File.
filename3 = strcat(label,'_Transducers_XOR.dxf');
[fid, err] = DXF.start(filename3, 1); % The 1 signifies a scaling factor of one.

% In other words the units are in um.

%% Place Center Alignment Marks
% xStart = [0, -finalXDimension/2+insetDistance]; % Lower left corner
% yStart = [0, 0]; % Lower left corner
% for i=1:length(xStart)
% P = markSize*unitBox; % Create One rectangle
% DXF.poly(fid, xStart(i)+P(:,1), yStart(i)+P(:,2), size(P,1), linecolour,
% linetype); % Draw upper right Rectangle
% DXF.poly(fid, xStart(i)-P(:,1), yStart(i)-P(:,2), size(P,1), linecolour,
% linetype); % Draw lower left Rectangle
% end
% clear('P','xStart','yStart');

%% Place Label
xStart = gratingSize/2+insetDistance−finalXDimension/2;

labelDist = −(totalGratingSize/2+channelOffset−labelHeight−channelWidth);

DXF_text(fid, xStart, −labelDist, labelHeight, label, linecolour, linetype, 'LEFT');

clear('xStart');

% Draw Transducers

for i = 1:numChannels
    % Make Transducer
    yStart = channelCenter2Center∗(i−1)−(numChannels−1)/2∗channelCenter2Center+
             channelOffset;
    xStart = finalXDimension/2−0.5∗transducerX−outputDistance;
    DXF_transducer(fid, 'tr', 'clk', 90, channelWidth, transducerX, xStart, yStart,
                   startf, stopf, busWidth);
end

clear('X', 'Y', 'xStart', 'yStart');

% Make the Polishing Line

X = polishLineX;
Y = finalYDimension;
P = unitBox.*repmat([X, Y], [5, 1]);

DXF_poly(fid, P(:,1)−finalXDimension/2−polishLineX,P(:,2)−finalYDimension/2,
          size(P,1), linecolour, linetype);

% Make XOR Bounding Box

partY = max(labelDist+channelWidth,finalYDimension/2);
allX = finalXDimension+polishLineX+200;
allY = finalYDimension/2+partY;
P = unitBox.*repmat([allX, allY], [5, 1]);

DXF_poly(fid, P(:,1)−finalXDimension/2−polishLineX−200,P(:,2)−partY, size(P,1),
          linecolour, linetype);

% Close the file
DXF_end(fid);

%%% Output Constants to file
filename4 = strcat(label, '_Parameters.txt');
fid = fopen(filename4, 'w');

fprintf(fid, '%%% User Parameters
');
fprintf(fid, 'label = \x27%s\x27 ;
', label);
fprintf(fid, '\n');

fprintf(fid, '%%% Device Dimensions – This will define your exposed sample area
');
fprintf(fid, 'finalXDimension = %d ; %%% longer side\n', finalXDimension);
fprintf(fid, 'finalYDimension = %d ; %%% shorter side\n', finalYDimension);
fprintf(fid, '\n');

fprintf(fid, '%%% Label and Alignment Parameters
');
fprintf(fid, 'labelHeight = %d ;
', labelHeight);
fprintf(fid, 'lineThick = %d ;
', lineThick);
fprintf(fid, 'markSize = %d ;
', markSize);
fprintf(fid, '\n');

fprintf(fid, '%%% Holochip Parameters
');
fprintf(fid, 'numChannels = %d ; %%% Number of transducers\n', numChannels);
fprintf(fid, 'channelSpacing = %d ; %%% Space between channels\n', channelSpacing);
fprintf(fid, '
');

fprintf(fid, '%%% Transducer Parameters
');
fprintf(fid, 'startf = %d ; %%% Transducer Chirp Start Frequency\n', startf);
fprintf(fid,'stopf = %d; \%% Transducer Chirp Stop Frequency\n',stopf);
fprintf(fid,'transducerX = %d; \%% Length of the Transducer\n',transducerX);
fprintf(fid,'busWidth = %d; \%% Transducer bus width\n',busWidth);
fprintf(fid,'outputDistance = %d; \%% Transducer distance from the end of the sample\n',outputDistance);
fprintf(fid,'\n');
fprintf(fid,'% % Input Coupling Gratings\n');
fprintf(fid,'polishLineX = %d; \%% mark where to stop polishing\n',polishLineX);
fprintf(fid,'insetDistance = %d; \%% distance right of polish line to center of grating\n',insetDistance);
fprintf(fid,'gratingSize = %d; \%% side dimension of square input coupling grating\n',gratingSize);
fprintf(fid,'gratingPeriod = %d; \%% period of the grating\n',gratingPeriod);
fprintf(fid,'HornCouplerEntryWidth = %d; \%% Y dimension of the initial opening of the Horn coupler\n',HornCouplerEntryWidth);
fprintf(fid,'FF = %1.2f; \%% Grating Fill Factor\n',FF);
fclose(fid);
%
Finish

% Warnings

if (allY>finalYDimension)
disp(['Warning the created Y (',num2str(allY),') is larger than the desired Y (',num2str(finalYDimension),')']);
end

if (0>straightWaveguideLength)
disp('Horn coupler entry width too wide');
end

disp(['Final Draw Dimensions: x=',num2str(allX),', y=',num2str(allY)]);
% Move all files into the correct folder
ZerosIsGood = fclose('all');   % verify that all files are closed
copyfile([label,'*'],[oldPath,'./DXF_Files/','label]);
delete([label,'*']);
cd(oldPath);
disp('Done!');