Waveguide-Based Spatial Light Modulators for Use in Holographic Video Displays

Kamran Qaderi
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Waveguide-Based Spatial Light Modulators for Use in Holographic Video Displays

Kamran Qaderi

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Daniel Smalley, Chair
Gregory Nordin
Aaron Hawkins
Steven Schultz
Karl Warnick

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ABSTRACT

Waveguide-Based Spatial Light Modulators for Use in Holographic Video Displays

Kamran Qaderi
Department of Electrical and Computer Engineering, BYU
Doctor of Philosophy

Film display holograms typically diffract light over a wide enough view-angle to be viewed, directly, without intervening optics. However, all holographic video displays must use optics beyond the hologram surface to overcome the challenges of small display extent and low diffraction angle by using some form of demagnification and rotation. We report a leaky mode waveguide spatial light modulator (SLM) with sufficiently high angular diffraction to obviate the need for demagnification in scanned aperture systems. This was achieved by performing a number of experiments to determine the depth of the annealed, proton-exchanged waveguide which corresponded to a maximized diffracted angle. Diffraction sweeps were recorded in excess of 19.5° for 632.8 nm light which is above the 15° required for direct view display.

Moreover, we present a paired set of waveguide SLMs capable of a maximum light deflection nearing 28° for red. This deflection, which is several times larger than the angular sweep of current, state-of-the-art modulators, is made possible by the unilateral, near-collinear waveguide nature of the leaky mode interaction. The ability to double angular output in this way, which is either not possible or not practical in other SLMs, is possible in leaky mode devices, thanks to the absence of zero-order light and the lack of high-order outputs. This combined structure has angular deflection high enough to enable color holographic video monitors that do not require angular magnification. Furthermore, the low cost and high angular deflection of these devices may make it possible to make large arrays for flat-screen video holography.

One improvement that could be made to the current setup would be to increase the device’s diffraction efficiency. One highly influential factor of diffraction efficiency for a Bragg-regime surface acoustic wave (SAW) grating is the length of the interaction between the light and the grating. In this work, we have shown that guided light in a reverse proton exchanged (RPE) waveguide experiences less loss. This enables us to create longer devices which eventually results in devices with higher diffraction efficiency.

We have also researched on LCoS SLMs and used them for two different applications: (a) photophoretic-trap volumetric displays and (b) holographic video displays. In the first case, aberrations including spherical, astigmatism, and coma can make particles to trap tighter in the focal point of the beam. Also, a new approach for holographic computations is presented which uses the electromagnetic nature of light in Maxwell Equations to find a unique phase map for every specific 3D object in space.

Keywords: holography, holographic video displays, 3D displays, spatial light modulators, leaky mode waveguide light modulators, proton exchange
ACKNOWLEDGMENTS

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To Shiva, My Dearest
# TABLE OF CONTENTS

**ACKNOWLEDGEMENTS** ................................................................. iii

**LIST OF TABLES** ................................................................. vii

**LIST OF FIGURES** .............................................................. viii

**LIST OF LISTINGS** ............................................................. xiii

**Chapter 1 Introduction** ......................................................... 1
  1.1 Why 3D Displays? ............................................................. 1
  1.2 How 3D is Different from 2D? Through 3D Cues. ...................... 2
  1.3 Why Holography? ............................................................ 4
  1.4 Overview of Dissertation .................................................. 6

**Chapter 2 Background** ......................................................... 7
  2.1 Static Holograms ............................................................... 9
    2.1.1 On-Axis Hologram (Linear Fringes) ............................... 9
    2.1.2 Gabor Hologram (In-Line: Fresnel Zone Plate) ............... 11
    2.1.3 Leith-Upatnieks (Off-Axis) Hologram .......................... 13
    2.1.4 Benton (Rainbow) Hologram ....... ................................. 14
    2.1.5 Denisyuk Hologram .................................................. 14
    2.1.6 Physics of the First Hologram Made by Denis Gabor .......... 16
  2.2 Dynamic Holograms ......................................................... 20
    2.2.1 Holographic Video Displays ....................................... 20
    2.2.2 Spatial Light Modulators .......................................... 22
  2.3 My Contributions ............................................................ 37

**Chapter 3 Leaky Mode Waveguide Light Modulators with High Deflection Angle** ........... 38
  3.1 Introduction ................................................................. 38
    3.1.1 Theory ................................................................. 42
    3.1.2 Fabrication ........................................................... 43
  3.2 Testing and Experiment ................................................... 44
  3.3 Results ..................................................................... 45
  3.4 Conclusion ................................................................. 47
  3.5 Funding ....................................................................... 49

**Chapter 4 Tileable Leaky Mode Devices** ....................................... 50
  4.1 Introduction ................................................................. 50
  4.2 Design and Fabrication ................................................... 54
  4.3 Experiments ................................................................. 54
  4.4 Results ....................................................................... 56
  4.5 Conclusion ................................................................. 57
### Chapter 5 Low-Loss Waveguides with Reverse Proton Exchange Technique

- **5.1 Introduction**
- **5.2 Principles**
- **5.3 Fabrication and Results**
- **5.4 Conclusion**

### Chapter 6 LCoS Spatial Light Modulators

- **6.1 Liquid Crystals**
- **6.2 LCoS as a Spatial Light Modulator**
- **6.3 Applications of LCoS**
  - 6.3.1 Optical Trapping in Photophoretic-Trap Volumetric Displays
  - 6.3.2 Maxwell Holography
- **6.4 Conclusion**

### Chapter 7 Conclusion and Future Work

- **7.1 Conclusion**
- **7.2 Future Work**

### REFERENCES

### Appendix A Matlab Codes and Supplementary Images
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>3D displays and their respective 3D depth cues. Discretized view zone displays cannot provide continuous accommodation since there are only a couple focal plane. Volumetric displays are not capable of occlusion, but holographic displays can possess all the cues so depth perception is successfully achieved.</td>
<td>4</td>
</tr>
<tr>
<td>3.1</td>
<td>Mode characteristics of different devices with different waveguides’ depth. The first four columns shows the device label, proton exchange time, waveguide depth, and number of guided modes respectively. The fifth column identifies the highest guided mode leaky mode transition and the sixth column gives the guided to leaky mode transition originated from the second highest guided mode.</td>
<td>46</td>
</tr>
<tr>
<td>4.1</td>
<td>Different SLMs.</td>
<td>52</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

1.1 This image shows the bottleneck between abundant 3D information in the world and human visual system (optimized for 3D viewing of the world around us) imposed by 2D displays. These images are free to use with modification for noncommercial purposes. 1

1.2 Representations of the three-dimensional depth cues that the brain uses to create a 3D perception of the world. (a) Parallax: the difference in position between the two eyes creates two different views of the cubes. (b) Accommodation: in the left image, while red cube is in focus, the blue cube is out of focus and vice versa for the image at the right side. (c) Occlusion: depending on the viewing angle, different part of the objects at the back are blocked. For instance, in the left image, the right side of the blue cube is blocked, in the middle image, only top of the blue cube is seen, and in the right image, the left part of the blue cube is blocked. 3

2.1 Hologram recording layout of a cube. First, a coherent laser beam is split by a beam splitter. One part illuminates the object and the other part operates as a reference beam. The reflected beam from the object and the reference beam create a diffraction pattern on the photographic plate which is called the Hologram. Image: Wikimedia Commons 7

2.2 Hologram reconstruction layout. A reconstruction beam illuminates the hologram at the same angle of the reference beam. This will produce a virtual image at the same location of the object. Image: Wikimedia Commons 8

2.3 This graph shows different types of holograms recorded at different locations in space. For instance, at location B, Gabor hologram can be made. A diffraction pattern here performs like a focusing lens which can focus light to different points in space or a hologram at location D, is called Denisyuk hologram. This type of hologram is the first invented white-light illumination static hologram. 10

2.4 On-axis hologram (linear fringes), plotted in Matlab. 11

2.5 Gabor hologram (in-line: fresnel zone plate), plotted in Matlab. 12

2.6 Leith-Upatnieks (off-axis) hologram, plotted in Matlab. 13

2.7 Principle of Benton’s rainbow hologram. A) The interference pattern of the object (this object has volume) and the reference beam 1 is recorded on H1, the master hologram. B) The image of H1 is reconstructed through a slit on H1 by the conjugate reference beam 1. H2 plate, the transfer hologram, is positioned on the location of the reconstructed image. C) The diffraction pattern of H1 image (through the slit) and the reference beam 2 is recorded on H2. D) The final hologram, H2, is illuminated by the conjugate reference beam 2. It reconstructs a colored image depending on the angle of viewing. 15

2.8 Schematic of a transmission and reflection grating. A) The grating is on the surface of the plate. B) The grating is volume Bragg grating inside the gelatin film on the plate. 16

2.9 Denisyuk hologram setup. 16

2.10 Illustration of Gabor’s method of imaging by reconstructed wavefronts. (a) Recording the hologram. (b) Reconstruction of the hologram. (c) Equivalent one-step imaging using a 2f imaging system. 18

2.11 The Hurter-Driffield curve (photographic response). 19
2.12 Imaging by reconstructed wavefronts. The noisy background is mainly due to the imperfections of the illuminating objective. (After Denis Gabor, Proc. Roy. Soc., A, 197 (1949), 454.) .................................................. 21

2.13 Single channel leaky mode device. .......................................................... 24

2.14 Reflection and refraction of a plane wave at a boundary of two different media with different optical properties. All the vectors are in the plane of incidence. .............. 28

2.15 Dielectric slab waveguide of width 2d. ......................................................... 29

2.16 Graphical solution of the eigenvalue equations for both TE and TM modes for a specific waveguide depth. .......................................................... 31

2.17 Thin Sinusoidal Phase Grating. ................................................................. 32

2.18 (a) (left) An index guided mode is evanescent in both the air and substrate. (right) A leaky mode is evanescent in the air but has a propagating component in the substrate. (b) k-space diagram of the waveguide and substrate modes. Here the large semicircle has a larger radius corresponding to the larger momentum vector of light travelling in the material. For rays traveling below critical angle, the projection of the momentum vector will lie inside the waveguide semicircle where it is guided and outside the substrate circle where it is evanescent. The projection of a leaky mode would be inside both semicircles which means the wave in the waveguide passes the boundary between the media and propagates inside the substrate. .................................................. 36

3.1 a) 15° is needed for eye to view a static hologram with both stereopsis and motion parallax at a standard viewing distance of 500 mm from the hologram. b) 3° deflection of a typical spatial light modulator adds the need for a telescope to increase the view angle to 15° by utilizing the two lenses of different focal length. The light is also optically multiplexed via a scanner. c) Our fabricated device with deflection of larger than 15° used in the holovideo without demagnification (the focal length of both lenses is the same). d) It is now possible to multiplex devices physically to enable direct-view architectures. .......................................................... 40

3.2 Leaky-Wave device physics. a) TE light enters the waveguide as a high-order guided mode, then, interacts anisotropically with the surface acoustic wave. The result of this interaction is that a portion of the guided light is polarization rotated and therefore no longer guided. The light then exits the waveguide as TM-polarized leaky mode light. b) Light illuminating a grating at the normal deflects less than light which illuminates the grating from glancing angles (as is the case for light interacting with a grating in a waveguide) c) This graphic shows the k-space diagram for the cases of normal and near-collinear illumination which enable widely disparate deflections given the same grating period. .......................................................... 41

3.3 Modulation amplitude of the off-diagonal dielectric tensor element, $\Delta \varepsilon_{r}$, for a specific proton-exchanged device which is mainly responsible for the conversion of TE-guided modes to TM-leaky modes in proton-exchanged lithium niobate. [From Rust and Strake, PADERBORN UNIV (GERMANY FR) (1992).] .................................................. 43

ix
3.4 Fabrication process. a) The slab waveguide is created via proton exchanging the device. The interdigital transducers are written on the aluminum side of the sample. The light interaction length in this device is 4 mm. b) The smallest spacing (p) between the fingers is 6.54 (µm) and the maximum is 9.74 (µm). Width (W) and length (L) of the IDTs are 100 (µm) and 800 (µm) respectively. c) The index profile of the device. \( n_{\text{eg}}, n_{\text{og}}, n_{\text{es}}, \) and \( n_{\text{es}} \) are the ordinary and extraordinary refractive indexes of the waveguide and the substrate.

3.5 Apparatus used for data acquisition.

3.6 Angular Bandwidth. For example, for red, the highest guided mode in sample Y2 is TE2. Transitions from TE2 to the leaky mode have an angular bandwidth in excess of 19°. This angular output along with the angular output for sample Y3 forms the local and global maxima for the highest order transition for all depths.

3.7 Bandwidth for RGB of multiple devices.

3.8 Method of doubling the deflection angle. a) Unilateral angular output from one device. b) Bilateral angular output from two devices glued together (both positive and negative angles). c) Bilateral angular output with one monolithic device having waveguide and IDTs at both sides of the sample.

4.1 Comparison between combining LCoS SLMs and leaky mode SLMs.

4.2 Leaky mode device physics. a) TE light enters the waveguide as a high-order guided mode, then, interacts anisotropically with the surface acoustic wave. The result of this interaction is that a portion of the guided light is polarization rotated and therefore no longer guided. The light then exits the waveguide as TM-polarized leaky mode light. b) Light illuminating a grating (7 µm period and \( \lambda = 633 \) for this specific graph) at the normal deflects less than light illuminating the grating from glancing angles (as is the case for light interacting with a grating in a waveguide).

4.3 Fabrication steps. a) 600 nm aluminum is evaporated on the sample followed by coating a positive photoresist. b) The sample is patterned with the grating input couplers. c) The aluminum is etched away and 200 nm new aluminum is coated on the sample. d) The waveguides are written on the sample. e) The sample is proton-exchanged. f) The aluminum is etched off and 200 nm new aluminum is evaporated on the sample. g) The IDTs are written on the sample. h) The IDT is composed of several fingers with a set of chirped frequencies.

4.4 Apparatus used to record data.

4.5 A typical tested device. A) TE polarized light illuminating the grating input coupler at an incident angle of 40° from the bottom of the crystal. B) Grating input coupler along the whole width of the edge of the device. C) Light streak coupled into the waveguide. D) Transducers. E) PCB board connecting RF input to the device. F) Sample holder. TE-guided light interacts with the surface acoustic waves created by the IDT and TM polarized leaky wave exits the end of the substrate as a result of the interaction.

4.6 Color-map response of the paired devices. It shows a deflection angle of 28° for this device.

4.7 Deflected dots. a) Bilateral angular output from two devices glued together (both positive and negative angles). b) Angular and frequency bandwidths are respectively 28° and (65 MHz for both side devices).
5.1 Light enters the AO SLM by way of prism coupling. As the light travels along the waveguide, it encounters a surface acoustic wave (SAW) produced by interdigital transducers laid on top of the waveguide. Some of the light leaks out of the waveguide and exits the device at an angle determined by the frequency of the light and the acoustic wave. By modulating the frequency of the SAW, different angles can be achieved.

5.2 Interaction length in a leaky mode waveguide light modulator.

5.3 Increasing the interaction length in leaky mode waveguide light modulators compared to increasing the size of the pixelated spatial light modulators.

5.4 RPE steps.

5.5 Comparison of the refractive index profile for PE, DPE, and RPE leaky mode modulators.

5.6 a) Working DPE leaky mode device. b) Working RPE leaky mode device.

5.7 Loss comparison in RPE and DPE. Based on this image, it is clear that more light exits the RPE device. The pictures are squashed vertically to fit them in a tighter space.

5.8 Output light on a screen. The top image shows the output light existing a DPE waveguide. The bottom image demonstrates the output light exiting the RPE waveguide. It shows that the light from the RPE sample is brighter and more light is present in the output. The pictures are squashed vertically to fit them in a tighter space.

6.1 Isotropic, Nematic, Smectic phase of liquid crystals (LCs). As discussed in the text, LCs in isotropic phase have no specific orders as opposed to the nematic phase in which they have a orientational order. Besides orientational order LCs have positional order as well in the smectic phase.

6.2 Anisotropy property vs voltage applied. A weak voltage rotates the liquid crystal not all the way along the external electric field. However, the liquid crystals will get in line with the electric field if it is strong enough.

6.3 Birefringence property. The refractive index of the optical axis is larger than the refractive index of the other two axes. In positive liquid crystals, extraordinary refractive index is larger than ordinary refractive index. This makes the optical axis "the slow axis" since the speed of light is slower due to higher refractive index in that direction.

6.4 Hamamatsu X10468-01 phase-only 792x600 pixel spatial light modulator.

6.5 Solid-state aberration trap. A) An LCoS pattern used to encode an aberration optical trap. B) The display trapping function can be changed to that of a solid-state display by encoding the phase pattern of the holographic trap on an SLM as shown.

6.6 Optical path of a holographic video display. Red (638 nm), green (520 nm), and blue (450 nm) lasers are used to create a white illumination system. a, b, and c are long-pass dichroic mirrors specific to RGB lasers which combine the light beams to create a white beam. d is a non-polarizing beam splitter that transmits half of the incident light and reflect the other half to the light trap, e, designed to block the unwanted light. Eventually, transmitted light illuminates the LCoS, f, and half of the diffracted light is reflected to the other unblocked side of the beam splitter. The holographic image can be projected on a screen (with different planes of accommodation) or be observed in a direct-view mode.
6.7 This model was a set of vertices and polygons which was downloaded from Stanford Computer Graphics Laboratory’s website. The vertices were then used in a commercially available game platform called Unity to create a model made of points.

6.8 Hologram (Phase Map) for each separate color. Blue always diffracts less than green and red and green diffracts less than red based on diffraction grating equation. Light with shorter wavelength diffracts to a lower output angle.

6.9 Reconstructed holographic image of the famous Stanford bunny. The model was first imported to Unity and was fed to the LCoS.

A.1 Sketch of the waveguide channels and interdigital transducers (IDTs) created in Klayout software.

A.2 A complete fabricated device ready to test.

A.3 Results of metricon of a leaky mode device with 9 TE-polarized waveguide modes.

A.4 A typical frequency and angular response of a leaky mode device.

A.5 A complete paired device ready to test held in a sample holder designed in Solidworks and 3D printed using our lab’s Formlabs 3D printer.

A.6 3 dimensional plot of the intensity of the diffracted light vs surface acoustic frequency and position of the light meter.

A.7 Star Trek Enterprise image made in the volumetric displays built in our lab.

A.8 Charmander image made in the volumetric displays built in our lab. It shows the image at two different view angles, front and back.
LIST OF LISTINGS

A.1 Matlab code for off-axis hologram (linear fringes) . . . . . . . . . . . . . . . . . . . . 91
A.2 Matlab code for Gabor hologram (in-Line: Fresnel zone plate) . . . . . . . . . . . . . 91
A.3 Matlab code for Leith-Upatnieks (off-axis) hologram ................................. 92
A.4 Matlab code for different kinds of aberrations. ................................. 92
CHAPTER 1. INTRODUCTION

1.1 Why 3D Displays?

Much of the information in the world that we are interested in visualizing is 3D, from MRI data (Magnetic Resonance Imaging) to LIDAR images (Light Detection and Ranging) to 3D animated games and movies. We humans live in a 3D world and our visual system is optimized to receive and process 3D data. We have learned to compromise by using 2D media, mostly books, pictures and TV which has created a bottleneck between our eyes and the world’s vast and rapidly growing trove of 3D information (see Figure 1.1). The increasing of memory and decreasing cost of computations has brought us to the threshold of using 3D in many of the things we do. We can expect an increasing number of 3D medical, military, and personal augmented reality (AR) devices in near future. While technically feasible to use 3D displays, the economics of adopting it requires major changes to how it’s recorded and displayed.

![Figure 1.1: This image shows the bottleneck between abundant 3D information in the world and human visual system (optimized for 3D viewing of the world around us) imposed by 2D displays. These images are free to use with modification for noncommercial purposes.](image)

Although too much work and research has been conducted in the field of 3D displays, an inexpensive commercial display capable of true 3D has not yet been successfully deployed. Mark
II of MIT, one of the very first holographic video displays in history of 3D displays, tend to be large and inevitably expensive that makes them difficult to reach consumers. Cheaper displays such as Google Cardboard, rely only on a few true 3D cues which makes the images and videos feel like 3D. This means some capabilities of 3D displays are sacrificed in order to make the display cheaper and smaller in size. This kind of 3D brings about side effects of nausea, fatigue, and strain since viewer’s brain compensates the lack of capabilities such as accommodation.

1.2 How 3D is Different from 2D? Through 3D Cues.

Human brain can convert a pair of two images on top of each other into a 3D image through eyes. There are a couple 3D cues that brain relies on to differentiate between 2D and 3D images. In 2D displays, shape and size of the objects and shading are 2D cues that can be displayed on a 2D display. However, the 3D cues of parallax and accommodation, and occlusion are the elusive cues that must be mastered to create a true 3D display.

Parallax, describes the difference between two view angles and how the human eye sees the image. This difference in view becomes more pronounced as close objects are observed. Objects far from the viewer (like trees on the horizon) look the same when viewed from one eye or the other; but, objects nearby change perspective between the eyes. If a display does not provide parallax, it destroys the 3D aspect of the visual data (see Figure 1.2(a)).

The second cue, accommodation, arises from the physical nature of the human eye which is a perfectly designed flexible optical lens. In order to bring an object into focus, the lens inside the eyeball becomes thicker or thinner depending on the object location which changes the curvature of the lens and as a result changes the focal point of the lens (see Figure 1.2(b)).

The last 3D cue is occlusion which is basically blocking an object by another one. This helps to establish depth even at great distances. For instance, in a specific view angle, an object is blocked by the other one, but at a different view angle both objects are observed. Occlusion occurs at much further distances as opposed to accommodation and parallax that can be felt only for close objects. For example, 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 brain uses to establish depth (see Figure 1.2(c) to understand occlusion).
Figure 1.2: Representations of the three-dimensional depth cues that the brain uses to create a 3D perception of the world. (a) Parallax: the difference in position between the two eyes creates two different views of the cubes. (b) Accommodation: in the left image, while red cube is in focus, the blue cube is out of focus and vice versa for the image at the right side. (c) Occlusion: depending on the viewing angle, different part of the objects at the back are blocked. For instance, in the left image, the right side of the blue cube is blocked, in the middle image, only top of the blue cube is seen, and in the right image, the left part of the blue cube is blocked.
1.3 Why Holography?

There are different techniques of displaying 3D such as stereoscopic displays, lenticular array displays, volumetric displays, and holographic displays. Holographic method is superior to all of these 3D display techniques since the holographic images can possess all the 3D depth cues important for depth perception. As mentioned before, if one of the depth cues (parallax, accommodation, occlusion) is missing in a 3D display, it can cause eye fatigue, nausea to the viewer. Besides, the viewer may not perceive depth at all in this condition. Due to these reasons, holographic displays which contain all the necessary depth cues should be developed if 3D displays are to replace 2D displays used today.

Table 1.1 is an over-generalization, but it is useful for understanding the advantages and limitations of the dozens of different three-dimensional displays available.

Table 1.1: 3D displays and their respective 3D depth cues. Discretized view zone displays cannot provide continuous accommodation since there are only a couple focal plane. Volumetric displays are not capable of occlusion, but holographic displays can possess all the cues so depth perception is successfully achieved.

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Parallax</th>
<th>Accommodation</th>
<th>Occlusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discretized View Zone</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Volumetric</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Holographic</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Stereoscopic and lenticular array displays are discretized view zone displays that don’t provide accommodation continuously. This is because a discrete number of focal planes exist in the system which results in discrete depth perception. If the number of views is high enough, these displays can begin to approach holographic displays. In the dense-view system, the differences that remain between holographic and discretized-view zone are subtle since they can provide accommodation. However, it incurs the huge bandwidth requirement that is typical of holographic displays.

In a volumetric display, every point that an observer observes originates from a luminous or illuminated bit of matter such as the surface of a spinning disk, a light emitting diode, or a speck of glowing plasma. Since every image point originates from a tangible object, the viewer experiences
no eyestrain. However, the key limitation of volumetric displays is that they produce image points which are transparent to one another so that one luminous object cannot fully occlude another. Dr. Daniel Smalley has conducted research on a levitated opto-mechanical volumetric display that might be able to provide occlusion through anisotropic scattering off of tiny particles [1].

Holographic displays use diffraction to form images that possess all 3D depth cues, and have the potential to display images that appear nearly indistinguishable from their original physical forms. You can already observe this level of realism in static full color reflection holograms and pulsed laser holographic portraits [2]. Spatial light modulators are the key components of holographic displays that enable dynamic diffraction gratings which will result in drawing dynamic images or videos. More details about static and dynamic holograms and different kinds of spatial light modulators used in holographic video displays will be discussed in the next chapter.

Based on these discussions, it’s now reasonable to state why holographic displays are superior to their other peers with respect to possession of 3D depth cues. It may be that in the near future, when we glance out our windows, we will not be entirely sure we are not actually looking into a holographic video display.

In the current state-of-the-art holographic video displays, many complex optical components are added to the holographic system to compensate for the low viewing angle of the spatial light modulators. According to standards in holography, at least 15° is required for eye to view a static hologram with both stereopsis and motion parallax. These mean observing different perspectives of the same object with different eyes and also when head is moving horizontally. Achieving this minimum view angle is not possible with the current modulators such as bulk wave Bragg acouto-optic modulators (AOM), liquid crystal-based modulators (LCoS), or micromirror-based modulators (MEMs). In a bulk wave AOM, the maximum deflection angle is 3°. LCoS and MEMs are capable of producing maximum 5° view angle. This low view angle in pixelated modulators is due to the difficult fabrication process of high resolution modulators. The pixel size in a modulator with 5° deflection angle is about 3 µm. To achieve higher angles the pixel sizes need to be smaller which is difficult to get with current fabrication equipment. In a leaky mode modulator, we can produce view angles higher than 15° if we change the structure of the AOM device. In a bulk wave AOM, the input light is illuminating the grating normally as opposed to the leaky mode AOMs that the input light interacts with the gratings almost colinearly. According the diffraction grating
theories, colinear or waveguide illumination always results in larger view angles. This is discussed in great details in the next chapters.

1.4 Overview of Dissertation

This dissertation is organized as follows: Chapter 2 provides a detailed explanation of static and dynamic holograms and different methods of building holographic displays using different kinds of spatial light modulators (SLM). Chapter 3 presents a new design of leaky mode waveguide light modulators optimized with respect to waveguide depth to obtain the highest angular bandwidth in the history of SLMs (19.5), published as my first first-author paper. This solves the problem of low bandwidth SLMs in holographic displays and removes the need to add any other complicated optics to compensate for the low angular bandwidth. Chapter 4 talks about my second first-author published paper that implements the proposed idea in Chapter 3 that increases the deflection angle even more. Chapter 5 discusses the fabrication process of a new modulator device that makes the waveguides less lossy, resulting in higher acousto-optic interaction length which increases the number of resolvable points in the output when used in a holographic display. The results of my work on LCoS SLMs and details about use of them in holographic video displays have been also presented in Chapter 6. Chapter 7 concludes the dissertation and presents future work.
CHAPTER 2. BACKGROUND

Holograms are created using the interference pattern of a reference laser beam and an object beam on a photosensitive film or plate as shown in Figure 2.1. This way both amplitude and phase of the light can be recorded in the sensitized gelatin on the plate’s surface. The recording of an interference pattern is different from the process of normal photography in which only the intensity of the light from the object is recorded on (and replayed from) the photographic film. Instead, if the hologram is illuminated with a reconstruction beam at the same angle as that of the reference beam, a virtual object is reconstructed at the same position as the original object (see Figure 2.2).

Figure 2.1: Hologram recording layout of a cube. First, a coherent laser beam is split by a beam splitter. One part illuminates the object and the other part operates as a reference beam. The reflected beam from the object and the reference beam create a diffraction pattern on the photographic plate which is called the Hologram. Image: Wikimedia Commons
Figure 2.2: Hologram reconstruction layout. A reconstruction beam illuminates the hologram at the same angle of the reference beam. This will produce a virtual image at the same location of the object. Image: Wikimedia Commons
2.1 Static Holograms

Static holograms have a constant and invariable diffraction pattern on them and once they are written, it is impossible to change the hologram. In this section, different categories of static holograms are introduced and details about how they are recorded will be briefly reviewed.

Suppose two monochromatic point sources of $S_1$ and $S_2$ are placed at two different positions in $xyz$ coordinate system. The interference pattern of these two sources at different locations creates different kinds of holograms. Equations below show what the total intensity will be on a screen away from the two sources at a particular position on $z$-axis.

\[
E_1 = \text{Re}\{a_1 \exp\left(j(\omega t - \phi_1)\right)\} \quad (2.1)
\]
\[
E_2 = \text{Re}\{a_2 \exp\left(j(\omega t - \phi_2)\right)\} \quad (2.2)
\]
\[
I_{tot} = \left<(E_1 + E_2)(E_1 + E_2)^*\right>_{\text{time average}} \quad (2.3)
\]
\[
= I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\phi_1 - \phi_2), \quad (2.4)
\]

where $E_i$ is the electric field, $a_i$ is the initial electric field, $\omega$ is the working frequency of the sources, $\phi_i$ is the initial phase of the source, $I_i$ is the intensity of the electric field, and $I_{tot}$ is the total electric field resulting from the interference between sources 1 and 2. Equation 2.4 is called the “Master Interference Equation” which is derived by calculating the time average of the total intensity of $S_1$ plus $S_2$ signals.

Figure 2.3 demonstrates distinct layouts that make different hologram recordings.

2.1.1 On-Axis Hologram (Linear Fringes)

When in Figure 2.3 we are at location A, the interference fringes are straight lines radiating from a point midway between the sources, and they intersect the recording plane at equally-spaced points, which become lines if we consider them in 3D space. Equation below confirms the point that the interference pattern is independent of $y,z$ axes, of course this is occurring in the far-field and mathematical approximations have been taken into considerations.
Figure 2.3: This graph shows different types of holograms recorded at different locations in space. For instance, at location B, Gabor hologram can be made. A diffraction pattern here performs like a focusing lens which can focus light to different points in space or a hologram at location D, is called Denisyuk hologram. This type of hologram is the first invented white-light illumination static hologram.

\[ \phi_1(x, y) = \frac{2\pi}{\lambda} Z + \frac{\pi}{\lambda Z} \left( (x - \frac{s}{2})^2 + y^2 \right) \]  
\[ \phi_2(x, y) = \frac{2\pi}{\lambda} Z + \frac{\pi}{\lambda Z} \left( (x + \frac{s}{2})^2 + y^2 \right) \]  
\[ I_{tot}(x, y) = 1 + 1 + 2\sqrt{1}\cos \left( \frac{\pi}{\lambda Z} \left( (x - \frac{s}{2})^2 + y^2 \right) - \frac{\pi}{\lambda Z} \left( (x + \frac{s}{2})^2 + y^2 \right) \right) \]

\[ = 2 + 2\cos \left( \frac{2\pi}{\lambda Z} \frac{s}{2} \right), \]
where $I_1 = I_2 = 1$. In these equations, $\lambda$ is the wavelength of the light source, $Z$ shows the depth in which the interference pattern is captured, and $s$ is the offset between the two sources. Figure 2.4 shows the interference pattern that two sources at an equal distance from the screen create.

![Diagram](image)

**Figure 2.4:** On-axis hologram (linear fringes), plotted in Matlab.

Now if we assume that one of the sources is an object, we can divide the object up to millions of coherent light sources and calculate the interference pattern. Then, the superposition of all these patterns creates the final hologram on the photographic plate. This can only be done using coherent light sources because interference patterns can not be captured with incoherent light sources (temporally and spatially).

### 2.1.2 Gabor Hologram (In-Line: Fresnel Zone Plate)

At location “B,” the interference fringes are circles on the recording plane which are not equally spaced. They become closer and closer as we move away from the line that passes through both sources. This kind of interference pattern is called Fresnel zone plate which is shown in 2.5.
\[ \varphi_1(x,y) = \frac{2\pi}{\lambda} Z_1 + \frac{\pi}{\lambda Z_1} \left( x^2 + y^2 \right) \]  
\[ \varphi_2(x,y) = \frac{2\pi}{\lambda} Z_2 + \frac{\pi}{\lambda Z_2} \left( x^2 + y^2 \right) \]  
\[ I_{\text{tot}}(x,y) = 1 + 1 + 2\sqrt{1} \cos \left( \frac{2\pi}{\lambda} (Z_1 - Z_2) + \frac{\pi}{\lambda Z_1} (x^2 + y^2) - \frac{\pi}{\lambda Z_2} (x^2 + y^2) \right) \]
\[ = 2 + 2 \cos \left( \varphi_o + \frac{\pi}{\lambda} \left( \frac{1}{Z_1} - \frac{1}{Z_2} \right) (x^2 + y^2) \right), \]

where \( I_1 = I_2 = 1 \) and \( \varphi_o \) is a constant.

Now imagine one of the sources is an object, it can be said that the object contains millions of coherent light sources (reflecting the incoming beam toward the screen). Then, the superposition of all the calculated interference patterns creates the final hologram on the photographic plate.
2.1.3 Leith-Upatnieks (Off-Axis) Hologram

In this version of hologram, there is a large angle between the reference and the object beams. The main consequence of this is the separation between the orders. Since there is a fairly large angle between the beams, the true image (first order) will be well-separated from the conjugate image. Also, when the hologram is observed the zero order (undiffracted portion of light) does not go into the viewer’s eye. According to Figure 2.3, this happens at location C. In this layout, the hologram will have both on-axis linear grating feature that acts like a prism and also the Fresnel zone plate that operates as a lens as shown in Figure 2.6 the interference pattern will have both lines and circles in it. The phase footprint becomes as follows:

\[
\varphi_{\text{ref}}(x,y) = \varphi_{\text{ref}} + \frac{2\pi}{\lambda} \sin \theta_{\text{ref}} + \frac{\pi}{\lambda} \left( \cos^2 \theta_{\text{ref}} \frac{x^2}{R_{\text{ref}}} + \frac{1}{R_{\text{ref}}} y^2 \right) \quad (2.13)
\]

\[
\varphi_{\text{obj}}(x,y) = \varphi_{\text{obj}} + \frac{2\pi}{\lambda} \sin \theta_{\text{obj}} + \frac{\pi}{\lambda} R_{\text{obj}} \left( x^2 + y^2 \right) \quad (2.14)
\]

\[
I_{\text{tot}}(x,y) = 1 + 1 + 2\sqrt{1.1} \cos \left( \varphi_{\text{ref}}(x,y) - \varphi_{\text{obj}}(x,y) \right)
= 2 + 2 \cos \left( \varphi_o + \frac{\pi}{\lambda} \left( \frac{\cos^2 \theta_{\text{ref}}}{R_{\text{ref}}} - \frac{1}{R_{\text{obj}}} \right) x^2 + \left( \frac{1}{R_{\text{ref}}} - \frac{1}{R_{\text{obj}}} \right) y^2 \right), \quad (2.16)
\]

where \( I_1 = I_2 = 1 \) and \( \varphi_o = \varphi_{\text{ref}} - \varphi_{\text{obj}} + \frac{2\pi}{\lambda} \sin \theta_{\text{ref}} \) is a constant.

Figure 2.6: Leith-Upatnieks (off-axis) hologram, plotted in Matlab.
A real object will be a collection of so many points that create a special interference pattern like Figure 2.6. The superposition of all these diffraction patterns will produce the hologram of the object that once illuminated the same object will be reconstructed.

2.1.4 Benton (Rainbow) Hologram

Rainbow holograms are holograms first introduced by Steven Benton (Dr. Smalley’s first advisor) which enables white light illumination. This holography technique also happens at location "C". They are fabricated by a double holographic process where an ordinary transmission hologram, H1, called “master hologram” is used as the object and a second hologram, H2, called “transfer hologram” is made through a slit on H1. A horizontal slit limits the vertical view of the first image so that there is no vertical parallax in the resultant rainbow hologram. This slit process removes the coherence requirement on the illuminating light so that full advantage can be taken of the image brightness obtained from ordinary room light, while maintaining the three-dimensional character of the image as the viewer’s eyes are moved horizontally. The reason for this is, the diffraction grating on the slit diffracts each wavelength of light to a different position vertically. The colors don’t interfere with each other since only a small view of the image is present vertically. When the viewer’s eyes are moved vertically, no parallax is observed, instead, the image color sweeps through the rainbow spectrum from blue to red, that is why it is called "rainbow hologram". Figure below shows how the rainbow hologram is mad in two steps and how the final reconstructed image will form. The slit size changes the properties of the hologram. If the slit size is small (0.5-2 mm), the image will become sharp over a great depth (150 mm in front and behind the hologram typically). As a result, the speckle contrast will also go up. If the slit is widened (8-25 mm) the speckle contrast will slowly fade but the image gets blurry at shallower depths [3, 4].

2.1.5 Denisyuk Hologram

Denisyuk or volume reflection holograms are made by putting the photographic plate between the source and the object shown in Figure 2.3, location D. A volume reflection grating is a reflecting Bragg grating that beside diffracting the input light it can filter out specific colors because there is a periodic modulation of the refractive index as opposed to transmission gratings...
Figure 2.7: Principle of Benton’s rainbow hologram. A) The interference pattern of the object (this object has volume) and the reference beam 1 is recorded on H1, the master hologram. B) The image of H1 is reconstructed through a slit on H1 by the conjugate reference beam 1. H2 plate, the transfer hologram, is positioned on the location of the reconstructed image. C) The diffraction pattern of H1 image (through the slit) and the reference beam 2 is recorded on H2. D) The final hologram, H2, is illuminated by the conjugate reference beam 2. It reconstructs a colored image depending on the angle of viewing.

that pass all the colors. For instance, if a hologram is made using a red laser (see Figure 2.8), the hologram can be illuminated by white light, but only red light reflects back and the virtual image is reconstructed. White light illumination is the most important property of Denisyuk holograms.

The Denisyuk technique simply shines a diverging laser beam through a holographic plate, which is so finely grained that it absorbs very little of the light, and on the object. The light reflects back from the object to the plate, where it creates an interference pattern with the incident light.

This technique is very simple and straightforward compared to other hologram systems, and can produce results of very high quality. It is well suited to very large holograms, because no additional optics is required and the system is readily engineered to be resistant to vibration. Off-axis reflection holograms are created at location "E". There is a main advantage for this over the on-axis reflection hologram which is, after the hologram is made, one doesn’t have to look directly into the illumination source to see the reconstructed holographic image.
2.1.6 Physics of the First Hologram Made by Denis Gabor

Holography dates from 1947 when Dennis Gabor developed the theory of holography while working to improve the resolution of an electron microscope. Gabor asked himself: "Why not take a bad electron picture, but one which contains the whole information, and correct it by optical means?". Gabor came up with the answer to this question while he was waiting for a game of tennis on Easter Day 1947 and it was to consider a two-step process. Gabor used the term hologram from the Greek words holos, meaning "whole," and gramma, meaning "message". It means a message
that contains all the information (phase and amplitude) about an object. He proposed this two-step method of optical imagery to improve power of the electron microscope. Gabor, in his Nobel prize lecture stated that he stood on the shoulders of W. L. Bragg for his work on x-ray microscope (two step x-ray imaging and reconstructing the crystal structure using the reciprocal pattern) and also Frits Zernike for his work on optical aberrations and coherent light sources [5]. According to this two-step technique, an object is first illuminated with a coherent light wave. A diffraction pattern is then formed by the interference of the object wave and the reference wave. It could later be reconstructed by illuminating the hologram by the background wave alone. This way the image will appear in the plane conjugate to the plane in which the object was situated. Below the optical principle of this first hologram will be presented [6].

Consider a monochromatic point source illuminating a semitransparent object $\sigma$ (see Figure 2.10). Assume $H$ is a screen at some distance behind the object and let $U = A e^{i\psi}$ represent the complex intensity at a typical point of $H$, $A$ being the amplitude and $\psi$ the phase of the intensity. We can then regard $U$ as the sum of two terms,

$$U = U^i + U^s = e^{i\psi_i} (A_i + A_s e^{i(\psi_s - \psi_i)}).$$  \hspace{1cm} (2.17)

Here $U^i$ denotes the incident light and $U^s$ represents the secondary, or diffracted, wave which contains the information about the object. The amplitude of the total intensity can be derived using the following equation.

$$A = \sqrt{UU^*} = \sqrt{A_i^2 + A_s^2 + 2A_i A_s \cos (\psi_s - \psi_i)},$$  \hspace{1cm} (2.18)

in which we have suppressed the time harmonic factor $e^{-i\omega t}$ to deal with the equations in frequency space.

Now suppose that a photosensitive plate (gelatine) is placed in the $H$-plane. Assume that $\alpha$ is the transmission coefficient of the plate. The corresponding transmission coefficient for the intensity is then $\tau = \alpha \alpha^*$ which can be converted to another quantity called the density of the plate, $D$.

$$D = -\log_{10} \tau = -\log_{10} \alpha \alpha^*.$$  \hspace{1cm} (2.19)
Figure 2.10: Illustration of Gabor’s method of imaging by reconstructed wavefronts. (a) Recording the hologram. (b) Reconstruction of the hologram. (c) Equivalent one-step imaging using a 2f imaging system.

We can calculate the exposure or light sum (E) by multiplying the intensity \( I = A^2 \) of light that reaches the plate and the time of exposure (t).

\[
E = tI.
\]  
(2.20)

The curve giving \( D \) with respect to \( \log_{10}E \) is known as the Hurter-Driffield curve shown in Figure 2.11. In the range between points P and Q, the curve is approximately linear with a slope of \( \Gamma \). The density of the negative (film) is given by

\[
D = D_0 + \Gamma \log_{10} \frac{E}{E_0},
\]  
(2.21)

where \( D_0 \) and \( E_0 \) are constants.
Therefore,
\[
\tau = \tau_0 \left( \frac{E}{E_0} \right)^{-\Gamma}. \tag{2.22}
\]

If no absorption in the film is assumed, \( \alpha \) becomes a real number which is the square root, \( \sqrt{\tau} \), of the transmission coefficient. So, the amplitude transmission coefficient \( \alpha_n \) of the negative hologram is given by the equation:

\[
\alpha_n = (K_n A)^{-\Gamma_n}, \tag{2.23}
\]

where \( K_n \) is proportional to \( \sqrt{\tau} \).

The amplitude transmission coefficient of a positive print of the negative hologram is

\[
\alpha_p = [K_p (K_n A)^{-\Gamma_n}]^{-\Gamma_p} = K A_\Gamma, \tag{2.24}
\]

where \( K = K_n^{\Gamma} K_p^{-\Gamma_p} \) and \( \Gamma = \Gamma_n \Gamma_p \) shows the overall gamma of the negative-positive process.
Now let’s analyze the reconstruction of the hologram. In this process the positive hologram made in step one, is illuminated by the same coherent reference source \( (U_i) \). This can be done simply by removing the real object and let the reference beam stay in the same position and angle. The plate transmits a substitute wave \( (U') \) which is represented by

\[
U = \alpha_p U^i = KA_i e^{i\psi_i} \left[ A_i^2 + A_s^2 + 2A_iA_s \cos (\psi_s - \psi_i) \right]^{\frac{1}{2}}. \tag{2.25}
\]

If \( \Gamma = 2 \) is chosen, then

\[
U = KA_i^2 e^{i\psi_i} \left[ A_i + \frac{A_s^2}{A_i} + A_s e^{i(\psi_s - \psi_i)} + A_s e^{-i(\psi_s - \psi_i)} \right]. \tag{2.26}
\]

It is seen that the first and third term together make up the reconstructed wave which is proportional to \( U \). The second term which has the same phase of the reference beam and an amplitude of \( \frac{A_s^2}{A_i} \) is called a zero order which is the undiffracted part of the light. The last term has the same amplitude as the reconstructed wave but has a phase shift of the opposite sign. This wave that is called the conjugate wave is similar to the true object but it is located in a different plane.

As depicted in Figure 2.10, if a lens is placed behind the hologram while being illuminated by the reference beam, and image of the original object \( (\sigma') \) will be formed in a plane conjugate to that of \( \sigma \). Figure 2.12 shows one of the very first holograms Gabor made.

### 2.2 Dynamic Holograms

Dynamic holograms are used in holographic video displays to create continuous images that look like a video to human eye. There are certain advanced optical components called spatial light modulators that can modulate phase or amplitude of light to reconstruct desired holographic images. In this section, some common terms used in dynamic holography is explained.

#### 2.2.1 Holographic Video Displays

A holographic video display is a type of display that utilizes light diffraction to create a virtual 3D video at frame rates more than 10 Hz. This is due to the fact that videos with higher than 10 fps sound continuous to human’s eye. Holographic displays are unique from other forms of
Figure 2.12: Imaging by reconstructed wavefronts. The noisy background is mainly due to the imperfections of the illuminating objective. (After Denis Gabor, Proc. Roy. Soc., A, 197 (1949), 454.)
3D displays in which they do not require the aid of any special glasses or external equipment for a viewer to see the image. One of the very first holographic video displays was developed at MIT in the 1980’s which was called Mark holovideo. This early work was directed by Dr. Stephen Benton and later continued by Dr. Michael Bove. Dr. Bove et al. at MIT kept on conducting more research on holovideos and achieved to improve upon the old holovideo in terms of angular bandwidth, resolution, cost, size and etc [7]. The details of why Dr. Smalley’s improvements made holovideos better will be explained in the following parts of this dissertation.

2.2.2 Spatial Light Modulators

There are some holographic elements used in holographic video displays called spatial light modulators (SLM) that are capable of rewriting the holograms on them. These SLMs can modulate the phase and amplitude of the incoming light in a way that they can reproduce several holographic images per second. SLMs form dynamic holograms that can be rewritten with a high refresh rate (more than 10-15 Hz). Below I will present briefly the principle behind some of the popular spatial light modulators used in holographic video displays.

MEMs SLM

MEMs spatial light modulators consist of arrays of micromirrors on semiconductor chips, whereby the number of mirrors varies depending on the application, from a few hundred to several millions. It requires an integrated electronic circuit as a backplane for the micromirrors in order to enable an individual analog deflection of each micromirror. The individual mirrors can be tilted or vertically deflected depending on the application, so that a surface pattern is created, for example to project defined structures. The tilting technique is used in the digital light projectors to create 2D patterns while the vertically deflecting technique uses diffraction gratings to control wavefronts. This method is very popular in adaptive optical systems since it can correct wavefront disturbances in broad spectral ranges resulting in sharper images with higher quality [8]. The deflecting technique is widely used in holographic displays. It modulates the phase of light by deflecting a set of desired mirrors vertically to create a diffraction grating [9]. This way the holograms can be patterned on the surface of the SLM and once illuminated the holographic images
shows up. Further applications of MEMs SLM are mask inspection and measurement technology for the semiconductor industry, microscopy, laser printing, marking, and material processing [10].

**LCoS SLM**

Liquid crystal on silicon (LCoS) technology has been developed for many years for image and video display applications. This technology combines the unique light-modulating properties of liquid crystal (LC) materials and the advantages of high-performance CMOS technology in a dedicated LCoS assembly process. The application of LC in SLMs is based on their optical anisotropy and piezoelectric effect. A defined voltage level across the LC cell leads to a variable tilt of the LC molecules due to their piezoelectric effect. Since LC molecules have anisotropic properties, this tilt results in different refractive indexes in the light propagation direction. This causes a modified optical path length within the LC cell. The addressed voltage level is now converted into a phase level. Unlike the conventional LC flat panel displays, an LCoS device can be either transmissive or reflective and can be used to alter the polarization or the phase of an incident light beam utilizing the electrically modulated optical properties of LCs [11].

The optical characteristics of the light such as the phase, polarization state, intensity, and propagation direction are changed by the information written into the address part, and the output light exits the panel according to that change, producing an optical output that corresponds to the written information. Among LCoS SLMs, those specifically designed to modulate the phase of light are referred to as phase-only spatial light modulators. A coherent source such as a laser beam entering the LCoS-SLM is phase-modulated and then reflected to control the wavefront of the light as required. This ability to precisely control the light wavefront makes the LCoS-SLM ideal for applications such as optical beam shaping [12] and aberration correction [13].

The LCoS-SLM has a wide range of applications that include fundus (the part of the eyeball opposite the pupil) imaging by corrective optics [14], optical tweezers utilizing optical manipulation techniques [15], femtosecond laser pulse shaping [16], and a host of other fields. A very novel application of LCoS SLMs is in the field of updatable holographic displays. Computed holograms (phase pattern) are fed into the readout panel on the LCoS display. Once the display is exposed to collimated laser beam, it reconstructs the holographic image accordingly. More details on this will be presented in Chapter 6.
Leaky mode waveguide light modulators

Leaky mode waveguide light modulators (LMWLM) are another form of spatial light modulators that work based on anisotropic leaky mode coupling between a dielectric waveguide and the substrate which the waveguide is fabricated on. This technique possesses many advantages over LC and MEMS devices when applied to holographic video displays.

Dr. Daniel Smalley first got the idea of multichannel leaky mode modulator from similar devices that had been used in the telecom industry for a long time where bandwidth was of prime importance. A combination of techniques in the field of integrated optics and acoustics were used to develop the devices in a way that met the requirements of advanced 3D displays [7]. Multichannel leaky mode modulators were first theoretically presented by Proklov who applied them in multichannel spectrum analyzers and as optical multiplexer/demultiplexers. He succeeded to fabricate single channel modulators using titanium indiffused waveguides [17]. Tsai et al. later reproduced Proklov’s experiments in proton exchanged waveguides rather than titanium indiffused waveguides, also single channel, to achieve higher diffraction efficiencies and described the devices as a general scanning solution [18]. Smalley’s research became the first to propose leaky mode modulators as a solution for holovideo and also to fabricate single and multichannel LMWLMs to use in holographic video displays [7].

Figure 2.13: Single channel leaky mode device.

Smalley, in his research with Massachusetts Institute of Technology (MIT) and Brigham Young University (BYU), has built a holographic video display (holovideo) using the leaky mode
technique [7]. His holovideo display relies on a LMWLM capable of about 20 degrees of diffraction for red laser beam, 638 nm [19]. With scanning optics, it is capable of 30 fps refresh rates, has 30 degrees of encoded angular output through telescopic optical stages, and a display size of 4 cm by 12 cm. The design is scalable and image size is currently limited by the parabolic mirror reflecting the light into viewer’s eyes.

Design and fabrication of these modulators are presented in the next chapters along with all the principles and physics behind leaky mode devices. However, below, I briefly state the reasons why our group has chosen LMWLM over LC and MEM devices.

- **Polarization Rotation.** In LCoS or MEM devices, the polarization of input and output light is the same so there is no way one could filter the diffracted output from the undiffracted zero order. But, in LMWLM, the diffracted output is polarization rotated making it easy to filter the undiffracted light using a simple linear polarizer.

- **Wider Angular Deflection.** The incident angle of the input light has a great impact on the angular diffraction at the output. The diffraction angle increases as the incident angle decreases with respect to the plane of the SLM. For instance, in LCoS and MEM devices, the incident angle is normal to the plane which makes the diffraction angle low compared to LMWLM which light enters the device at glancing angles.

- **Simultaneous Superimposed RGB Modulation.** LCoS and MEM devices employ a color sequential method or some pixels are dedicated to one color, thereby resulting in lower resolution or slower refresh rate. However, LMWLM devices are capable of multiplexing color in frequency rather than in time or space. This happens because the phase matching condition is wavelength dependent. Red light diffracts at a lower frequency than green light which in turn couples at a lower frequency than blue, allowing one to choose which color to modulate by ‘coloring’ the frequency spectrum of the electrical signal sent to the modulator’s transducers.

- **Complexity of Design.** LC and MEM devices’ fabrication requires heavy and complex cleanroom steps and process in which several masks (more than 20) is needed to be done in order to make one device. While LMWLM devices can be fabricated with two masks which can easily be done in a university cleanroom.
• **Higher Orders and Undiffracted Zero Order.** As mentioned in item 1, undiffracted zero order can be filtered out using a linear polarizer in LMWLM devices as opposed to LC and MEM devices that the zero order remains a part of the output light. Also, in LC and MEM devices, higher orders of diffraction exist which are observed in the output while in LMWLM the higher orders of diffraction are prohibited due to the very low angle of incident light resulting in imaginary output angles for higher orders.

In this part, some fundamental concepts in optics will be provided to better understand the operation of the leaky mode waveguide light modulators. Let’s start by comparing the terms reflection, refraction, and diffraction. Reflection involves a change in the direction of waves when they bounce off a barrier; refraction of waves involves a change in the direction of waves as they pass from one medium to another; and diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path.

**The laws of reflection and refraction**

When a plane wave hits a boundary between two homogeneous media of different optical properties (refractive indices), it is split into two waves: a reflected wave propagating back into the first medium and a transmitted wave passing through the boundary toward the second medium. Both these electrical waves can be derived using the boundary conditions. In order to determine these fields, the boundary conditions for these specific materials and the angle of incident wave should be satisfied.

Assume that a plane wave is propagating in the direction of unit vector $s_i$. It can be said that if $F(t)$ represents the the time behavior of the wave at any one point, the time behavior at another point is given by $F[t - (\bar{r} \cdot s)/v]$ in which $r$ is vector of the distance of the second point to the initial point. At the boundary attaching the two media, the secondary fields will be the same as the incident field. Therefore, the time behaviour ($F(t)$) of all these waves are equal at the boundary $z = 0$:

$$t - \frac{\bar{r} \cdot \bar{s}_i}{v_1} = t - \frac{\bar{r} \cdot \bar{s}_r}{v_1} = t - \frac{\bar{r} \cdot \bar{s}_t}{v_2},$$  

(2.27)
where \( s_r \) and \( s_t \) denote the unit vectors in the direction of reflected and transmitted waves. Also, \( v_1 \) and \( v_2 \) are the velocities of propagation in the two media. These values will be different due to the different refractive indices. This equation can be simplified to:

\[
\frac{x s_{ix} + y s_{iy}}{v_1} = \frac{x s_{rx} + y s_{ry}}{v_1} = \frac{x s_{tx} + y s_{ty}}{v_2}.
\] (2.28)

Since this equation must hold for all \( x \) and \( y \) values on the boundary,

\[
\frac{s_{ix}}{v_1} = \frac{s_{rx}}{v_1} = \frac{s_{tx}}{v_2}, \quad \frac{s_{iy}}{v_1} = \frac{s_{ry}}{v_1} = \frac{s_{ty}}{v_2}. \] (2.29)

In Figure 2.14, the plane specified by \( s_i \) and the normal vector to the boundary is called the plane of incidence. Equations 2.29 show that both \( s_t \) and \( s_r \) lie in this plane. Assuming the plane of incident as \( xz \) plane and calling the angles which \( s_i, s_r, \) and \( s_t \) make with \( Oz, \theta_i, \theta_r, \) and \( \theta_t, \) we will get:

\[
s_{ix} = \sin \theta_i, \quad s_{iy} = 0, \quad s_{iz} = \cos \theta_i, \] (2.30)
\[
s_{rx} = \sin \theta_r, \quad s_{ry} = 0, \quad s_{rz} = \cos \theta_r, \] (2.31)
\[
s_{tx} = \sin \theta_t, \quad s_{ty} = 0, \quad s_{tz} = \cos \theta_t. \] (2.32)

Combining Equations 2.29 with Equations 2.32 gives

\[
\frac{\sin \theta_i}{v_1} = \frac{\sin \theta_r}{v_1} = \frac{\sin \theta_t}{v_2}. \] (2.33)

Hence, \( \sin \theta_i = \sin \theta_r, \) and based on Figure 2.14

\[
\theta_r = \theta_i. \] (2.34)

This relation along with the statement that the reflected wave is in the plane of incidence, constitute the law of reflection.
Moreover, combining Equation 2.35 and Maxwell’s relation for velocity and dielectric constant,

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{v_1}{v_2} = \sqrt{\frac{\varepsilon_2 \mu_2}{\varepsilon_1 \mu_1}} = \frac{n_2}{n_1} = n_{12}. \quad (2.35)$$

This relation together with the statement that the transmitted wave is in the plane of incidence, constitute the law of refraction or Snell’s law.

[Diagram of reflection and refraction of a plane wave at a boundary of two different media with different optical properties. All the vectors are in the plane of incidence.]

**Optical waveguides**

An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum. At optical frequencies, the loss associated with the induced current in the metal
walls is too high. A transmission line filled with dielectric material but without conducting walls is another structure that may be used to guide electromagnetic waves. This dielectric slab waveguide eliminates the metallic absorption loss.

Figure 2.15 demonstrates a dielectric slab surrounded by another dielectric material that has a lower permittivity and air at the other side of the material. Once light is coupled into a waveguide, there are certain angles depending on the refractive indices of the materials and depth of the waveguide that light can propagate in those direction. For instance, TE modes inside a waveguide van be derived by solving the Maxwell equations for the specific boundary conditions at both top and bottom boundaries of the media. Equations below gives the TE modes inside a waveguide surrounded by two media with different refractive indices smaller than the waveguide’s index of refraction \( (n_c < n_s < n_f) \). This conditions helps the light stay in the waveguide based on total internal reflection concept.

\[
\begin{align*}
\frac{n_c}{n_f} & = 1 \\
\frac{n_f}{n_s} & = \cos \theta - \phi_{f_s}^p(\theta) - \phi_{f_c}^p(\theta) = 2\pi\nu, \\
\nu & = 0, 1, 2, \ldots
\end{align*}
\] (2.36)

Figure 2.15: Dielectric slab waveguide of width 2d.

In order to have constructive interference of the wave bouncing off of the boundaries, the following condition should be satisfied.
where \( k_0 \) and \( h \) are the free-space wavenumber and waveguide depth. Also, \( \phi_{fs}^p(\theta) \) and \( \phi_{fc}^p(\theta) \) are the change in phase of the wave when hitting the boundaries. These two phase shifts are different for TE and TM polarization and can be derived using the law of reflection. This waveguide modes can be found via the electromagnetic approach as well. The electric field in the waveguide is a sine wave while the fields are evanescent outside the waveguide. Feeding the boundary conditions into the Maxwell equations will give all the constants for the fields in all regions.

In Equation 2.37, all the electric fields for all 3 regions are given.

\[
E_y = E_o \begin{cases} 
\cos (k_f x h - \phi_o) e^{-\gamma_s (x-h)} e^{-j\beta_z}, & x > h, \\
\cos (k_f x - \phi_o) e^{-j\beta_z}, & 0 < x < hh, \\
\cos \phi_o e^{\gamma_s x} e^{-j\beta_z}, & x < 0,
\end{cases}
\]

(2.37)

where \( \phi_o \) and \( E_o \) are the initial phase and intensity of the coupled light inside the waveguide. Moreover, solving equation below graphically or numerically gives all the TE modes that can propagate inside the waveguide.

\[
\tan (k_f x) = \frac{\gamma_s}{k_{fs}} + \frac{\gamma_c}{k_{fc}} \frac{1}{1 - \frac{\gamma_s \gamma_c}{k_{fs} k_{fc}}}.
\]

(2.38)

Figure 2.16 is graphical solution for Equation 2.38 which is also the eigenvalue equation derived from setting the determinant of the electric fields matrix to zero. The figure has the TM modes as well. In the figure, \( N_{eff} \) is the effective refractive index in the direction of propagation which is given by \( N_{eff} = n_f \sin \theta \).

**Diffraction gratings**

A diffraction grating can be defined as any arrangement which imposes on an incident wave a periodic variation of amplitude or phase, or both. Characterization of any particular grating can be done through its transmission function. In the "Introduction to Fourier Optics" book, Goodman [20] has derived the transmission function for a thin sinusoidal phase grating which is also called a surface relief grating transmission function shown in the following equation.
Figure 2.16: Graphical solution of the eigenvalue equations for both TE and TM modes for a specific waveguide depth.

- **N\text{eff} for TE Modes:** 2.1700, 2.0783, 1.9190, 1.6831
- **N\text{eff} for TM Modes:** 2.1642, 2.0542, 1.8636, 1.5968
this equation, \( m \) denotes the maximum phase contrast on the grating which can be calculated by Equation 2.40.

\[
g_t(x) = \exp \left\{ i \frac{m}{2} \sin \left( 2\pi \frac{x}{\Lambda} \right) \right\},
\]

(2.39)

\[
m = 2\pi \frac{(n - 1)s}{\lambda}.
\]

(2.40)

In Equations 2.39 and 2.40, \( x \) is the position on the grating, \( \lambda \) is the wavelength of the incident light, \( \Lambda \) is the grating period, and \( s \) is the peak-to-peak distance on the grating as shown in Figure 2.17.

Figure 2.17: Thin Sinusoidal Phase Grating.

Here, we could use a very useful mathematical identity (Jacobi–Anger expansion) to decompose Equation 2.39 into a sum of Bessel functions of the first kind.

\[
\exp \{ i\alpha \sin \theta \} = \sum_q J_q(\alpha) \exp (iq\theta).
\]

(2.41)
Now applying this relationship to the transmission function gives the following expression:

\[ g(x, z) = \exp \left\{ \frac{i}{2} \sin \left( \frac{2\pi x}{\Lambda} \right) + i2\pi \frac{z}{\lambda} \right\} \]

\[ = \sum_j J_q \left( \frac{m}{2} \right) \exp \left( i2\pi q \frac{x}{\Lambda} + i2\pi \frac{z}{\lambda} \right), \]

where \( J_q \left( \frac{m}{2} \right) \) is the amplitude of each order and \( \exp \left( i2\pi q \frac{x}{\Lambda} + i2\pi \frac{z}{\lambda} \right) \) is a plane wave for each order, \( q \). One could derive the propagation angle based on the phase of this plane waves.

\[ \sin \theta_q = \frac{\lambda}{\Lambda}, \]

in which \( \theta_q \) shows the output angle which is different for each diffraction order. Therefore, the \( q \)-th exponential physically is a plane wave propagating at angle \( \theta_q \) (i.e. the \( q \)-th diffraction order). This equation is in the case of normal illumination on the grating. It can be easily concluded from the above equations that if the incident angle, \( \theta_i \), is not zero, the equation will become

\[ \sin \theta_q - \sin \theta_i = q \frac{\lambda}{\Lambda}, \]

which is called the "grating equation". Also, the diffraction efficiency of any specific order can be calculated using the amplitude of the transmission function. It could be written as

\[ DE_q = J_q^2 \left( \frac{m}{2} \right). \]

**Theory of leaky mode modulators**

Based on what was mentioned in the previous parts, light is coupled into the waveguide through the diffraction grating and then depending on the waveguide depth and the refractive indices some discrete waveguide modes can propagate in the waveguide. In this part, we will talk about how this guided light is diffracted by surface acoustic waves (SAW) as smart updatable holographic gratings. SAWs are created by the interdigital transducers patterned on the surface of the crystal. These SAWs hit the guided wave and apply a momentum to it resulting in a change
in direction. As a result of this interaction, the light will no longer stay guided and leaks to the substrate. That is why this light called a "substrate mode" or "leaky mode". In our case, the waveguide is made through a diffusion of hydrogen atoms into the lithium niobate crystal which is an anisotropic crystal. This means it has different refractive index depending on the direction the wave is propagating. In this work, X-cut Y-propagating lithium niobate has been used. Only TE modes are supported by the waveguide which are then polarization-rotated after interaction with the SAW and exit the end of the sample. A very detailed discussion on leaky mode devices has been done by Matteo [21], however a brief analysis of these devices are presented here.

Piezoelectricity is the mechanical displacement that occurs in the presence of an electric field in many of the crystals. Lithium niobate (LiNbO3), in addition to being a good piezoelectric material, has good transmission in the visible region of the electromagnetic spectrum and lends itself readily to the formation of surface waveguides by proton exchange and titanium in-diffusion. Once an electric field is applied to lithium niobate, it distorts the crystal structure. This strain follows Hooke’s Law [22] given below:

\[ T_{ij} = c_{ijk} S, \] (2.47)

where \( T \) is the stress induced by the electric field, \( S \) is the strain, and \( c \) is the intrinsic elastic stiffness constant of the material. SAW creates a periodic excitation in lithium niobate crystal which is governed by the following electro-mechanical sets of equations:

\[ c_{ijkl} \frac{\partial^2 u_k}{\partial x_i \partial x_l} + e_{ijk} \frac{\partial^2 \phi}{\partial x_i \partial x_k} = \rho \frac{\partial^2 u_j}{\partial t^2} \] (2.48)

\[ e_{ikl} \frac{\partial^2 u_k}{\partial x_i \partial x_l} - \epsilon_{ik} \frac{\partial^2 \phi}{\partial x_i \partial x_k} = 0 \] (2.49)

In these differential equations, \( u \) is the mechanical displacement caused by the SAW, \( \phi \) is the electrical potential, \( \rho \) is the density of the material, \( c \) is the elastic stiffness constant of the material, \( e \) is the piezoelectric coefficient, and \( \epsilon \) is dielectric coefficient for a constant strain. The solution for this sets of equations is a Rayleigh surface wave with transverse and longitudinal components and a wave speed given by 2.50. Given the density and elasticity coefficient of lithium
niobate in the y-direction, \( v = 3906 \text{ m/s} \) is the velocity of SAW for an X-cut Y-propagating lithium niobate sample.

\[
v = \sqrt{\frac{c}{\rho}}.
\]  

(2.50)

As mentioned above, in X-cut Y-propagating proton exchanged lithium niobate sample only TE polarized light can propagate in the waveguide. The surface waves interacting with the TE light change the polarization to TM due to the non-diagonal modulation in the dielectric tensor. The TE to TE coupling efficiency is negligible compared to the TE to TM coupling efficiency. This is the fundamental phenomenon behind the operation of the modulators described in this dissertation, i.e., mode-coupling from guided to leaky modes (see Figure 2.18). Three conditions should be met or this to occur:

- Asymmetry in the material structure.
- Overlap of TE and TM mode shapes.
- Phase matching between TE and TM modes.

The asymmetric nature of lithium niobate crystal structure provides the asymmetry required to convert light from one polarization to another.

In coupled mode theory, these mode-couplings are derived and the coupling efficiencies are calculated. Through coupled mode theory, one could derive the equations for the conversion of light from one polarization to another. The coupled mode equations that govern that transfer are (from Marcuse [23]):

\[
dg(y)/dy = -i\beta_{gm}g(y) - i \int K_{gr}r(y)db_r
\]  

(2.51)

\[
 Dr(y)/dy = iK_{gr}^*s(y) - i\beta_r r(y)
\]  

(2.52)

\[
 K_{gr} = \frac{\omega}{4P} \int \Delta\varepsilon_{zx} E_z^{(TE)}(y) E_x^{(TM)}(y) dx,
\]  

(2.53)

where \( r(y) \) is the complex amplitude of the TM leaky mode and \( g(y) \) the complex amplitude of the TE guided mode. \( E_z^{(TE)} \) is guided mode \( z \) component, \( E_x^{(TM)} \) is the leaky mode \( x \) component. \( P \) is the optical power normalization factor, \( \Delta\varepsilon_{zx} \) is the modulation of the dielectric tensor and, \( \omega \) is the
Figure 2.18: (a) (left) An index guided mode is evanescent in both the air and substrate. (right) A leaky mode is evanescent in the air but has a propagating component in the substrate. (b) k-space diagram of the waveguide and substrate modes. Here the large semicircle has a larger radius corresponding to the larger momentum vector of light travelling in the material. For rays traveling below critical angle, the projection of the momentum vector will lie inside the waveguide semicircle where it is guided and outside the substrate circle where it is evanescent. The projection of a leaky mode would be inside both semicircles which means the wave in the waveguide passes the boundary between the media and propagates inside the substrate.
angular frequency of light. $K_{gr}$ is the TE-TM coupling coefficient. As it can be seen, the coupling coefficient is dependent on the overlap of the mode shapes as well as the modulation term caused by the SAW. For X-cut Y-propagating lithium niobate (TE-TM coupling) the modulation term is

$$\Delta e_{zx} = P_{yzyz} S_{zx}^2 + P_{yzxx} S_{xy}^2 + r_{zxx} E_x.$$  \hspace{1cm} (2.54)

Note that this modulation (which gives the change in index of refraction induced by the surface acoustic wave and electric field) includes contributions from the piezoelectric effect (which gives rise to the strain, $S$ and the field $E$ in these equations) and also the electro-optic effect (shown as $r$).

The last requirement for the mode-coupling to work is the phase matching condition. This can be stated in terms of momentum. For this mode-coupling to occur momentum must be conserved along the propagation direction. This follows from as a mathematical result found by Emmy Noether. The phase matching condition is given below:

$$\beta_{leaky} = \beta_{guided} - K_{SAW}.$$  \hspace{1cm} (2.55)

The TM mode wavenumber plus the momentum of the surface acoustic wave is equal to the TE mode wavenumber. $K_{SAW}$ is equivalent to $\frac{2\pi}{\Lambda}$ where $\Lambda$ is the period of the acoustic wave.

2.3 My Contributions

In this dissertation, I have succeeded to design, fabricate, and test modulators with deflection angles high enough to employ them in holographic video displays without any complex optics to make up for the view angle. This has been done by optimizing for the depth of the waveguide and then by titling two devices to achieve higher angles. I have also designed and fabricated devices with lower loss in the waveguide to solve the problem of low number of resolvable points in the output by increasing the length of the modulator. This has been done by proposing a different technique for making the waveguides in the devices. The results of my work on LCoS SLMs and details about use of them in holographic video displays have been also presented in Chapter 6.
CHAPTER 3. LEAKY MODE WAVEGUIDE LIGHT MODULATORS WITH HIGH DEFLECTION ANGLE

3.1 Introduction

Spatial light modulators are limited to low diffraction angles relative to those of traditional film holography as it is difficult to fabricate active pixels to match the scale of the smallest holographic fringes (<1 μm feature size). At a minimum, to achieve a direct-view holographic display with both binocular parallax and motion parallax, the display would have to be capable of diffracting light over an angle of 15° as shown in Figure 3.1(a). The modulators currently used in holographic displays (pixelated spatial light modulators and acousto-optic modulators) are currently incapable of achieving this angle of deflection and instead rely on demagnification and derotation to achieve wide angles and large extents (see Figure 3.1(b)). Pixelated modulators, such as liquid crystal spatial light modulators, illuminated normal to the modulator surface would require a pixel size of 1.2 μm to deflect 632.8 nm light over this angle. Such a pixel density is beyond the current state of the art. Once such devices are created and connectivity (fan-out) issues are resolved, the resulting pixel density of > 1 Mpixel/mm² will make necessary a drive solution with extremely high bandwidth (such a display with 120 cm² would require a drive bandwidth of 360 Gpixels/s). An acousto-optic modulator, illuminated at the Bragg angle, would require a similar minimum acoustic fringe size which, in a slow-shear mode tellurium dioxide acousto-optic modulator with an acoustic velocity of 617 m/s, would require a signal with an RF bandwidth of 255 MHz which lies well outside its capacity (currently these modulators are limited to bandwidths of approximately 70 MHz). Lithium niobate bulk wave modulators are capable of much higher bandwidths, but they also possess higher acoustic velocities (~4000 m/s) so that a 15° deflection would require a signal bandwidth in excess of 1.65 GHz per acoustic channel. In order to avoid the computational complexity associated with these high bandwidths and the fabrication complications associated
with physically small diffractive features, it would be desirable to have a modulator which could achieve high angular deflection with low drive bandwidth and relatively large diffractive features.

In this work we report a leaky mode guided-wave modulator capable of deflecting 632.8 nm light over an angle above 19.5° scattering off of acoustic structures with a minimum period of approximately 7 \( \mu m \) driven by an RF signal only 70 MHz in bandwidth. This result shows a six-fold increase over the current state of the art for scanned aperture holovideo displays. To the best of our knowledge this result also represents the highest scanned angle per period for all spatial light modulators. Further improvements in device geometry will make it possible to achieve aggregate deflections in excess of 20° for green and blue light as well.

Holographic video displays utilize spatial light modulators to encode holographic wavefronts. Typically these modulators are limited in their angular deflection to a few degrees. For example, the first two generations of scanned-aperture holographic video displays [24–28] utilized acousto-optic Bragg cells with an RF bandwidth of 50 MHz and a corresponding angular sweep of 3°.

Waveguide light modulators have been introduced as an alternative to acousto-optic Bragg cells and pixelated modulators for holographic video displays. They advance the state-of-the-art bulk wave modulators by providing a low-cost, highly parallel, high-bandwidth design with unique capabilities such as the ability to rotate the polarization of the signal light, the ability to control color in the frequency domain and the ability to deflect light over a greater angle for a given grating period [29–32]. This last advantage is a result of the nonlinear nature of the grating equation shown in Equation 3.1. A grating illuminated from a glancing angle will have orders that deflect at higher relative angles than light entering normal to the grating (see Figure 3.2(b,c)).

This increase grows further as the light exits the high-index waveguide substrate and enters the air according to Snell’s law [see Equation 3.2] as shown in Figure 3.2(a).

\[
\sin \theta_1 - \sin \theta_{in} = \frac{m \lambda}{\Lambda} \rightarrow \theta_1 = \arcsin (\sin \theta_{in} + \frac{m \lambda}{\Lambda}),
\]

(3.1)

where \( \theta_1, \theta_{in}, m, \lambda, \) and \( \Lambda \) are respectively angle of incident light, angle of diffracted light in the substrate, integer value, wavelength of light, and grating period.
Holograms can be viewed directly.

Holovideo requires demagnification and derotation.

Holovideo with no Demagnification (this work)

No Demagnification and No Derotation (possible for the first time)

Figure 3.1: a) 15° is needed for eye to view a static hologram with both stereopsis and motion parallax at a standard viewing distance of 500 mm from the hologram. b) 3° deflection of a typical spatial light modulator adds the need for a telescope to increase the view angle to 15° by utilizing the two lenses of different focal length. The light is also optically multiplexed via a scanner. c) Our fabricated device with deflection of larger than 15° used in the holovideo without demagnification (the focal length of both lenses is the same). d) It is now possible to multiplex devices physically to enable direct-view architectures.
Figure 3.2: Leaky-Wave device physics. a) TE light enters the waveguide as a high-order guided mode, then, interacts anisotropically with the surface acoustic wave. The result of this interaction is that a portion of the guided light is polarization rotated and therefore no longer guided. The light then exits the waveguide as TM-polarized leaky mode light. b) Light illuminating a grating at the normal deflects less than light which illuminates the grating from glancing angles (as is the case for light interacting with a grating in a waveguide) c) This graphic shows the k-space diagram for the cases of normal and near-collinear illumination which enable widely disparate deflections given the same grating period.
\[ n_{\text{air}} \sin \theta_{\text{out}} = n_{\text{sub}} \sin \theta_1 \rightarrow \theta_{\text{out}} = \arcsin (n_{\text{sub}} \sin \theta_1), \]  

(3.2)

where \( \theta_{\text{out}}, n_{\text{air}}, \) and \( n_{\text{sub}} \) are respectively angle of light exiting the substrate, refractive index of air, and refractive index of the substrate. This increased angle appears to come at the cost of point spread function. As the angle of incidence approaches the grating parallel the apparent aperture of the grating is reduced even as the pattern itself is effectively foreshortened. The result is that as the deflected angle increases the output spot size increases, likely to preserve space-bandwidth product.

Previous efforts have resulted in further optimization of the frequency control of color in these devices [29–32]. Currently scanned aperture holography systems are built with target view angles between 15°-30°. This has required the use telescopes which demagnify the acoustic image up to ten times. A modulator with the ability to sweep angles in excess of 15° would make possible holographic displays with little or no need for demagnification. In this work, an effort is made to improve the angular behavior of guided wave modulators by characterizing the change in angular bandwidth with respect to a key fabrication parameter: waveguide depth. The goal is to identify guided to leaky mode transitions that are both efficient and wideband and to identify the maximum achievable deflection angle for leaky mode transitions in proton-exchanged waveguide systems.

3.1.1 Theory

When surface acoustic waves (SAW) produced by the interdigital transducers (IDTs) hit the TE-guided light, light is coupled into TM-leaky mode which is no longer guided and it exits the substrate. According to couple mode theory, the coupling coefficient is defined and calculated as following [21]:

\[ K = \frac{\omega \varepsilon_0}{4} \int E_n(x) [\Delta \varepsilon_r(x)] E_v(x) dx, \]  

(3.3)

where \( \omega, \varepsilon_0, E_n, E_v, \) and \( \Delta \varepsilon_r \) are respectively temporal frequency of light, the permittivity of free space, electrical field of guided mode, electrical field of leaky mode, and change in dielectric coefficient in proton-exchanged lithium niobate due to SAWs. Therefore, based on the behavior of \( \Delta \varepsilon_r \), coupling coefficient change. Rust and Strake [33] have calculated \( \Delta \varepsilon_r \) for lithium
niobate and proton-exchanged lithium niobate which is a piezoelectric media through solving the electro-mechanical wave equations [34–36]. Figure 3.3 shows the modulation amplitude of the off-diagonal dielectric tensor element, $\Delta \varepsilon_r$, for a specific proton-exchanged device which is mainly responsible for the conversion of TE-guided modes to TM-leaky modes in proton-exchanged lithium niobate function with respect to the depth.

![Figure 3.3: Modulation amplitude of the off-diagonal dielectric tensor element, $\Delta \varepsilon_r$, for a specific proton-exchanged device which is mainly responsible for the conversion of TE-guided modes to TM-leaky modes in proton-exchanged lithium niobate. [From Rust and Strake, PADERBORN UNIV (GERMANY FR) (1992).]](image)

It is known that inside a multimode waveguide, the higher modes have more external evanescent fields and based on the $\Delta \varepsilon_r$, Rust et al. calculated, the fields outside of the waveguide are more strongly coupled into the TM-leaky mode so coupling coefficient and consequently diffraction efficiency of those higher modes is higher. This is proved theoretically by Rust and Strake in [33].

### 3.1.2 Fabrication

For this study eight devices are fabricated with different proton-exchange timing which result in devices with different waveguides of different depth. Figure 3.4 depicts the fabrication of a completed device. First a layer of aluminum (200 nm) is coated on a 9 mm x 15 mm X-cut
Y-propagating lithium niobate sample and then is patterned using Heidelberg uPG-01 to be proton-exchanged inside a pure Benzoic acid bath. Once the device is proton-exchanged and annealed at 375°C for 45 minutes the sample is etched by the aluminum etchant and then cleaned in Piranha acid (mixture of sulfuric acid (H2SO4) and hydrogen peroxide (H2O2)) and Isopropanol (IPA). 200 nm aluminum is coated on the cleaned sample and then patterned again to put the interdigital transducers (IDTs) on the sample. The sample is then polished with multiple polishers and cleaned with Piranha acid and IPA. The device is then mounted on a piece of glass slide next to PCB boards and then wire bonded. The wideband IDTs are designed with an impedance of 50 ohms at the target center frequency of 400 MHz. The IDT was chirped to cover a band from 350 MHz to 450 MHz, though less efficient SAW generation continues beyond these frequencies [37].

Table 3.1 shows eight samples. The first four columns give the device label, proton exchange time, waveguide depth, and number of guided modes respectively. The fifth column identifies the highest guided mode. In this experiment, the guided to leaky mode transition originating at the highest guided mode was used in all red and green experiments. In blue experiments, the guided to leaky mode transition originated from the second highest guided mode (as shown in column six). Waveguide depth and the proton-exchange time are related through the following equation.

\[ d = \sqrt{4Dt}, \quad (3.4) \]

where d, D, and t are the waveguide depth, acid diffusion length, and proton exchange time respectively.

3.2 Testing and Experiment

The testing of these samples was performed by mounting each sample in a custom, semi-automatic characterization apparatus [37] which sweeps the RF input with and sample the optical output in angle. From this data we can map input frequency to output angle and determine the RF and angular bandwidth of each device as depicted in Figure 3.5.

The lasers used in this work have the following specifications: red (diode, 632.8 nm), green (diode, 554 nm), blue (diode, 445 nm).
Figure 3.4: Fabrication process. a) The slab waveguide is created via proton exchanging the device. The interdigital transducers are written on the aluminum side of the sample. The light interaction length in this device is 4 mm. b) The smallest spacing (p) between the fingers is 6.54 (µm) and the maximum is 9.74 (µm). Width (W) and length (L) of the IDTs are 100 (µm) and 800 (µm) respectively. c) The index profile of the device. \( n_{eg}, n_{og}, n_{es}, \) and \( n_{es} \) are the ordinary and extraordinary refractive indexes of the waveguide and the substrate.

### 3.3 Results

The primary result of this work, as shown in Figure 3.6 is showing proton-exchanged leaky mode devices with angular deflection of 19.5° for red light (15.6°, and 11° respectively for Green, and Blue). This angular output maps to an input of 70 MHz giving a 3.5 MHz per degree of deflection compared to 16.7 MHz per degree of deflection for traditional high-deflection TeO2 slow shear Bragg modulators. There are 3 guided modes in sample Y2 (TE0, TE1, and TE2) which the highest guided mode is TE2.
Table 3.1: Mode characteristics of different devices with different waveguides’ depth. The first four columns shows the device label, proton exchange time, waveguide depth, and number of guided modes respectively. The fifth column identifies the highest guided mode leaky mode transition and the sixth column gives the guided to leaky mode transition originated from the second highest guided mode.

<table>
<thead>
<tr>
<th>Device</th>
<th>Proton-Exchange Time (minutes)</th>
<th>Waveguide Depth (µm)</th>
<th>Number of TE Modes</th>
<th>Highest Transition from TE-Guided to TM-Leaky for Red and Green</th>
<th>Highest Transition from TE-Guided to TM-Leaky for Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y1</td>
<td>12</td>
<td>0.8194</td>
<td>2</td>
<td>TE1</td>
<td>-</td>
</tr>
<tr>
<td>Y2</td>
<td>20</td>
<td>1.1401</td>
<td>3</td>
<td>TE2</td>
<td>TE1</td>
</tr>
<tr>
<td>Y3</td>
<td>45</td>
<td>1.5887</td>
<td>4</td>
<td>TE3</td>
<td>TE2</td>
</tr>
<tr>
<td>Y4</td>
<td>80</td>
<td>2.1868</td>
<td>5</td>
<td>TE4</td>
<td>TE3</td>
</tr>
<tr>
<td>Y5</td>
<td>140</td>
<td>2.9631</td>
<td>6</td>
<td>TE5</td>
<td>TE4</td>
</tr>
<tr>
<td>Y6</td>
<td>190</td>
<td>3.3813</td>
<td>7</td>
<td>TE6</td>
<td>TE5</td>
</tr>
<tr>
<td>Y7</td>
<td>260</td>
<td>3.9513</td>
<td>8</td>
<td>TE7</td>
<td>TE6</td>
</tr>
<tr>
<td>Y8</td>
<td>330</td>
<td>4.2717</td>
<td>9</td>
<td>TE8</td>
<td>TE7</td>
</tr>
</tbody>
</table>

Figure 3.5: Apparatus used for data acquisition.
Figure 3.6: Angular Bandwidth. For example, for red, the highest guided mode in sample Y2 is TE2. Transitions from TE2 to the leaky mode have an angular bandwidth in excess of 19°. This angular output along with the angular output for sample Y3 forms the local and global maxima for the highest order transition for all depths.

Transitions from TE2 to the leaky mode have an angular bandwidth in excess of 19° (for red). This angular output along with the angular output for sample Y3 forms the local and global maxima for the highest order transition for all depths.

The data shown in Figure 3.7 follows a trend that is not linear and not monotonic. Instead, it follows a curve with three extrema. This supports the assumption of a waveguide region with depleted piezoelectric and electro-optic properties. A depleted waveguide region gives rise to a modulation function like the one shown in Figure 3.3 which, when integrated (see Equation 3.3), leads to the path with multiple extrema like those in Figure 3.7.

3.4 Conclusion

In this study a leaky mode modulator with high angular bandwidth of 19.5° and moderate RF input 70 MHz is presented. This result occurs at a depth of \(1.1401 \mu m\) which demonstrates optimal angular deflection for not only red input light, but for green and blue input lights as well. The principle conclusion from these results is that it is possible to fabricate high order leaky mode devices with angular bandwidths more than six times greater than the TeO2 modulators traditionally used in scanned aperture holographic video displays. The angular bandwidth for red and green input light is sufficiently high to obviate the need for demagnification entirely (\(>15°\)). Blue light
also showed relatively high angular output at the optimal waveguide depth. However, blue was somewhat anomalous in this study as its most efficient transition was not the highest, but instead, the second highest guided to leaky mode transition. This may have been due to the fact that the blue transition usually occurs at higher frequencies than the red and green transitions. It is possible that the highest order transition for blue did not fit within the sample transducer’s 350-450 MHz range. Additional experiments might better determine the maximum potential angular output of blue light. By reducing or eliminating the need for demagnification, high order leaky mode devices promise to greatly advance the effort to create relatively simple, low-cost holographic video displays.

Future work includes the creation of a bilateral device which will effectively double the angular output reported here. The angular output of the waveguide leaky mode modulators is unilateral, creating only positive or negative angles of deflection as shown in Figure 3.8(a). A sandwich of these devices would provide both positive and negative angles, effectively doubling the angular deflection (see Figure 3.8(b)). A single sample could have waveguide devices fabricated on both sides of the substrate. In this case a monolithic device would produce both positive and negative angles from a single device aperture as depicted in Figure 3.8(c).
Figure 3.8: Method of doubling the deflection angle. a) Unilateral angular output from one device. b) Bilateral angular output from two devices glued together (both positive and negative angles). c) Bilateral angular output with one monolithic device having waveguide and IDTs at both sides of the sample.

3.5 Funding

Air Force Research Laboratory contract FA8650-14- C-6571; DAQRI LLC
CHAPTER 4. TILEABLE LEAKY MODE DEVICES

4.1 Introduction

Holographic video displays must have at least 15° of viewing angle in order to provide the user with both stereopsis and motion parallax [19]. The best pixelated spatial light modulators (SLMs) can only provide <5° of direct view angle without using demagnification optics which add cost, complexity, and bulk. In order to increase the angular output of these pixelated SLMs, researchers have tried to combine the output of two or more SLMs [38], but this is difficult for three reasons (see Figure 4.1): (1) pixelated SLMs diffract light into multiple positive and negative orders, (2) pixelated SLMs have undiffracted light (i.e. zero order light) that must be eliminated, and (3) the most common pixelated SLMs for holovideo (e.g. liquid crystal on silicon or LCoS) have all of the light (input light, output light, desired orders and undesired orders) on the same side of the modulator and these must be carefully filtered to give the desired output. Transmission SLMs can be used to allow the user to input light from the opposite side of the light output.

In this paper we discuss the combination of leaky mode modulators to double the deflection angle. Not only do leaky mode modulators have much higher diffraction angles, but it is also trivial to combine two such modulators to double their angular output. Leaky mode modulators can be combined easily, because, unlike pixelated SLMs, leaky mode modulators have: (i) only one output order, (ii) no zero order light at the output, and (iii) a unilateral diffraction sweep, that is, leaky mode modulators only diffract over positive angles. As a result of these advantages, paired leaky mode modulators can achieve maximum combined angular outputs approaching 28° obviating the need for any demagnification. Table 4.1 compares the maximum deflection angle of different types of spatial light modulators (SLM) in which except for our device, none of the others are applicable in video holography industry without any intervening demagnification optics.

SLMs are devices which can shape the wavefront of light as well as deflecting that light to propagate in a specific direction. There are many fields that utilize SLMs in their systems for
the purpose of modulating the intensity and phase of the light. Holographic optical tweezers [39] and video holography [40, 41] are among the applications of SLMs. The most common SLMs are pixelated devices (models are available commercially from vendors like Holoeye and Hamamatsu Corp. [42, 43]). These are typically liquid crystal on silicon (LCoS) devices which display an updateable phase grating. A typical, high resolution, SLM will have a pixel pitch just under 4 µm and a maximum diffraction angle of < 5° [42]. This pixel pitch (4 µm) results in a 4.85° deflection angle. This is calculated using the grating equation (Equation 4.1):

$$\sin(\theta_{out}) = \sin(\theta_{in}) + \frac{\lambda}{\Lambda},$$

(4.1)

where $\theta_{in}$ is input angle (chosen to be zero or normal in this case) and $\theta_{out}$ is the output deflected angle. $\lambda$ (633 nm) and $\Lambda$ ($=2*$pixel pitch) are the laser light wavelength and the grating period respectively.

In video holography SLMs are used to create the optic wavefront that gives rise to the 3D image. In these modulators, the holographic diffraction pattern is formed by the superposition
Table 4.1: Different SLMs.

<table>
<thead>
<tr>
<th>Type of SLM</th>
<th>Maximum deflection angle at $\lambda=633,\text{nm}$</th>
<th>Video holography without intervening optics</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO3 bulk wave SLM</td>
<td>0.5° [7]</td>
<td>no</td>
</tr>
<tr>
<td>TeO2 bulk wave SLM</td>
<td>3° [44]</td>
<td>no</td>
</tr>
<tr>
<td>LCoS SLM</td>
<td>4.85° [42]</td>
<td>no</td>
</tr>
<tr>
<td>leaky mode SLM</td>
<td>19.5° [19]</td>
<td>yes</td>
</tr>
<tr>
<td>Paired leaky mode SLM</td>
<td>28° [this work]</td>
<td>yes</td>
</tr>
</tbody>
</table>

of acoustic waves in the material. A transducer is attached to a photoelastic crystal and a radio frequency electric signal drives the transducer to vibrate creating acoustic waves in the crystal. These will produce expansion and compression on the crystal which change the refractive index in different locations. This index modulation is periodic since the input signal is an oscillating signal creating a grating in the crystal. Incident light diffracts off the grating to a specific direction for a given input frequency. In leaky mode SLMs, a channel waveguide is created on the crystal (X-cut Y-propagating LiNbO3 in this work) in a process called proton exchange, and then an interdigital transducer (IDT) is written on the unproton exchanged part of the crystal to launch surface acoustic waves (SAW). The guided light illuminates the SAWs at a near-collinear angle outputting a high deflection angle (see Figure 4.2(b)). Figure 4.2(a) depicts the process in which light is deflected. First guided TE polarized light is coupled into the waveguide through the input grating coupler, then, it interacts anisotropically with the surface acoustic waves. As a result of this interaction, a large portion of the guided light is polarization rotated and therefore no longer guided. This polarized light is a leaky TM polarized light that exits the end of the substrate [21].

In our last work [19], a single leaky mode waveguide modulator was presented with 19.5° deflection angle for red color. The result occurred at a specific optimal waveguide depth (1.1401 $\mu\text{m}$ equivalent to 20 minutes in pure benzoic acid). This is about a four-fold increase output angle compared to the best commercially available LCoS SLMs [42]. In this work, a design is proposed in which the deflection angle is doubled by attaching two devices together with a solvent-based adhesive.
Figure 4.2: Leaky mode device physics. a) TE light enters the waveguide as a high-order guided mode, then, interacts anisotropically with the surface acoustic wave. The result of this interaction is that a portion of the guided light is polarization rotated and therefore no longer guided. The light then exits the waveguide as TM-polarized leaky mode light. b) Light illuminating a grating (7 µm period and λ=633 for this specific graph) at the normal deflects less than light illuminating the grating from glancing angles (as is the case for light interacting with a grating in a waveguide).

In this study, dilute benzoic acid (1% lithium benzoate by weight) is used since the mode coupling efficiency of the device is higher and the waveguides are less lossy compared to pure proton exchanged waveguides. In our last work, the highest angular bandwidth occurred in a device with 3 TE guided modes. For this work, a device with only 2 TE modes (taking 4.5 hours in the acid) is studied. The primary result of this work is to fabricate a paired leaky mode SLM with 28° deflection.
4.2 Design and Fabrication

The leaky mode waveguide modulators used for this study are fabricated in a set of clean-room steps shown in Figure 4.3. First 600 nm aluminum is evaporated on a clean X-cut Y-propagating lithium niobate sample. The sample is then coated with a positive photoresist, 1:1 S1805:EBR and baked in oven at 100°C for 15 minutes (a). Then, the grating input couplers are written on the sample using a tabletop maskless aligner. The photoresist is developed and the unexposed part of the aluminum is etched away. The gratings are then etched into the substrate using reactive ion etch (RIE) machine. The sample goes through 8 runs of 11 minutes of etching in the machine. The sample is cleaned in piranha clean and rinsed with acetone and isopropyl alcohol (IPA) and air dried (b). The aluminum is etched off and 200 nm new aluminum is coated on the sample. It is then coated with 1:1 S1805:EBR. Next the sample is baked in oven at 100°C for 15 minutes after coating it with photoresist. The gratings will still be visible for alignment purposes (c). The waveguides are written on the sample. It is then etched and cleaned (d). The sample is placed in hot dilute acid (benzoic acid at 220°C for 4.5 hours) to form the waveguides. After rinsing with acetone and IPA, it is dried and placed in the oven to be annealed (at 375°C for 45 minutes) (e). The aluminum is etched away and new aluminum (200 nm) is evaporated on the sample. It is then coated with s1805. Then, it is baked in oven at 100°C for 15 minutes after coating it with photoresist (f). The IDTs are written on it and etched and cleaned. This shows a complete device (g).

4.3 Experiments

Testing the device has been done using a custom semiautomatic characterization machine [29] (Figure 4.4) which sweeps the radio frequency (RF) input using a LabVIEW program and records the optical output using a power meter on a linear actuator in the setup.

1. The waveguide modulator is mounted on a rotation stage, connected to a RF amplifier and signal generator, and is coupled with a monochromatic laser beam. Input RF power to the device is typically set to 27 dBm in this project.

2. A computer controlling the RF signal generator, linear actuator, and power meter is programmed to sweep the RF frequency and detector position.
Figure 4.3: Fabrication steps. a) 600 nm aluminum is evaporated on the sample followed by coating a positive photoresist. b) The sample is patterned with the grating input couplers. c) The aluminum is etched away and 200 nm new aluminum is coated on the sample. d) The waveguides are written on the sample. e) The sample is proton-exchanged. f) The aluminum is etched off and 200 nm new aluminum is evaporated on the sample. g) The IDTs are written on the sample. h) The IDT is composed of several fingers with a set of chirped frequencies.

3. The linear actuator is set to a position step by the computer (0.1 mm for this study).

4. The RF signal generator output is enabled.

5. The RF frequency is set to a frequency step by the computer (0.5 MHz for this study).

6. The measurement of the optical power meter, the RF frequency, and the position of the optical power meter/linear actuator are recorded simultaneously in an excel sheet.

7. Steps (5) and (6) are repeated until data spanning the entire frequency range of interest is recorded (320 MHz to 430 MHz for this work).

8. The RF signal generator output is disabled to record background noise for each position.

9. This process will continue until data spanning the entire position range of interest is recorded (0 to 12 mm in this work).
10. A new dataset is created by subtracting the optical power background noise of each position step from the optical power measurements made at that location.

11. The output power as a function of input RF frequency and position is plotted using the new dataset.

Figure 4.4: Apparatus used to record data.

Figure 4.5 shows the image of a device while being tested. First, the laser input illuminates the grating input coupler coming from the bottom of the crystal. Then, the light gets coupled into the channel waveguide as seen in the image and interacts with the surface acoustic waves. The result of this interaction is the TM polarized leaky mode output exiting the end of the substrate which can be filtered from the input TE mode by placing a polarizer at the output.

4.4 Results

Figure 4.6 shows the color map response of the combined leaky mode spatial light modulators. The horizontal axis depicts the RF input frequency and the vertical axis demonstrates the output angle. It shows that both negative and positive angles exist at the output. The bandwidth
Figure 4.5: A typical tested device. A) TE polarized light illuminating the grating input coupler at an incident angle of 40° from the bottom of the crystal. B) Grating input coupler along the whole width of the edge of the device. C) Light streak coupled into the waveguide. D) Transducers. E) PCB board connecting RF input to the device. F) Sample holder. TE-guided light interacts with the surface acoustic waves created by the IDT and TM polarized leaky wave exits the end of the substrate as a result of the interaction.

of the device is about 65 MHz and the minimum and maximum deflection angles are -14° and 14° resulting in a total angular bandwidth of 28°. This angular output over 65 MHz bandwidth gives a 2.32 MHz per degree of deflection compared to 16.7 MHz per degree of deflection for traditional high deflection TeO2 slow shear Bragg modulators.

Figure 4.7 depicts the deflected beam at different frequencies for the paired leaky mode spatial light modulators. As seen in Figure 4.7(a), both positive (back device) and negative (front device) output angles are created resulting in 28° deflection totally. Figure 4.7(b) shows the images of the deflected beams of both devices at different frequencies.

4.5 Conclusion

Paired leaky mode spatial light modulators with near 28° deflection are presented by attaching two singular leaky mode devices together resulting in a bilateral angular output.

The next step in this work is to fabricate transducers on the top and bottom of the same monolithic substrate which would enable output light to exit from the same aperture and also do analysis for color. The design in this project makes it possible to create flat screen holographic
Figure 4.6: Color-map response of the paired devices. It shows a deflection angle of 28° for this device.

video displays for the first time if many of these spatial light modulators are multiplexed physically. In the most straightforward instantiation, the area of the multiplexed display would be equal to the one sum of the areas of the paired devices.

4.6 Funding

Air Force Research Laboratory contract FA8650-14- C-6571; DAQRI LLC
Figure 4.7: Deflected dots. a) Bilateral angular output from two devices glued together (both positive and negative angles). b) Angular and frequency bandwidths are respectively 28° and (65 MHz for both side devices).
CHAPTER 5. LOW-LOSS WAVEGUIDES WITH REVERSE PROTON EXCHANGE TECHNIQUE

5.1 Introduction

In the past, leaky mode waveguide light modulators (LMWLM) have been demonstrated to have superior angular output when compared to standard spatial light modulators [19, 41, 45]. The physics of leaky mode modulators is shown in Figure 5.1. First, TE polarized light couples into the waveguide. It then hits the surface acoustic waves leaking into the substrate as TM polarized light.

One improvement that could be made to the current setup would be to increase the device’s diffraction efficiency, making the output of the device stronger across all angles. Diffraction efficiency for a Bragg-regime surface acoustic wave (SAW) grating is complicated, but one highly influential factor is the length of the interaction between the light and the grating (see Figure 5.2).

Figure 5.1: Light enters the AO SLM by way of prism coupling. As the light travels along the waveguide, it encounters a surface acoustic wave (SAW) produced by interdigital transducers laid on top of the waveguide. Some of the light leaks out of the waveguide and exits the device at an angle determined by the frequency of the light and the acoustic wave. By modulating the frequency of the SAW, different angles can be achieved.
Although the equation is complicated and won’t be given in this paper, diffraction efficiency increases as interaction length squared [46]. This means that there is a strong correlation between the length that the light is interacting with the SAW and the diffraction efficiency of the SAW.

Increasing the interaction length in a leaky mode device will be simply done by increasing the length of the device and change the technique with which the waveguides are made (Figure 5.3.a). However, in pixelated spatial light modulators, in order to make size bigger, many changes are needed to be done in the system. This includes adding more phase elements and transistors (CMOS) which cannot be done simply in a cleanroom environment (Figure 5.3.b).
In this work, we will show that the current limiting factor for interaction length in a lithium niobate LMWLM is optical loss in the waveguide. We then will demonstrate how a reverse proton exchanged (RPE) waveguide is an ideal candidate for increasing interaction length.

Proton exchange is a surface diffusion process in which the H+ ions in the acid are exchanged with Li+ ions in the crystal. This will change the refractive index of the surface of the crystal which forms the waveguide. This process can be reversed by putting the sample in salt which has Li in it. The lithium ions in the salt are exchanged with the H+ ions in the surface of the proton exchanged crystal. Figure 5.4 demonstrates the two steps involved in the RPE process: a first, deeply penetrating $H^+ \Rightarrow Li^+$ exchange followed by a second, weaker $Li^+ \Rightarrow H^+$ exchange [47].

Figure 5.4: RPE steps.

Among the many advantages of RPE the following ones are the most important:

• **Longer interaction length.** This parameter as discussed above is important for diffraction efficiency. A longer interaction length results in a higher numerical aperture (NA) as well. NA directly controls the number of resolvable points in holographic displays and also a higher NA increases the physical distance between the minimum and maximum points the
holographic display can accommodate (focus). More details on the NA will be studied in a future paper. Moreover, if we are spatially multiplexing the leaky mode devices, we can use fewer devices to cover more area with longer interaction lengths.

- **Restoration of material properties at surface.** Proton exchange destroys electro-optical, nonlinear optical, piezoelectric, and acousto-optical properties of lithium niobate [48]. Different methods have been introduced in literature to overcome the reduction in those mentioned useful coefficients. Soft proton exchange (PE process without post-exchange annealing in a highly diluted melt of benzoic acid) and RPE are among those techniques [49]. Fedorov et al. have studied second harmonic generation in proton exchanged lithium niobate waveguides and concluded that the nonlinear properties of annealed proton exchanged lithium niobate waveguides can be effectively recovered by the reverse proton exchange technique [50].

- **Higher optical power in the evanescent field.** There is more optical power in the evanescent field where material parameters (electro-optical, nonlinear optical, piezoelectric, and acousto-optical constants) are higher compared to inside the waveguides. This is an advantage since according to the coupled mode theory most of the guided to leaky mode conversion occurs at this region resulting in higher diffraction efficiencies [21].

- **Lower optical loss.** This advantage is important for transparent displays since it increases confinement inside the waveguides and less absorption and scattering happen inside the display.

5.2 Principles

For light travelling in any dielectric medium, loss can be described with the following equation:

\[
I(\lambda, L) = I_0 e^{-\alpha(\lambda) L},
\]

where \( \alpha \) is a constant that describes attenuation in the medium. This loss may be due to wavelength-dependent absorption as well as scattering off molecular imperfections. If the dielectric is finite,
further scattering may occur at the boundaries. This effect is compounded by any particulates present on the surface of the dielectric. On the other hand, the constant describing acoustic loss in lithium niobate is given by the following equation:

$$\text{Acoustic Attenuation}(dB/\mu s) = 0.88F^{1.9} + 0.19F,$$

where $F$ is the frequency in GHz. Acoustic energy is lost due to natural dampening in the material as well as any imperfections in the material. There is also a small amount of loss due to the SAW coupling with the surrounding air, but this is negligible when compared to the first two effects, but is included in the equation above as the second term. For our system, the frequency of the SAW is, on average, about 500 MHz; this means the attenuation constant is 0.33 dB/s. Combined with the speed of sound in x-cut, y-propagating LN (3909 m/s), the 3 dB drop-off point for the SAW is about 36 mm. This can be considered to be indicative of an upper bound to the interaction length in our device. The optical loss for a LN waveguide varies widely based on the procedure used to create the waveguide. For our dilute proton exchange (DPE) waveguides, the 3 dB loss was found to be approximately 1.5 mm. This is significantly shorter than the 36 mm length afforded by the acoustic loss in the waveguide. While the 3 dB loss point should not be considered the guideline for the interaction length between the SAW and the light, it still indicates where the limits of the system lie: the optical loss. Clearly, reducing acoustic loss would provide little in the way of increasing interaction length because the optical loss would still be far greater than the acoustic loss. Instead, we need to focus on increasing optical throughput in order to increase the length of our acousto-optic interaction. As mentioned above, optical loss in a waveguide depends heavily on boundaries and molecular imperfections.

Wavelength-dependent losses are ignored here because, given the material, there is little to be done in that regime. Molecular imperfections arise in LN from the proton exchange process by replacing the interstitial Li+ ions with H+ ions. Past proton exchange processes have used soft melts or long anneal times to make the proton exchanged waveguides lower-index, meaning there are fewer interstitial exchanges in any given area of the waveguide, which reduces losses due to lattice imperfections. Boundary losses are also important. In a surface LN waveguide, there are two boundaries: one with the surrounding air (or any deposited surface material, such as a
metal or oxide layer), and one with the virgin LN beneath. Momentarily ignoring any surface imperfections or dirt, the boundary with the virgin LN is more important, since it is the preferred side for the energy stored within the waveguide. In other words, since the index contrast is lower at the PE LN, virgin LN boundary, more interactions will occur at that boundary and therefore more boundary loss will occur on that side as well. However, proton exchange, and in particular, dilute annealed proton exchange, has the benefit of smoothing the bottom of the waveguide so as to create a soft, tapered boundary between the two layers. This means that although less energy is contained in the waveguide, the boundary is also less susceptible to boundary loss. Returning to the top surface, we notice that the index contrast is high, which means containment is high, but also losses per interaction are also higher. Furthermore, we can no longer ignore defects such as scratches or etching pock marks, as well as absorption due to dust, etc. as well as any metals or oxides. While an optimal device obviously would try to mitigate these losses, it would be prudent to make them a non-issue. Reverse proton exchange will remove many of these issues. First, it brings the waveguide away from the surface, reducing or eliminating losses due to the aforementioned defects. This also means that both sides of the waveguide are now surrounded by virgin LN, giving a more favorable symmetric mode shape as shown in Figure 5.5. Annealing leads to the diffusion of protons deeper into the substrate, such that the peak $n_e$ is reduced and the material phase changes into a lower loss. Removal of protons from the waveguide surface lowers the refractive index near the surface, shifting the maxima of the modes deeper into the substrate (and away from the dead layer), while simultaneously forcing the peaks of the modes to coincide in depth [51]. An additional advantage of this process is that the spatial modes of channel waveguides can be engineered to be symmetric in both width and depth, leading to better overlap with optical fiber modes [52].

5.3 Fabrication and Results

Two samples with same length and width (15 mm x 9 mm) were cut. First, waveguide channels were patterned on a 200 nm layer of aluminum on the LN using the maskless aligner (Heidelberg). Then, the channels were proton exchanged in dilute benzoic acid (1 % lithium benzoate by weight). The DPE sample was taken out after 4.5 hours in the acid bath at 220°C and put in the oven to be annealed at 375°C for 45 minutes. While the RPE sample stayed in the acid
for 16 hours. Next, the sample was placed in a quartz test tube with a hole at the bottom and put in the RPE melt gently for 45 minutes at 375°C. In order to protect the sample from cracking, the sample is taken out very slowly so it does not experience the change in temperature abruptly. Then, it is placed on the hotplate at 200°C and let it cool down gradually with a cover to prevent breezes.

The samples are rinsed and cleaned with acetone to wash away all the debris and residues on their surface making them ready for testing. Figure 5.7 shows an image of the two devices when TE polarized light was coupled into the waveguide using a rutile prism. It clearly shows that the output of the sample in the bottom which is the RPE sample is much higher than the output of the DPE sample. Another way of knowing the lower loss of the RPE sample is by looking at the waveguide channel. The light streak is less bright as opposed to the DPE sample in which the light streak is very bright at the beginning and it dims as it travels inside the waveguide.

Also, pictures of the output on a screen were taken at a distance of about 20 cm from the end of the samples. More light is observed on screen when the RPE sample is tested as seen in Figure 5.8. The reason for the line is because light is exiting a small aperture so according to Fourier...
Figure 5.6: a) Working DPE leaky mode device. b) Working RPE leaky mode device.

optics, the output will be wide at a fairly long distance (compared to the width of the waveguide channel).

5.4 Conclusion

Leaky mode devices have a wide range of possible uses in holographic video and in other optical applications, but their overall utility is strongly dependent on their interaction length of the light with the surface acoustic waves by reverse proton exchanging the waveguide. Longer interaction lengths lead to larger diffraction efficiencies, high numerical apertures and lower noise. In leaky mode devices, interaction length is limited by two bounds: the acoustic loss bound and the optical loss bound. To date, most leaky mode devices have been limited by the optical-loss bound.
Figure 5.7: Loss comparison in RPE and DPE. Based on this image, it is clear that more light exits the RPE device. The pictures are squashed vertically to fit them in a tighter space.

Figure 5.8: Output light on a screen. The top image shows the output light exiting a DPE waveguide. The bottom image demonstrates the output light exiting the RPE waveguide. It shows that the light from the RPE sample is brighter and more light is present in the output. The pictures are squashed vertically to fit them in a tighter space.
In this work, we reduce optical loss by utilizing reverse proton exchange instead of pure proton exchange to increase the effective interaction length of our leaky mode devices from approximately 6 mm to over 20 mm which comes much closer to the theoretical acoustic bound of 40 mm.
CHAPTER 6. LCOS SPATIAL LIGHT MODULATORS

6.1 Liquid Crystals

Liquid crystals are an important intermediate phase of matter which exhibit features from both the solid and the fluid state. Liquid crystals flow like liquids and at the same time have the ordering properties of solids. Liquid crystalline materials have been observed for over a century but were not recognized as such until 1880s. In 1888, Friedrich Reinitzer started describing the liquid crystal phase systematically and reported his observations when he prepared cholesteryl benzoate, the first liquid crystal.

Liquid crystals are composed of small-size organic molecules (10-30 Å) which tend to be elongated, like a cylindrical rod. At high temperatures, the molecules will be oriented arbitrarily forming an isotropic liquid which appears optically, magnetically, electrically, etc. to be the same from any direction in space. Due to their elongated shape, under proper conditions, the molecules exhibit a specific order such that all the axes line up and form a nematic liquid crystal. In this phase, the molecules are still able to move around in the fluid, but their orientation remains the same. In lower temperatures, liquid crystals exhibit both orientational and positional order forming a smectic phase.

The nematic liquid crystal phase is by far the most important phase for applications. In the nematic phase all molecules are aligned approximately parallel to each other. In nematic phase, the liquid crystals possess two interesting phenomena: reorientation of the LC in an electric field due to the anisotropy nature of the LC and optical birefringence of the LC.

Anisotropy means that the properties of the material differ depending on what direction they are measured. Liquid crystal behaves differently depending on what direction electric or magnetic fields are applied relative to the director (optical axis). Applying an electric field to an LC molecule with a permanent or induced electric dipole will cause the dipole to align with the field (see Figure 6.2. Since the electric dipole across liquid crystal molecules varies in degree
Figure 6.1: Isotropic, Nematic, Smectic phase of liquid crystals (LCs). As discussed in the text, LCs in isotropic phase have no specific orders as opposed to the nematic phase in which they have a orientational order. Besides orientational order LCs have positional order as well in the smectic phase.

Figure 6.2: Anisotropy property vs voltage applied. A weak voltage rotates the liquid crystal not all the way along the external electric field. However, the liquid crystals will get in line with the electric field if it is strong enough.

along the length and the width of the molecule, some kinds of liquid crystal require less electric field and some require much more in order to align the director. This ratio is called the dielectric constant of the LC which is different for the ordinary and extra-ordinary (optical) axes. In positive LCs, the extra-ordinary dielectric constant is larger than the ordinary dielectric constant as opposed to negative LCs where the ordinary dielectric constant is larger than the extra-ordinary dielectric constant.

Liquid crystal is also birefringent, meaning that it possesses two different indices of refraction in the axes direction perpendicular to each other. One index of refraction corresponds to light polarized along the director of the liquid crystal, and the other is for light polarized perpendicular
Figure 6.3: Birefringence property. The refractive index of the optical axis is larger than the refractive index of the other two axes. In positive liquid crystals, extraordinary refractive index is larger than ordinary refractive index. This makes the optical axis "the slow axis" since the speed of light is slower due to higher refractive index in that direction.

to the director. Light propagating along a certain direction has electric and magnetic field components perpendicular to that direction. Essentially, what this birefringence property amounts to is that these two components of either the electric or the magnetic field will propagate through the LC at different velocities and, therefore, possibly be out of phase when they exit the crystal.

6.2 LCoS as a Spatial Light Modulator

At the end of Chapter 2, we discussed about dynamic holograms and how LCoS SLMs fit in that category. As stated before, liquid crystals are the key components of LCoS SLMs. Using the two compelling phenomena of the LCs, anisotropy and birefringence, 3D images could be reconstructed after the phase map for that specific object on the LC panel is exposed to collimated coherent light. Several voltage levels can be put on the LC panel resulting in titled LC with different rotation angle for each voltage level. In our case, an 8 bit LCoS SLM is used to build our holographic displays which results in 256 levels of voltages. Figure 6.4 shows the LCoS SLM that was used in our lab.
6.3 Applications of LCoS

The LCoS-SLM has a wide range of applications that include fundus imaging by corrective optics [14], optical tweezers utilizing optical manipulation techniques [15, 53–56], femtosecond laser pulse shaping [16], and a host of other fields. In this chapter, two important applications of LCoS that I have worked and researched on will be explained. The first one is creating smart aberrations on LCoS to trap small particles in the focal plane of the beam. Another novel application of LCoS SLMs is in the field of updatable holographic displays. Computed holograms (phase pattern) are fed into the readout panel on the LCoS display. Once the display is exposed to coherent collimated laser beam, it reconstructs the holographic image accordingly.

6.3.1 Optical Trapping in Photophoretic-Trap Volumetric Displays

Freespace volumetric displays, or displays which create luminous image points in space, are the technology that are capable of producing images in 'thin air' that are visible from virtually all directions and are not subject to clipping. One way to build volumetric displays is to use the
photophoretic optical trapping concept [57–60]. This display works by first isolating a cellulose particle in a photophoretic trap created by spherical and astigmatic aberrations. There are two ways to make these aberrations: A) manually through spherical and tilted lenses [57,61]. B) using LCoS SLMs. The trap and particle are then scanned through a display volume while being illuminated with red, green, and blue light. The result is a 3D image in freespace with a large color gamut, fine detail, and low apparent speckle.

A number of researchers currently use spatial light modulators for trapping and manipulating particles [62–65]. To achieve parallel, independent trapping, an active SLM may be used to simultaneously trap multiple particles for scanning. A combination of two SLMs would provide independent trapping and illumination. For this effort, we have confirmed that a particle can be held with a phase-only modulator displaying a diffraction pattern meant to both steer input light as well as to modify the astigmatic and spherical aberration of the trap at the focus of the output lens [1,66].

The LCoS experiments were performed by using a Hamamatsu X10468-01 phase-only 792x600 pixel spatial light modulator. The device was illuminated by a 100 mW 405 nm laser diode approximately 10° from normal. Due to beam clipping required for uniform illumination and internal reflections the power delivered to the trap was only 48 mW. The phase map displayed on the LCoS was created numerically from combining the spherical aberration, astigmatism, and coma that can also be created by lenses. This was then combined with the factory provided correction phase map and an offset grating to create the final phase image. The following equations were used to create the phase map in Figure 6.5.

\[
P_{SA} = A_{SA}\rho^4
\]
\[
P_{A} = A_{A}\rho^2(\cos^2\theta - 1)
\]
\[
P_{C} = A_{C}\cos\theta(3\rho^3 - 2\rho)
\]
\[
P_{IMG} = P_{SA} + P_{A} + P_{C} + P_{CAL}
\]

where \(P_{SA}, P_{A}, P_{C},\) and \(P_{IMG}\) stand for the spherical aberration, astigmatic aberration, coma and total phase images, respectively. PCAL is a calibration phase image specific to the LCoS being used and...
Figure 6.5: Solid-state aberration trap. A) An LCoS pattern used to encode an aberration optical trap. B) The display trapping function can be changed to that of a solid-state display by encoding the phase pattern of the holographic trap on an SLM as shown.

is often provided by the manufacturer. The scalar coefficients $A$ represent aberration weights ($A_A$, weight for astigmatic aberration; $A_{SA}$, weight for spherical aberration; and $A_C$, weight for coma aberration), $\theta$ describes the rotation of the lens from the perpendicular, and $\rho$ is the radial distance from the center of the LCoS display. These equations are the same Zernike coefficient for different aberration functions [67, 68].

### 6.3.2 Maxwell Holography

In classical optics, traditional Fourier transforms are used to compute holograms. Maxwell holography approaches this field from an electromagnetic point of view. Light is at its core a time-varying electromagnetic field. The famous Maxwell Equations (shown below [69]) describe the behavior of electromagnetic fields. As the name suggests, the Maxwell model simply treats the desired hologram as an electromagnetic field instead of an optical phenomenon.

According to temporal symmetry of Maxwell Equations, we can reverse the time and imagine the holographic image we want to create already exists, and then calculate the values of its electric field on a surface that entirely surrounds it. A portion of that surface could be the LC panel of an LCoS SLM. Finally, when we illuminate the LC panel with coherent collimated light, the holographic image appears.
As it is known, the solution for a spherical wavefront (point source) in Maxwell Equations is \( \frac{1}{r^2} \exp(jkr) \) with \( r \) being the distance of the point source to the location in space and the "k" factor is the wavenumber which is different for each color in free space [70]. Now assume that every point on the image is a point source creating spherical wavefronts. Thereby, a sum of these spherical wavefronts on the holographic element (hogel [71]) becomes the contribution of that hogel to the whole hologram. This is shown in Equation 6.8.

\[
E(n,i,ii) = \frac{1}{r^2(n,i,ii)} \exp(jkr(n,i,ii))
\]  

\[
\phi(n,i,ii) = \text{angle}(E(n,i,ii))
\]  

\[
\text{Phase} - \text{Hogel}(i,ii) = \sum_N (\phi(n,i,ii)),
\]

in which, \( N \) is the number of points that is making up the image and \( E(n) \) gives the electric field emitted from the image point "n" at (i,j) hogel on the LCoS panel and \( \phi \) represents the phase of that electric field on that hogel. Also, Phase-Hogel(i,j) is the sum of all those phases on location (i,j) on the LCoS.

Figure 6.6 shows the optical setup that is used mostly in holographic video displays with normal light illumination for all red, green, and blue colors. Red, green, and blue lasers are combined and aligned using dichroic mirrors to create a white collimated output illuminating the non-polarizing beam splitter. Half of the light is blocked using the light trap and half of it goes through the beam splitter hitting the LCoS normally. Then half of this diffracted light exits the beam splitter
Figure 6.6: Optical path of a holographic video display. Red (638 nm), green (520 nm), and blue (450 nm) lasers are used to create a white illumination system. a, b, and c are long-pass dichroic mirrors specific to RGB lasers which combine the light beams to create a white beam. d is a non-polarizing beam splitter that transmits half of the incident light and reflect the other half to the light trap, e, designed to block the unwanted light. Eventually, transmitted light illuminates the LCoS, f, and half of the diffracted light is reflected to the other unblocked side of the beam splitter. The holographic image can be projected on a screen (with different planes of accommodation) or be observed in a direct-view mode.

as shown in Figure 6.6. Then, it can be observed on a screen (a projected image that has different planes of accommodation) or in direct-view mode.

Now assume that the object (model) is a white bunny as depicted in Figure 6.7 which is a very famous model called the Stanford bunny. The model is a set of vertices and polygons which was downloaded from Stanford Computer Graphics Laboratory’s website [72]. The vertices were then used in a commercially available game platform called Unity to create a model made of points. Using the equations mentioned above, one could compute the hologram for all colors. Figure 6.8 shows the phase map for each color. The phase maps are put onto the LCoS sequentially (red,
green, and blue) with a high frame rate 90 fps resulting in an image which sounds continuous to human eye. According to this phase maps it is clear that blue diffracts less than green and red. Green also diffracted less than red. This is all due to the fact that the shorter the wavelength the less light diffracts in a grating based on diffraction grating equation shown below.

Figure 6.9 demonstrates the reconstructed holographic image of the Stanford bunny model shown above. The higher orders are also present in the image which could be blocked using an aperture at the output of the beam splitter.

6.4 Conclusion

Anisotropy and birefringence are two unique properties of liquid crystals which enable holographers to use them in LCoS SLMs to modulate the phase and in some applications the amplitude of the incoming light. Two main applications of LCoS SLM discussed in this chapter, are
Figure 6.8: Hologram (Phase Map) for each separate color. Blue always diffracts less than green and red and green diffracts less than red based on diffraction grating equation. Light with shorter wavelength diffracts to a lower output angle.
Figure 6.9: Reconstructed holographic image of the famous Stanford bunny. The model was first imported to Unity and was fed to the LCoS.

(a) trapping particles optically for use in photophoretic-trap volumetric displays and (b) building holographic video displays. In the first one, smart, purposeful aberrations including spherical, astigmatism, and coma were introduced into the system in order to achieve better particle trap. In the second application, a new approach for holographic computations was presented which uses the electromagnetic nature of light in Maxwell Equations to find a unique phase map for every specific 3D object in space.
CHAPTER 7. CONCLUSION AND FUTURE WORK

7.1 Conclusion

In my prospectus defense I promised to have the following tasks completed:

- Successful fabrication and test of leaky mode modulators with 19° angular bandwidth for red.
- Increase the leaky-mode modulators’ viewing angle through pairing leaky mode devices.
- Test reverse proton exchange technique to create low-loss waveguides.

Except all of these projects, I have included another chapter (Chapter 6) on the work and research I have conducted on pixelated LCoS spatial light modulators. Optical trapping using LCoS and Maxwell holography on LCoS are among the two applications I worked on.

In my first paper, a leaky mode modulator with high angular bandwidth of 19.5° and radio frequency input of 70 MHz was presented. The device was optimized in terms of waveguide depth. The optimal result occurred at a depth of 1.1401 μm which demonstrated optimal angular deflection for not only red input light, but for green and blue input lights as well. The principle conclusion from these results is that it is possible to fabricate high order leaky mode devices with angular bandwidths more than six times greater than the TeO2 modulators traditionally used in scanned aperture holographic video displays. The angular bandwidth for red and green input light is sufficiently high to obviate the need for demagnification entirely (>15°). Blue light also showed relatively high angular output at the optimal waveguide depth. However, blue was somewhat anomalous in this study as its most efficient transition was not the highest, but instead, the second highest guided to leaky mode transition. This may have been due to the fact that the blue transition usually occurs at higher frequencies than the red and green transitions. It is possible that the highest order transition for blue did not fit within the sample transducer’s 350-450 MHz range.
Additional experiments might better determine the maximum potential angular output of blue light. By reducing or eliminating the need for demagnification, high order leaky mode devices promise to greatly advance the effort to create relatively simple, low-cost holographic video displays.

In the second paper we discussed the combination of leaky mode modulators to double the deflection angle. Not only do leaky mode modulators have much higher diffraction angles, but it is also trivial to combine two such modulators to double their angular output. Leaky mode modulators can be combined easily, because, unlike pixelated SLMs, leaky mode modulators have: (i) only one output order, (ii) no zero order light at the output, and (iii) a unilateral diffraction sweep, that is, leaky mode modulators only diffract over positive angles. As a result of these advantages, paired leaky mode modulators can achieve maximum combined angular outputs approaching 28° obviating the need for any demagnification reported in this work. Paired leaky mode spatial light modulators with near 28° deflection were introduced by attaching two singular leaky mode devices together resulting in a bilateral angular output.

Leaky mode devices have a wide range of possible uses in holographic video and in other optical applications, but their overall utility is strongly dependent on their interaction length of the light with the surface acoustic waves by reverse proton exchanging the waveguide. Longer interaction lengths lead to larger diffraction efficiencies, high numerical apertures and lower noise. In leaky mode devices, interaction length is limited by two bounds: the acoustic loss bound and the optical loss bound. To date, most leaky mode devices have been limited by the optical-loss bound. In this work, we have reduced optical loss by utilizing reverse proton exchange instead of pure proton exchange to increase the effective interaction length of our leaky mode devices from approximately 6 mm to over 20 mm which comes much closer to the theoretical acoustic bound of 40 mm.

Anisotropy and birefringence are two unique properties of liquid crystals which enable holographers to use them in LCoS SLMs to modulate the phase and in some applications the amplitude of the incoming light. Two main applications of LCoS SLM discussed in this chapter, are (a) trapping particles optically for use in photophoretic-trap volumetric displays and (b) building holographic video displays. In the first one, smart, purposeful aberrations including spherical, astigmatism, and coma were introduced into the system in order to achieve a better particle trap. In the second application, a new approach for holographic computations was presented which uses
the electromagnetic nature of light in Maxwell Equations to find a unique phase map for every specific 3D object in space.

7.2 Future Work

In our leaky mode waveguide light modulators, the input coupling grating is a simple symmetric binary grating etched into the surface of the waveguide. Optimizing the coupling design for mode shape could greatly improve coupling efficiency. Many researchers have used blazed gratings to couple the most amount of light into the waveguides in their devices. We could use these blazed gratings in our leaky mode devices to improve input coupling efficiency further.

Output coupling gratings could be used in our leaky mode devices to couple the leaky mode diffracted light out of the substrate from the bottom. This gives us an advantage of having a larger output aperture in the device as opposed to our current devices in which light leaves the modulator from the end of the substrate. Output coupling gratings could also benefit both from similar geometric optimizations applied to the input coupling grating above such as blazed gratings as well as the creation of a hard mask process to etch the output coupling gratings directly into the surface of the lithium niobate instead of Interferometry lithography which makes the process harder and less efficient in terms of output coupling.

Tsai et al [21] in their work, have presented the results of a detailed theoretical study on guided-to-leaky mode conversion caused by the diffraction grating from a collinear surface acoustic wave in PE:LiNbO3/LiNbO3 planar waveguides for red color (optical wavelength of 632.8 nm). In their simulations they have researched the waveguide depth and number of modes in the waveguide and diffraction efficiency of each mode. We could do the same simulation to get a table relating number of mode (waveguide depth), diffraction efficiency of each mode, and the frequency response gap (peak to peak) between different colors and optimize for those based on application. Couple-mode theory could be used to get the simulation done.

Regarding the paired leaky mode devices in Chapter 4, the next step is to fabricate transducers on the top and bottom of the same monolithic substrate which would enable output light to exit from the same aperture. We could also do the same analysis for green and blue colors. The design in this project makes it possible to create flat screen holographic video displays for the first time if many of these spatial light modulators are multiplexed physically. In the most straightfor-
ward instantiation, the area of the multiplexed display would be equal to the one sum of the areas of the paired devices.

Now that we have proved that reverse proton exchange technique helps decrease the loss of the waveguide, we need to fabricated devices that have interdigital transducers. The light modulation should be tested and be compared to those of different techniques of proton exchange such as pure proton exchange, dilute proton exchange, and annealed proton exchange. based on our work in Chapter 5, the devices should show a better diffraction efficiency since less amount of light is lost in the waveguide. Also, if these RPE-based waveguide light modulators are used in our holovideo monitors, the increased in interaction length results in more addressable points in the output and these means tighter output spot size with higher numerical aperture can be achieved. Moreover, this increases the accommodation range which is a very important cue of holography.

In our work on photophoretic-trap volumetric display, image complexity in a single-particle display is constrained primarily by the speed of the scanning system. This limitation may be overcome by the use of solid-state scanning and parallelism. Parallelism is achieved by simultaneously manipulating multiple trapped particles. That is to say, instead of having one particle responsible for all of the points in an image (one particle per image volume), multiple particles may be trapped, manipulated and illuminated independently using solid-state SLMs (LCoS SLM). The scanning requirements are reduced as more particles are added. A line of trapped particles reduces the drawing complexity to a two-axis scan (one particle per image plane), a 2D array of trapped particles reduces the scan complexity to a single-axis scan (one particle per image line), and a 3D array of trapped particles could eliminate the need for scanning entirely (one particle for every image point). SLM trapping and SLM particle manipulation have been used previously [73–76]; we have successfully trapped particles using an LCoS SLM, with the phase pattern designed to create a spherical and astigmatic aberration trap (see Figure ??). We could use the same LCoS system to focus light at different locations so multiple particles are trapped. These was as mentioned above, more complex images can be created at shorter times and with bigger sizes.

Also, a simulation of all photophoretic forces applied to the particle can be done so that different sets of aberrations which lead to tighter traps are achieved. Tighter traps cause the particles to be held better in the focal point of the beam which results in higher particle speed and acceleration values.
REFERENCES


87


APPENDIX A. MATLAB CODES AND SUPPLEMENTARY IMAGES

These codes have been imported from the Matlab codes I wrote to plot the interference pattern for each specific hologram layout. See Chapter 2 for more details about the plots and the variables used in the codes. The Matlab version used for these codes is Matlab R2017a on MacBook Pro 2014 with 2.8 GHz Intel Core i7 processor and NVIDIA GeForce GT 750M graphics card.

Listing A.1: Matlab code for off-axis hologram (linear fringes)

```matlab
1 x = -0.5:0.01:0.5;
2 y = -0.5:0.01:0.5;
3 lambda = 633e-9;
4 Z = 1000;
5 s = 100;
6
7 [X, Y] = meshgrid(x, y);
8 Itot = 2*(1+cos(X*s/Z*2*pi/lambda));
9
10 figure(1)
11 pcolor(Itot);
12 axis equal tight
13 figure(2)
14 imshow(Itot, [])
```

Listing A.2: Matlab code for Gabor hologram (in-Line: Fresnel zone plate)

```matlab
1 x = -2:0.01:2;
2 y = -2:0.01:2;
3 lambda = 633e-9;
4 Z1 = 7000;
5 Z2 = 7200;
6 iZdiff = 1/Z1-1/Z2;
```
\begin{verbatim}
[X,Y] = meshgrid(x,y);
rho = sqrt(X.^2+Y.^2);
Itot = zeros(401,401);
for i=1:401
    for j=1:401
        if rho(i,j) < 2
            Itot(i,j) = 2*(1+cos(rho(i,j)^2*iZdiff*pi/lambda));
        else
            Itot(i,j) = 0;
        end
    end
end
figure (1)
pcolor(Itot);
axis equal tight
figure (2)
imshow(Itot,[0])
\end{verbatim}

Listing A.3: Matlab code for Leith-Upatnieks (off-axis) hologram

\begin{verbatim}
x = -2:0.01:2;
y = -2:0.01:2;
lambda = 633e-9;
Robj = 7000;
Rref = 7500;
[X,Y] = meshgrid(x,y);
Phi_tot = 2*pi/lambda*sind(45)+pi/lambda*(cosd(45).^2*X.^2+Y.^2)/Rref-... -pi/lambda*(X.^2+Y.^2)/Robj;
Itot = 2*(1+cos(Phi_tot));
figure (1)
pcolor(Itot);
axis equal tight
figure (2)
imshow(Itot,[0])
\end{verbatim}
Figure A.1: Sketch of the waveguide channels and interdigital transducers (IDTs) created in Klay-out software.

Figure A.2: A complete fabricated device ready to test.
Figure A.3: Results of metricon of a leaky mode device with 9 TE-polarized waveguide modes.

Figure A.4: A typical frequency and angular response of a leaky mode device.
Figure A.5: A complete paired device ready to test held in a sample holder designed in Solidworks and 3D printed using our lab’s Formlabs 3D printer.

Figure A.6: 3 dimensional plot of the intensity of the diffracted light vs surface acoustic frequency and position of the light meter.
Listing A.4: Matlab code for different kinds of aberrations.

```matlab
%% Beams formed from Aberrations

close all;
clear all;

%% Balanced spherical aberration
As = 1e-16;
for a = 1:15
    Bd_over_As = 0;
    [X,Y] = meshgrid(20*((1:792)-792/2),20*((1:600)-600/2)); % in microns
    row2 = X.^2 + Y.^2;

    BSA = As*a.*(row2.^2+Bd_over_As.*row2);
    phase = angle(exp(1i*BSA));

    figure(1);
    imshow(phase);

    imwrite(phase,['BSA_'+num2str(As*a)='_'+num2str(Bd_over_As)='.bmp']);
end

%% Balanced Astigmatism aberration
[X,Y] = meshgrid(20*((1:792)-792/2),20*((1:600)-600/2)); % in microns
row2 = X.^2 + Y.^2;
theta = atan2d(Y,X);

% for a = 1:15
%   % a = 7;
%   Aa = a*1e-4;
%   
%   BAA = Aa*row2.*(cosd(theta).^2-2*.5);
%   phase = Aa*BAA + Cal;
%   encodedPhase = angle(exp(1i*phase));
% end
```

96
% imshow (encodedPhase);

% figure(2);
% surface(phase,'edgealpha',0);
% view([1,1,1]);
% zMax = (round(max(phase(:))/(pi)+1)*pi;
% zMin = (round(min(phase(:))/(pi)-1)*pi;
% count = 1;
% zLabel = cell(1,round((zMax-zMin)/pi)+1);
% for t = zMin/pi:zMax/pi
%     zLabel(count) = {[num2str(t),' pi ']};
%     count = count+1;
% end
% set(gca,'ZTICK',zMin:pi:zMax,'ZTickLabel',zLabel);

% imwrite(encodedPhase,['Corrected_AA_Y_',num2str(Aa),'.bmp']);
% end

%%% Balanced Coma Aberration
% [X,Y] = meshgrid(20*((1:792)-792/2),20*((1:600)-600/2)); % in microns
% row = sqrt(X.^2 + Y.^2);
% theta = atand(X,Y);

% for a = 7:15
%     a = 15;
%     Ac = a*1e-12;
% %
%     BCA = cosd(theta).*row.^3-2/3.*row;
%     phase = Ac*BCA + Cal;
%     encodedPhase = angle(exp(i*phase));
% %
%     figure(1);
%     imshow(encodedPhase);
% %
%     figure(2);
%     surface(phase,'edgealpha',0);
Figure A.7: Star Trek Enterprise image made in the volumetric displays built in our lab.
Figure A.8: Charmander image made in the volumetric displays built in our lab. It shows the image at two different view angles, front and back.