INTEGRATION AND APPLICATION OF MICROLENS ARRAYS WITHIN HEADS-UP DISPLAY

by

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Abstract

Heads-up display technology is a subject of growing interest for virtual reality and augmented reality systems. The proposed work recognizes this interest and targets a key challenge for integrating this technology within eyewear, in that such systems must enable tight imaging while having a flat form factor. A Gabor lens, being coupled plano-concave and plano-convex microlens arrays, is developed in this work to meet this challenge.

In the first stage of the work, the MLAs are designed with three design criteria. For Criterion I, the coupled MLAs must project an image of the microdisplay into the relaxed eye at infinity with an angular field-of-view between 15° and 25°. For Criterion II, the coupled MLAs must project a clear image of the microdisplay with a resolution of 30 cycles-per-mm or greater. For Criterion III, the coupled MLAs must be implemented with a flat form factor to enable integration within contemporary eyewear by having a thickness of less than 23.4 mm.

In the second stage of the work, the optimized design for the MLAs is realized by the development and implementation of a specialized fabrication process. The process applies a tunable plasma pre-treatment to a glass substrate followed by dispensing, curing, and casting of microlenses on the substrate to realize arrays with the necessary diameters and radii of curvature. The plano-concave and plano-convex MLAs are then fabricated and coupled to form the Gabor lens, which is packaged with a baffle and microdisplay to function as the heads-up display.

In the third and final stage of the work, the developed heads-up display undergoes performance testing to define its modulation transfer function (MTF). The measured MTF results are compared to those of the ray-based simulations and strong agreement is seen. Moreover, it is found that the developed heads-up display has an FOV of 18.2°, a resolution of 30 cycles/mm, and a net length of 11.4 mm, and thus it meets the above design criteria. Ultimately, the developed heads-up display can enable the tight imaging and flat form factor that are being sought for future virtual reality and augmented reality systems.
Lay Summary

The research in this thesis targets on generating a compact optical component that can project images far away from the human eye, with a good imaging performance at the same time. The compactness of this optical component enables it to be integrated into the contemporary eyewear.

The designed optical component in this thesis takes the form of a regular arrangement of thousands of small lenses within an area of less than one centimeter square. This arrangement gives the optical component a flexible way to shape the beams and generate virtual images with a high imaging performance. A fabrication method with a short process cycle time and low cost is proposed to fabricate the designed optical components and a following imaging performance test is also carried out to verify the design. This research will enable a more compact display part in the application of smart goggles in the future.
Preface

The work presented in this thesis was carried out in the Integrated Optics Laboratory, in the School of Engineering, at the University of British Columbia’s Okanagan campus. All of the work was carried out under the supervision of Dr. Jonathan Holzman.

For most of the work in Chapter 2, including the derivations and Zemax OpticStudio® simulations of the microlenses and their arrays, I was the principal investigator. The presented tradespace analysis was based off the approach used by H. S. Park. The image of the human eye in Figure 2.2 was rendered from a SOLIDWORKS® model created by Sergey White and was used in this work with the permission. The remaining images generated from SOLIDWORKS® models in this chapter were created by A. L. Blanc under my supervision.

The majority of the work in Chapters 3 and 4 was based off an industrial collaboration with Intel Corp., formerly Recon Instruments Inc. I was the principal investigator for the majority of this work, including the fabrication, characterizations, and imaging performance tests. X. Jin developed the LabVIEW algorithm to dispense the plano-convex microlens arrays and assisted with the characterizations and packaging. The images generated by SOLIDWORKS® models in these chapters were created by A. L. Blanc and B. A. Hristovski under my supervision.
Table of Contents

Abstract ......................................................................................................................................................... iii
Lay Summary ..................................................................................................................................................... iv
Preface .............................................................................................................................................................. v
Table of Contents ........................................................................................................................................... vi
List of Tables .................................................................................................................................................... viii
List of Figures ................................................................................................................................................... ix
List of Variables ............................................................................................................................................... xx
List of Abbreviations ....................................................................................................................................... xxii
Acknowledgements .......................................................................................................................................... xxiii
Dedication .......................................................................................................................................................... xxiv

Chapter 1: Introduction ...................................................................................................................................... 1
  1.1 Background ............................................................................................................................................... 1
  1.2 Applications of microlens arrays ............................................................................................................. 2
  1.3 Microlens arrays in heads-up displays ..................................................................................................... 4
  1.4 Scope of this thesis .................................................................................................................................... 6

Chapter 2: Design of the coupled microlens arrays .......................................................................................... 8
  2.1 Criteria for the coupled microlens arrays ............................................................................................... 8
  2.2 Parameters of the coupled microlens arrays .......................................................................................... 12
    2.2.1 Parameters for the elementary model .......................................................................................... 13
    2.2.2 Parameters for the physical model ............................................................................................... 14
  2.3 Analyses of the coupled microlens arrays .............................................................................................. 15
  2.4 Design of the coupled microlens arrays ................................................................................................. 26

Chapter 3: Fabrication of the coupled microlens arrays ................................................................................... 39
  3.1 Motivation for the tunable dispensing process ....................................................................................... 39
  3.2 Sub-systems for the tunable dispensing process .................................................................................... 41
    3.2.1 Pneumatic sub-system ................................................................................................................ 43
    3.2.2 Actuation sub-system ................................................................................................................ 44
    3.2.3 Curing sub-system ..................................................................................................................... 46
    3.2.4 Monitoring sub-system .............................................................................................................. 48
    3.2.5 Integration of the sub-systems as the microlens array fabrication system ............................. 49
  3.3 Characterizations of the tunable dispensing process: Plano-convex microlens arrays .................. 51
    3.3.1 Characterization of the Norland Optical Adhesive ..................................................................... 52
    3.3.2 Characterization of the velocity and acceleration ..................................................................... 53
Chapter 3: Characterizations of the dispensing process

3.3 Characterization of the dwell time
3.3.3 Characterization of the dwell time .......................................................... 55
3.3.4 Characterization of the dispensing pressure ........................................... 57
3.3.5 Characterization of the dispensing time ................................................. 59
3.3.6 Characterization of the surface pre-treatment ....................................... 60

3.4 Characterizations of the tunable dispensing process: Plano-concave microlens arrays .... 63
3.5 Summary ...................................................................................................... 68

Chapter 4: Testing of the coupled microlens arrays ........................................ 70

4.1 Setup ......................................................................................................... 71
4.2 Procedures .................................................................................................. 74
4.3 Testing ....................................................................................................... 77
  4.3.1 Alignment .............................................................................................. 77
  4.3.2 Processing .............................................................................................. 78
  4.3.3 Results .................................................................................................. 81
4.4 Packaging ................................................................................................... 82
  4.4.1 Preparation of the coupled microlens arrays and microdisplay .............. 82
  4.4.2 Integration of the coupled microlens arrays and microdisplay ............... 85
4.5 Summary .................................................................................................... 87

Chapter 5: Conclusions ................................................................................... 88

5.1 Conclusions from the presented work ....................................................... 88
5.2 Recommendations for future work ............................................................ 90

Bibliography .................................................................................................... 92

Appendices ....................................................................................................... 96

Appendix A – Plano-convex MLAs fabrication procedure .................................. 96
Appendix B – Plano-concave MLAs fabrication procedure .................................. 101
Appendix C – MATLAB code for MTF test ...................................................... 107
List of Tables

Table 2.1. Optimized values for physical parameters of pitch, diameter, radius of curvature, and focal length for plano-concave and plano-convex MLAs. ..................33

Table 3.1. Characteristics of the four considered NOA optical polymers, including the viscosity, refractive index, physical characteristics, and glass adhesion characteristics. The data shown here is from Norland Product Inc. ......................52

Table 3.2. Standard deviations of diameters (as a percent of the mean) for microlenses within MLAs with nine different combinations of velocity and acceleration of the actuators. .................................................................55

Table 3.3. Contact angle of microlenses within the MLAs for various RF powers and treatment times. For all of the MLAs, the dispensing time is 0.25 second, the dispensing pressure is 5.5 psi, the pitch is 440 µm, the actuation velocity is 0.5 mm/s, the actuation acceleration is 0.5 mm²/s, the dwell time is 3 seconds, and the spacing between the dispensing needle tip and glass substrate is (0.08 ± 0.01) mm. Each contact angle quoted here for a given MLA is an average of the contact angles for the measured microlenses within the MLA. The row corresponding to a contact angle of 20º is shown in bold. .................................................................63

Table 3.4. Firmness of the fabricated plano-concave MLAs of various combinations of PDMS mix ratio (of prepolymer base to curing agent) and curing time. All of the MLAs were cured at a temperature of 60°C. ..................................................66

Table 3.5. Process parameter values for fabrication of the plano-concave and plano-convex MLAs. .................................................................68

Table 3.6. Physical parameter values for the coupled plano-concave and plano-convex MLAs along with their respective processing times. .........................69

Table 4.1. The comparison of the tested results with the three design criteria of the coupled MLAs. .................................................................87
List of Figures

Figure 1.1. A sketch of the Köhler light integrator showing its arrangement of two identical and coupled MLAs and a condenser lens. The MLAs split the incident collimated beam into discrete channels and the condenser lens recombines these channels to create a homogeneous beam in the far-field. ........... 2

Figure 1.2. Photograph of a heads-up display within a vehicle. Such a display has three main components: a video generator, a projection unit, and a combiner. These components project an image toward the user. This image is from Wikimedia common, under the Creative Commons BY-SA 3.0 Unported license. ................................................................. 4

Figure 2.1. Schematics of the eyebox for coupled MLAs. The eyebox is shown as the cross-section enclosed by dashed lines for (a) coupled plano-convex and plano-convex MLAs with a relatively small separation, s, (b) coupled plano-convex and plano-convex MLAs with a relatively large separation, s, and (c) coupled plano-concave and plano-convex MLAs with a relatively small separation, s. The focal length between the microdisplay and the principal plane of the leftmost MLA is denoted by f. ...................................................... 11

Figure 2.2. Schematic of the coupled plano-concave and plano-convex MLAs. The MLAs project an image of the microdisplay on the retina of the relaxed human eye. The focal length between the microdisplay and principal plane of the plano-concave MLA is denoted by f. The separation between the principal planes of the plano-concave and plano-convex MLAs is denoted by s. ................................................................. 11
Figure 2.3. Schematic showing the aggregate parameters of the elementary (thin lens) model of the coupled MLAs within the imaging system, including the microdisplay, the coupled plano-concave and plano-convex MLAs, and a representative human eye. The focal length between the microdisplay and the principal plane of the plano-concave MLA is denoted by $f$, the separation between the principal planes of the MLAs is denoted by $s$, and the distance between the principal plane of the plano-convex MLA and the entrance of the eye is denoted by $d$. The focal length and pitch of the plano-concave MLA are denoted by $p_{cc}$ and $f_{cc}$, respectively, while those of the plano-convex MLA are denoted by $p_{cv}$ and $f_{cv}$, respectively.

Figure 2.4. Schematic showing the physical parameters of physical (thick lens) model of the coupled MLAs within the imaging system, including the microdisplay, the coupled plano-concave and plano-convex MLAs, and a representative human eye. The thicknesses of the plano-concave and plano-convex MLAs are denoted by $t_{cc}$ and $t_{cv}$, respectively. The distance between the microdisplay and the planar surface of the plano-concave MLA is denoted by $l_0$, the distance between the curved surface of the plano-concave MLA and the planar surface of the plano-convex MLA is denoted by $l_1$, and the distance from the curved surface of the plano-convex MLA and the entrance of the eye is denoted by $l_2$. The pitch, radius of curvature, diameter, and contact angle of the plano-concave MLAs are denoted by $p_{cc}$, $R_{cc}$, $d_{cc}$, and $\alpha_{cc}$, respectively, while those of the plano-convex MLA are denoted by $p_{cv}$, $R_{cv}$, $d_{cv}$, and $\alpha_{cv}$, respectively.

Figure 2.5. Schematic showing the input and output rays that define a ray transfer matrix of a generalized lens. The input ray strikes the input plane at a distance of $y_{in}$ from the optical axis and makes an angle of $\theta_{in}$ with respect to the horizontal; the output ray strikes the output plane at a distance of $y_{out}$ from the optical axis and makes an angle of $\theta_{out}$ with respect to the horizontal.
Figure 2.6. Schematic showing the input and output rays that define the ray transfer matrix of a microlens in an MLA. The input and output rays strike the input plane at a distance of $y_{in}$ and $y_{out}$ from the optical axis and make an angle of $\theta_{in}$ and $\theta_{out}$ with respect to the horizontal, respectively. The microlens of interest is a distance of $\Delta y = N_{cc/cv} p_{cc/cv}$ off the optical axis, where $N_{cc/cv}$ is an integer and $p_{cc/cv}$ is the pitch of the MLA, and is rotated by $\Delta \theta = 0$. ..........................17

Figure 2.7. Schematic showing the real and virtual rays traced through the elementary (thin lens) model of the coupled MLAs. The object is shown in black, and the virtual image is shown in red. The distance between the object and the principal plane of the plano-concave MLA is denoted by $f$, the separation between the principal planes of the MLAs is denoted by $s$, and the distance between the principal plane of the plano-concave MLA and the virtual image is denoted by $v$. The input ray leaves the object at a distance of $y_{in}$ from the optical axis and makes an angle of $\theta_{in}$ off the horizontal; the output ray exits the plano-convex MLA at a distance of $y_{out}$ from the optical axis and makes an angle of $\theta_{out}$ off the horizontal. Real light rays are shown as solid red lines, and virtual light rays are shown as dotted red lines. ..........................20

Figure 2.8. Schematic showing the object and images generated by the plano-concave MLA (left) and plano-convex MLA (right). The black dot at a distance of $f$ to the left of the plano-concave MLA represents a single pixel on the microdisplay, which can be regarded as a point light source. The yellow dot at a distance of $u$ to the left of the plano-concave MLA is the image of the black dot, which acts as an object for the plano-convex microlens. The red dot at a distance of $v$ to the left of the plano-concave MLA is the virtual image of the yellow dot and the virtual image generated by the overall coupled plano-concave and plano-convex MLAs. ..........................24
Figure 2.9. Schematics (as top views) of the coupled MLAs. In (a), the schematic shows outlines of the plano-concave microlenses (dashed red) and plano-convex microlenses (solid black). In (b), the schematic shows plano-concave and plano-convex microlenses as red and black dots, respectively. The outlines and dots have displacements between paired microlenses that radiate out from the centre of the coupled MLAs. It is these radiating displacements that have the coupled MLAs function in a similar manner to a conventional lens.

Figure 2.10. Schematic showing a plano-convex microlens with its principal plane and focal length of $f_{cv}$ for a radius of curvature of $R_{cv}$. The beam radiates from the focal point on the optical axis at a distance of $f_{cv}$ to the left of the principal plane, passes through the microlens, and exits the microlens parallel to the optical axis.

Figure 2.11. Schematic of coupled plano-concave and plano-convex microlenses showing the dimensions “A”, “B”, and “C” as the three terms in (33). These terms correspond to the distance from the principal plane of the plano-concave microlens to the deepest point of its curved surface, the sag of the plano-concave microlens, and the distance from the planar surface of the plano-convex microlens to its principal plane, respectively.

Figure 2.12. Tradespace analyses for optimization of the coupled MLAs. The physical parameters of the MLAs are varied to optimize the (a) FOV$_A$, (b) separation, $s$, between the plano-concave and plano-convex MLAs, and (c) overall display length, $f + s$. The three characteristics being optimized are shown as colourmaps versus the negated focal length of the plano-concave MLA, $-f_{cc}$, and the focal length between the microdisplay and plano-concave MLAs, $f$. The linear band between black lines encloses values of $-f_{cc}$ and $f$ that yield the desired FOV$_A$ of 20° ± 0.5°. The curved band between black lines encloses values of $-f_{cc}$ and $f$ that yield a separation, $s$, in the desired range from 365 µm to 390 µm.
Figure 2.1. Ray-tracing simulations of the coupled plano-concave and plano-convex MLAs project an image of the microdisplay into the human eye. The figure shows light rays emanating from the microdisplay, passing through the coupled MLAs, and focusing onto the retina of the human eye. .................................................................33

Figure 2.14. A close-up view of the light rays passing through the coupled plano-concave and plano-convex MLAs. The left MLA is plano-concave, and the right MLA is plano-convex. .................................................................34

Figure 2.15. The MTF results from ray-tracing simulations of the coupled plano-concave and plano-convex MLAs with rays propagating (a) only through the microlenses, (b) only through the gaps between the microlenses, and (c) through both the microlenses and gaps between the microlenses. .................36

Figure 2.16. Imaging results from ray-tracing simulations of the coupled plano-concave and plano-convex MLAs showing (a) the image on the microdisplay and images resolved on the retina for MTF results with a resolution of (b) 30 cycles/mm (being that obtained with rays passing only through the microlenses), (c) 20 cycles/mm, and (d) 10 cycles/mm.................................................37

Figure 3.1. Schematic of (a) four steps of thermal reflow process for MLA fabrication, being photolithography, reflow, casting, and curing, and (b) the reflow step showing a photoresist cylinder transitioning into a spherical cap. .................40

Figure 3.2. Schematic of the proposed tunable dispensing process using a syringe and needle tip to form a microdroplet on a glass substrate. The surface profile of the microdroplet is defined by its contact angle of $\theta$, which is itself defined by the surface energies of the solid-gas (glass-air) interface, $\gamma_{sg}$, the solid-liquid (glass-polymer) interface, $\gamma_{sl}$, and the gas-liquid (air-polymer) interface, $\gamma_{gl}$. .................................................................42

Figure 3.3. Schematic of the MLA fabrication system for fabricating plano-convex MLAs. The system is composed of the pneumatic sub-system, actuation sub-system, curing sub-system, and monitoring sub-system. .........................43
Figure 3.4. The pneumatic control module in the pneumatic sub-system. Values of the dispensing pressure and dispensing time, for the dispenser, can be set and controlled in real-time via this LabVIEW module. .................................................................44

Figure 3.5. The actuation sub-system is presented by way of (a) a photograph, (b) its LabVIEW-based actuation control module, and (c) its Thorlabs-based actuation control module. The actuation sub-system enables 3-D motion of the stage holding the glass substrate while the syringe and needle tip are stationary. ........................................................................................................45

Figure 3.6. The (a) designed MLA dispensing platform and (b) its integration within the actuation sub-system. The platform has a 25 × 25 mm² recessed square, as shown in (a), to hold the glass substrate. The platform is integrated with a kinematic mirror mount in the manner shown in the photograph of (b). ..............46

Figure 3.7. Photographs of the curing sub-system showing (a) the complete system, (b) the UV LED module, (c) a close-up view of the fibre end and needle tip, and (d) a close-up view of the fibre end delivering UV optical power to a microdroplet. ........................................................................................................48

Figure 3.8. A photograph of the monitoring sub-system with its camera in the bottom left. A representative image of the needle tip and microdroplets is shown in the inset. ..............................................................................................................49

Figure 3.9. The integrated LabVIEW user control interface with its Thorlabs actuator control module (on the left) and its Nordson pneumatic control module (on the right). ..............................................................................................................50

Figure 3.10. A representative plano-convex MLA with the diameter of 340 µm and the pitch number of 440 µm is shown as (a) an optical microscope image and (b) an SEM image. ..............................................................................................................50

Figure 3.11. Profilometer curve for five microlenses in a representative plano-convex MLA. ..............................................................................................................51
Figure 3.1. Transmission and absorption spectra for NOA 65 showing its decreasing transmission and increasing absorption below a wavelength of 400 nm. The data shown here is from Norland Products Inc. ..........................................................53

Figure 3.13. Microlenses in an MLA shown as (a) the four individual images for the corresponding four steps of the imaging detection algorithm and (b) the final image produced by the algorithm with the recognized microlenses encircled in blue. ..........................................................54

Figure 3.14. Standard deviations of the microlens diameters (as a percent of the mean) within MLAs for five different dwell times. The MLAs are fabricated with a dispensing pressure of 4.8 psi, a dispensing time of 0.18 seconds, and a pitch of 440 µm. The pneumatic sub-system is operated at a velocity of 0.5 mm/s, an acceleration of 0.5 mm²/s, and a dwell time of 3 seconds. The spacing between the needle tip and glass substrate is (0.08 ± 0.01) mm. .............56

Figure 3.15. Representative optical microscope images of plano-convex MLAs having been fabricated with dwell times of (a) 1 second, (b) 2 seconds, (c), 3 seconds, (d) 4 seconds, and (e) 5 seconds. The corresponding standard deviations of the microlens diameters (as per sense of the mean) are 4.8%, 3.7%, 3.0%, 3.0%, and 3.2%, respectively. ..........................................................57

Figure 3.16. Microlens diameter as a function of the dispensing pressure for various MLAs. The MLAs are fabricated with a dispensing time of 0.25 seconds and pitch of 500 µm. The pneumatic sub-system is operated at a velocity of 0.5 mm/s, an acceleration of 0.5 mm²/s, and a dwell time of 3 seconds. The spacing between the needle tip and glass substrate is (0.08 ± 0.01) mm. Representative images of the MLAs are shown as insets. ..........................................................59

Figure 3.17. Microlens diameter as a function of the dispensing time for various MLAs. The MLAs are fabricated with a dispensing pressure of 6.5 psi and pitch of 500 µm. The pneumatic sub-system is operated at a velocity of 0.5 mm/s, an acceleration of 0.5 mm²/s, and a dwell time of 3 seconds. The spacing between the needle tip and glass substrate is (0.08 ± 0.01) mm. Representative images of the MLAs are shown as insets. ..........................................................60
Figure 3.18. Characterization of the diameter of each microlens within a plano-convex MLA on a plasma pretreated substrate versus its order of dispensing within the array. The results show random scatter with respect to a mean diameter, shown as a solid red line, which is indicative of little systematic error and good consistency in the process.

Figure 3.19. Representative microscopic images of plano-concave MLAs having been fabricated with a curing temperature of 60°C, a PDMS mix ratio of 5:1, and curing times of (a) 34 minutes, (b) 36 minutes, (c) 38 minutes, and (d) 40 minutes.

Figure 3.20. Thickness of plano-concave MLAs as a function of weights of the PDMS mixture being poured into the molding container. The container is square and it has an area of 25.4 × 25.4 mm². For these plano-concave MLAs, the PDMS mix ratio is 5:1, the curing time is 36 minutes, and the curing temperature is 60°C.

Figure 4.1. Optical image generated by an isolated plano-convex MLA. Each microlens in plano-convex MLA generates a separate image of a distant object within its focal plane. The diameter of the microlenses seen here is 300 µm.

Figure 4.2. Schematic of the experimental setup that is used to test the coupled plano-concave and plano-convex MLAs. An image generated on the microdisplay is captured by the coupled plano-concave and plano-convex MLAs and projected into the camera, which is focused at infinity.

Figure 4.3. The user interface of the EXC336A controller for the microdisplay. The brightness of the microdisplay can be adjusted by the “LUMINANCE” tab using five different levels.

Figure 4.4. The MLA mounts for (a) plano-convex MLA and (b) plano-concave MLA, and photographs of (c) plano-convex MLA and (d) plano-concave MLA.
Figure 4.5. The USAF-1951 test chart used to characterize imaging resolution. The chart contains grouping of tangential and sagittal lines with spatial frequencies spanning 0.5 cycles/mm to 912.3 cycles/mm. The chart and is used here under the Wikimedia Creative Commons Attribution-Share Alike 3.0 Unported License.

Figure 4.6. Sketch of a representative black-and-white test pattern showing its pixel frequency of $f_p$ in pixels/cycle. The pattern has $a$ pixels in the vertical dimension and $b$ pixels in the horizontal dimension with the pixels have a pitch of $p_m$ in units of microns.

Figure 4.7. Black-and-white test patterns on microdisplay with spatial frequencies of (a) 4.3 cycles/mm, (b) 5.3 cycles/mm, (c) 6.4 cycles/mm, (d) 10.7 cycles/mm, (e) 16.0 cycles/mm, and (f) 32.1 cycles/mm. The solid patterns in the test patterns with high spatial frequencies is used to prevent the spurious resolution, which is caused by the diffraction of the beam’s wavefronts as they pass through the periodic gaps between the microlenses.

Figure 4.8. Sketch of (a) a representative black-and-white test pattern being applied to the microdisplay versus the horizontal dimension and (b) its resulting image captured by the camera showing a profile of pixel signal values versus the horizontal dimension. The figures show a pixel frequency of $f_p$ in pixels/cycle and the resulting minimum value of $v_{min}$ and maximum value of $v_{max}$ in the profile of pixel signal values.

Figure 4.9. The image captured by the camera when the letter “A” is applied to the microdisplay. This image is formed by the coupled plano-concave and plano-convex MLAs without a baffle between them.

Figure 4.10. The (a) image captured by the camera and (b) resulting pixel signal values versus the horizontal dimension for a test pattern with a spatial frequency of $f_s = 0.8$ cycles/mm. In (b), the raw data is shown as a red curve and the finalized data is shown as a blue curve, resulting from bandpass filtering of the Fourier transform data around the spatial frequency of the black-and-white test pattern and inverse Fourier transforming the result.
Figure 4.1. Modulation depth versus spatial frequency, $f_s$, defining the MTF. The MTF results are shown as (experimental) solid black circles for the coupled MLAs with the baffle, (experimental) red crosses for the coupled MLAs without the baffle, and a (theoretical) solid black curve for the coupled MLAs with the baffle, generated via ray-based simulations.

Figure 4.2. Schematics of the mounting bracket used to firmly hold the plano-concave MLA, plano-convex MLA, and microdisplay, showing its (a) part for holding the plano-concave and plano-convex MLAs, with the baffle, and its (b) part for holding the microdisplay. The overall dimensions of the part in (a) are 12.0 mm × 12.0 mm × 12.0 mm, and the overall dimensions of the part in (b) are 11.0 mm × 8.8 mm × 4.0 mm.

Figure 4.3. Schematics of the images of the baffles fabricated by the laser micromilling machine (a) and the microscopic image of the aligned baffle with its corresponding plano-convex MLA.

Figure 4.4. Photographs of the monolithic package of the heads-up display as (a) a wide image, with a Canadian 10-cent coin for visual scaling, and (b) close-up image while it displays the digits “78”.

Figure 4.5. The fully-integrated Recon Jet™ eyewear containing the coupled plano-convex and plano-concave MLAs and microdisplay shown as a (a) photograph of the front of the eyewear, (b) photograph of the rear of the eyewear, (c) distant photograph of the projected image from the heads-up display, and (d) close-up photograph of the projected image from the heads-up display. In (c) and (d), the digits “78” are displayed.

Figure A.1. Top and side view of the coverslip and 25mm × 25mm coverslip holder.

Figure B.1. Zeroing the container weight.

Figure B.2. Two types of the liquid transfer tools: a disposable syringe (left) and a disposable pipette (right).

Figure B.3. Weighting the PDMS resin and curing agent.
Figure B.4. PDMS container snapped onto the floating vessel. ........................................102

Figure B.5. PDMS container and vessel floating in the ultrasonic bath. ..............................103

Figure B.6. A half of the square plastic container with a few droplets of PDMS deposited, 
before putting in the plano-convex MLA coverslip. ....................................................103

Figure B.7. Centering the square plastic container in a Petri dish. ......................................104

Figure B.8. The lid part of the Petri dish with water filled about half way. ............................104

Figure B.9. The dish with the centering piece and PDMS container floating on the lid........ 105
List of Variables

Diameter, plano-convex microlens \( d_{cv} \)
Diameter, plano-concave microlens \( d_{cc} \)
Pitch, plano-convex microlens \( p_{cv} \)
Pitch, plano-concave microlens \( p_{cc} \)
Radius of curvature, plano-convex microlens \( R_{cv} \)
Radius of curvature, plano-concave microlens \( R_{cc} \)
Contact angle, plano-convex microlens \( \alpha_{cv} \)
Contact angle, plano-concave microlens \( \alpha_{cc} \)
Focal length, plano-convex microlens \( f_{cv} \)
Focal length, plano-concave microlens \( f_{cc} \)
Refractive index, plano-convex microlens \( n_{cv} \)
Refractive index, plano-concave microlens \( n_{cc} \)
Thickness, plano-convex microlens \( t_{cv} \)
Thickness, plano-concave microlens \( t_{cc} \)
Separation between the principal planes of the MLAs \( s \)
Focal length between the microdisplay and plano-concave MLA’s principal plane \( f \)
Distance between the plano-convex MLA’s principal plane and the entrance of the eye \( d \)
Distance between the microdisplay and the back surface of the plano-concave MLA \( l_0 \)
Distance between the front surface of the plano-concave MLA and the back surface of the plano-convex MLA \( l_1 \)
Distance between the front surface of the plano-convex MLA and the entrance of the eye \( l_2 \)
Distance between the virtual image generated by the coupled MLAs and the plano-concave MLA’s principal plane \( v \)
Distance between an arbitrary input ray and the optical axis \( y_{in} \)
Distance between an arbitrary output ray and the optical axis \( y_{out} \)
Angle between an arbitrary input ray and the horizontal \( \theta_{in} \)
Angle between an arbitrary output ray and the horizontal \( \theta_{out} \)
Arbitrary coefficients as elements of a ray transfer matrix \( A, B, C, D \)
Rotation of the optical element of interest \( \Delta \theta \)
Spatial shift as the distance from the optical axis to the optical element of interest $\Delta y$

Compound ray transfer matrix for a given lens in an MLA $M$

Integer index for the plano-concave MLA $N_{cc}$

Integer index for the plano-convex MLA $N_{cv}$
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLA</td>
<td>Microlens arrays</td>
</tr>
<tr>
<td>3-D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>LED</td>
<td>Light emitting diode</td>
</tr>
<tr>
<td>MTF</td>
<td>Modulation transfer function</td>
</tr>
<tr>
<td>FOV&lt;sub&gt;A&lt;/sub&gt;</td>
<td>Angular field-of-view</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>NOA</td>
<td>Norland Optical Adhesive</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>USAF</td>
<td>United States Air Force</td>
</tr>
</tbody>
</table>
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For my parents,

Sumei Liu and Huaiyi Yan
Chapter 1: Introduction

1.1 Background

The concept of a microlens array (MLA) was first proposed by Robert Hooke over 300 years ago. Rods of Venetian glass were melted to form small lenses. If the lenses had sufficient quality, they could be used as an objective in a microscope to observe insects [1]. In 1908, Gabriel Lippmann went on to propose applications of these lens arrays for recording of three-dimensional (3-D) pictures via photographs. However, because of the imprecise fabrication processes, the applications of such MLAs were limited.

Today, given dramatic developments in fabrication processes and their precision, the MLA has emerged as a key component in many micro-optical systems. According to modern standards, from the International Standards Organization (ISO) [2], the term “microlens” is defined as “a lens with an aperture of less than a few millimeters”, and the term “MLA” is defined as “a regular arrangement of microlenses on a single substrate”. In more general terms, the MLA can be thought of as a repetitive arrangement of hundreds or thousands of microlenses that acts a single optical element within a given system. With such a definition, it is apparent that the MLA functions in a very different manner from the conventional (macroscopic) lens.

For the MLA, the incident light beams are separated by the microlenses on the MLA into thousands of discrete channels of light beams and each channel of beam is modulated by its corresponding microlens individually and simultaneously. The exact design that is implemented for the MLA dictates the modulation that is applied to the incident beam and the applications for which it can be used. The following section describes some of these applications.
1.2 Applications of microlens arrays

The uses of MLAs can be divided into the three general applications described in this section [3].

The first application of MLAs is beam shaping. This application uses a single MLA to generate an array of separated beamlets or layered MLAs to form a desired intensity profile for a single beam. A prime example of such an application is the generation of a uniformly distributed (i.e., homogeneous) beam from the wavefront of a laser diode or light emitting diode (LED). This homogeneity helps enhance the quality of indoor illumination. One of the designs for this beam homogenization is the Köhler light integrator [4].

The Köhler light integrator is shown in Figure 1.1. It has two identical and coupled MLAs followed by a condenser lens. The MLAs split the collimated incident beam into discrete beamlets, each of which has a homogeneous (roughly uniform) intensity across its transverse profile. Each beamlet, represented by a distinct colour in the figure, then passes through the condenser lens and is expanded into a beam in the far-field. The far-field beam manifests itself as an overlapping of all of the homogeneous beamlets. Thus, the Köhler light integrator can be used to homogenize light from a source by generating uniform illumination over a homogenized plane in the far-field.

![Figure 1.1. A sketch of the Köhler light integrator showing its arrangement of two identical and coupled MLAs and a condenser lens. The MLAs split the incident collimated beam into discrete channels and the condenser lens recombines these channels to create a homogeneous beam in the far-field.](image)

The second application of MLAs is interconnections. Such an application uses the MLAs to separate an incident beam into independent optical channels for subsequent (parallel) processing of the information in each channel. This application is usually carried out by merging the MLAs with other arrayed elements, such as laser diodes, spatial light modulators, and detector arrays [5].
The interconnected MLAs and arrayed elements can support highly parallel processing of optical information in telecommunications and optical computing. As one example, proposed by Jürgen Jahns in 1990 [6], the MLAs were used to implement arithmetic operations for the fast Fourier transform. Such a transform plays an important role in the digital computers and data networks.

The third application of MLAs is imaging. This application makes use of one or more layers of MLAs to create an array of beamlets and project these beamlets into a macroscopic image. Compared with the conventional lens, the MLA can enable imaging with a smaller size and a larger numerical aperture. Thus, it can be used in place of the conventional lens in imaging systems that require small sizes or tight imaging.

The MLA is usually applied in two types of imaging systems. The first system is called a “multi-aperture optical imaging system”. In this system, each microlens on the MLA serves as a single refractive lens that generates small-scale images of the object. This imaging system normally contains only one MLA and is widely used in apposition comping eyes [7], cluster eyes [8], mask projection lithography [9], and photocopy machines [10]. The second system that uses MLAs for imaging is called an “integral imaging system” [11]. This was first proposed by Gabriel Lippmann in 1908. In his proposed imaging system, a pair of MLAs with the same physical parameters was used to generate a unified and magnified image, with the same image distance and object distance. In 1941, Dennis Gabor proposed an alternative design that had two MLAs, with different pitches, being coupled to generate a single magnified image of the object.

This thesis focuses on the application of MLAs to an integral imaging system within heads-up displays. Further details on this pursuit are given in the following section.
1.3 Microlens arrays in heads-up displays

A heads-up display is an electronic display that presents visual information within the line of sight of a user. Such displays are becoming more and more prevalent in modern society—given the growing interest in virtual reality and augmented reality systems [12].

Heads-up displays are often used in vehicles to display information of relevance to driving. These systems have a relatively large physical size, as shown in Figure 1.2, and are composed of three major components: a video generation computer, a projection unit, and a combiner. The video generation computer provides the necessary images that will be displayed. The projection unit, also called the optical collimator, is the core of the heads-up display. It is composed of a convex or concave lens and a curved reflector that together generate a collimated image. The image is collimated so that it can be focused onto the retina of the user’s eyes while the eyes are focused at infinity and are therefore relaxed. The combiner is typically a flat beamsplitter that is located directly in front of the user. It has a special coating that allows it to reflect the light from the projection unit toward the user while allowing the visible light from the background to pass through it. In this way, the heads-up display can be placed within the line of sight of the user without obstructing the user’s view of the road.

Figure 1.2. Photograph of a heads-up display within a vehicle. Such a display has three main components: a video generator, a projection unit, and a combiner. These three components together project an image toward the user. This image is from Wikimedia common, under the Creative Commons BY-SA 3.0 Unported license, https://commons.wikimedia.org/wiki/File:BMW_F11_head_up_display_at_night.jpg.
The latest generations of heads-up displays are being seen within wearable devices, such as augmented reality and virtual reality goggles. These heads-up displays are different from those used within vehicles, however, because they are far more compact. The displays use a microdisplay as the image generator and a series of lenses to project an image of the microdisplay into the human eye. This allows for real-time viewing of data analytics, videos, etc. It has been especially successful for realizations within relatively large headgear, such as helmets [13] and goggles [14]. However, there has been growing demand to integrate heads-up displays within contemporary eyewear, having a much smaller size, and this has revealed a fundamental optical design challenge.

A heads-up display that is designed for contemporary eyewear has conflicting demands. It must project an image of the microdisplay into the relaxed human eye, in the form of a distant virtual image, and at the same time it must be implemented within a compact (predominantly flat) form factor, for integration within portable eyewear. The conflict arises because a conventional lens would need high curvature, over an equally large diameter, to capture an image of the microdisplay in the nearby focal plane and project this image into the human eye as a virtual image at infinity. This highly curved structure would not have the desired flat form factor. To address this problem, the Fresnel lens can be used. The Fresnel lens replaces the curved surface of the conventional lens with a series of concentric grooves that are shaped to bring about the desired refraction while having a relatively flat form factor [15]. However, the fabrication of Fresnel lenses is quite complex, requiring multiple photolithographic processes, and this can lead to a long fabrication cycle time [16]. Fortunately, there is an alternative for compact imaging, with a short fabrication cycle time, and it takes the form of a Gabor lens [17].

The Gabor lens was proposed by Gabor in the 1940’s. In his design, two or more layers of MLAs, having precise values for their microlens parameters, being pitch, diameter, and radius of curvature, were coupled together to form a structure that functions in a similar manner to a conventional lens. However, in contrast to a conventional lens, the Gabor lens can achieve tight focusing while having a flat form factor. This makes it an excellent candidate for heads-up displays within wearable devices.

This thesis presents the design, fabrication, and testing of a Gabor lens for use within a heads-up display. The design is carried out to identify the optimal physical parameters for the microlenses, being pitch, diameter, and radius of curvature. A tunable dispensing process is then developed to
introduce the needed tunability. It uses plasma pre-treatment and microlens dispensing, curing, and casting to create microlenses that have the optimal physical parameters. The fabricated plano-concave and plano-convex MLAs are then coupled as a Gabor lens and packaged with a baffle and microdisplay to function as a heads-up display. Testing is carried out to demonstrate the functionality and performance of the developed heads-up display.

1.4 Scope of this thesis

Details on the design, fabrication, and testing of coupled MLAs, towards the realization of heads-up displays, are given within the chapters of this thesis.

Chapter 1 of this thesis presents the history and applications of MLAs. It also introduces coupled MLAs, in the form of a Gabor lens, to carry out imaging within heads-up displays.

Chapter 2 of this thesis presents the design of the coupled MLAs as a Gabor lens. Such work seeks the optimal physical parameters for the microlenses within the MLAs. Given the large number of physical parameters in the system, an elementary model is applied first to give a general understanding on the functioning of the coupled MLAs and provide tractable solutions for the optimal values via ray transfer matrices. A more rigorous physical model is then applied, via ray-based simulations, to refine the optimal values.

Chapter 3 of this thesis introduces a tunable fabrication process that applies a plasma pre-treatment on the glass substrate followed by dispensing and curing of microdroplets on the substrate to form microlenses in a plano-convex MLA. The plano-convex MLA is then used as is or as a mold to cast a plano-concave MLA. It is shown that this fabrication process, in comparison to the standard reflow process, provides the tunability that is needed to realize the optimal physical parameters for the design of the MLAs. Ultimately, the optimized plano-concave and plano-convex MLAs are fabricated and coupled to form the Gabor lens.

Chapter 4 of this thesis shows the results from performance testing of the complete heads-up display, being comprised of the Gabor lens with a baffle and microdisplay. The imaging performance is quantified by way of its resolution, which is defined from tests of the heads-up display’s modulation transfer function (MTF). The results measured for the fabricated Gabor lens are compared to those of the ray-based simulations, and strong agreement is seen. Moreover, it is
found that the developed heads-up display can meet all of the design criteria that are deemed necessary for an effective heads-up display.

Chapter 5 concludes this work by summarizing the contributions of this thesis and suggesting prospects for future work.
Chapter 2: Design of the coupled microlens arrays

2.1 Criteria for the coupled microlens arrays

The Gabor lens, which will be referred to simply as the Gabor lens in the remainder of this work, was introduced in the prior chapter as an optical element that could meet the conflicting demands of heads-up displays within contemporary eyewear. This is because it has the potential to achieve the desired tight focusing while being realized with a flat form factor. In doing so, the coupled MLAs must meet three design criteria:

· Criterion I. The coupled MLAs must project an image of the microdisplay into the relaxed eye, being focused at infinity, with an unobstructed view of the surroundings. As such, this criterion would have the coupled MLAs form a virtual image of the microdisplay at infinity with an angular field-of-view (FOV_A) of between 15° to 25°. This FOV_A gives a clear image of the microdisplay and a suitable view of the surroundings—as its view of the microdisplay spans roughly 10% and 13% of the eye’s horizontal FOV_A (210°) and vertical FOV_A (150°), respectively [18].

· Criterion II. The image projected by the coupled MLAs must be an accurate reproduction of the image on the microdisplay. As such, this criterion would have the coupled MLAs function with a resolution of 30 cycles-per-mm or greater. Such a resolution would give a clear image of the microdisplay with performance being comparable or better than that in the literature [15: I2 tube].

· Criterion III. The coupled MLAs must be implemented with a flat form factor to enable integration within contemporary eyewear. As such, this criterion would have the net length of the coupled MLAs, being the sum of their focal length and separation, be less than 23.4 mm. This value is chosen because it is equal to that of the heads-up display in the Recon Jet™ eyewear.

In this work, coupled MLAs will be optimized to have them function as a Gabor lens that meets the above criteria. (The term Gabor lens will refer only to the coupled MLA structure that has been optimized to meet the above criteria.) In general, the above design criteria can be met by two or more layered MLAs. However, given the need for a flat form factor, in accordance with Criterion III, the number of MLAs should be minimized. Thus, only two MLAs are used in this work. The MLAs could be implemented as a plano-convex MLA coupled to a plano-convex MLA or a plano-concave MLA coupled to a plano-convex MLA. To decide upon the appropriate concavity, the
concept of an “eyebox” is considered. The eyebox is the volume of the space within which the relaxed eye can be positioned to see an image of the full microdisplay. The concept is illustrated in Figure 2.1. Figure 2.1(a) shows imaging by a plano-convex MLA coupled to a plano-convex MLA with a small separation, $s$, between the principal planes of the MLAs. Figure 2.1(b) shows imaging by a plano-convex MLA coupled to a plano-convex MLA with a large separation, $s$. Figure 2.1(c) shows imaging by a plano-concave MLA coupled to a plano-convex MLA with a small separation, $s$. The figures display light rays in green, red, and blue emanating from the bottom, middle, and top of the microdisplay, respectively, for a focal length of $f$ between the microdisplay and principal plane of the leftmost MLA. The rays are collimated for viewing by the relaxed eye. The eyebox, enclosed by dashed lines, is the only volume within which the collimated light rays from the full microdisplay can be viewed by the eye. Note that this figure illustrates trends in imaging with conventional lenses or MLAs when they are coupled in a confocal arrangement. Details on imaging with conventional lenses can be seen in [18]; details on imaging with MLAs can be seen in [17] and the upcoming work.

The size of the eyebox formed by the coupled MLAs in Figure 2.1 is dictated by the concavity and separation, $s$, of the MLAs. When two plano-convex MLAs are coupled, as in Figures 2.1(a) and (b), the structure exhibits positive magnification, i.e., light rays emanating from the top and bottom of the microdisplay are projected upwards and downwards to yield non-inverted and inverted images, respectively. This has the size of the eyebox increase as the separation, $s$, increases. Such a trend can be seen in Figures 2.1(a) and (b) by noting that the green and blue light rays exhibit a smaller divergence angle and have greater overlap with the red rays as the separation, $s$, increases. In contrast, when a plano-concave MLA is coupled to a plano-convex MLA, as in Figure 2.1(c), the magnification becomes negative and an even greater increase is seen in the size of the eyebox. The size of this eyebox increases as the separation increases, as before, but the separation cannot be increased without bound. Criterion III, relating to a flat form factor, restricts this separation. Ultimately, the plano-concave and plano-convex MLAs will be coupled in this work and designed to have them function as a Gabor lens that meets all three criteria. A 3-D view of the envisioned overall concept is shown as a schematic in Figure 2.2.
Plano-convex MLA
Microdisplay
Principal plane of plano-convex MLA

(a)

Plano-convex MLA
Microdisplay
Principal plane of plano-convex MLA

(b)
Figure 2.1. Schematics of the eyebox for coupled MLAs. The eyebox is shown as a cross-section enclosed by dashed lines for (a) coupled plano-convex and plano-convex MLAs with a relatively small separation, \( s \), (b) coupled plano-convex and plano-convex MLAs with a relatively large separation, \( s \), and (c) coupled plano-concave and plano-convex MLAs with a relatively small separation, \( s \). The focal length between the microdisplay and the principal plane of the leftmost MLA is denoted by \( f \).

Figure 2.2. Schematic of the coupled plano-concave and plano-convex MLAs. The MLAs project an image of the microdisplay on the retina of the relaxed human eye. The focal length between the microdisplay and principal plane of the plano-concave MLA is denoted by \( f \). The separation between the principal planes of the plano-concave and plano-convex MLAs is denoted by \( s \).
2.2 Parameters of the coupled microlens arrays

As mentioned in the prior section, plano-concave and plano-convex MLAs are to be coupled to have them function as a Gabor lens that meets the three design criteria. The necessary values for MLA’s physical parameters can be found by analysing the system with two lens models.

The first model, being the elementary model, characterizes the system with the thin lens equation, using “aggregate” parameters to enable analyses via ray transfer matrices. It treats each microlens as a thin lens with an infinitesimal thickness being positioned on the principal plane of the actual microlens. Since the microlens is infinitesimally thin, it does not need to be described by its “physical” parameters. It is instead described by its aggregate effects on light rays using definitions for its focal length and diameter. In this way, the elementary model enables tractable analyses of a system, via ray transfer matrices, to give a general understanding of its operation.

The second model, being the physical model, characterizes the system with the thick lens equation, using physical parameters, to enable analyses via ray-based (Zemax OpticStudio®) simulations. Each lens in the system is included in the model, from left to right along the optical axis, with physical parameters defined for its physical characteristics of radius of curvature, thickness, and diameter. Unfortunately, such an approach characterizes each optical element by the refraction that it yields at its two surfaces, and this greatly increases the complexity of the analyses. For this reason, the physical model is best applied with optical simulation software, such as Zemax OpticStudio®, which can simulate the propagation of light rays through highly complex systems. Such an approach is done here.

The above lens models are used together in this work to characterize the coupled MLAs. The elementary model is used first to analyse and optimize their aggregate parameters. The optimal aggregate parameters are then transformed to their equivalent physical parameters for use in the physical model, which is implemented by Zemax OpticStudio® simulations. The aggregate parameters of the elementary model are introduced in section 2.2.1; the physical parameters of the physical model are introduced in section 2.2.2.
2.2.1 Parameters for the elementary model

The aggregate parameters for the elementary (thin lens) model of the coupled plano-concave and plano-convex MLAs within the imaging system are shown in Figure 2.3. It is apparent from this figure that the elementary model has only a few parameters. This is because the physical characteristics of each microlenses within the MLAs are quantified by a simple focal length.

The displayed system includes the microdisplay, the coupled plano-concave and plano-convex MLAs, and a representative human eye. The plano-concave MLA has microlenses with a focal length and pitch of \(f_{cc}\) and \(p_{cc}\), respectively, while the plano-convex MLA has microlenses with a focal length and pitch of \(f_{cv}\) and \(p_{cv}\), respectively. In terms of dimensions, the focal length between the microdisplay and the principal plane of the plano-concave MLA is denoted by \(f\), the separation between the principal planes of the MLAs is denoted by \(s\), and the distance between the principal plane of the plano-convex MLA and the entrance of the eye is denoted by \(d\). These elementary-model parameters will be used here in the ray transfer matrixes analysis of the system and will ultimately be transformed to parameters for the physical model.

![Figure 2.3. Schematic showing the aggregate parameters of the elementary (thin lens) model of the coupled MLAs within the imaging system, including the microdisplay, the coupled plano-concave and plano-convex MLAs, and a representative human eye. The focal length between the microdisplay and the principal plane of the plano-concave MLA is denoted by \(f\), the separation between the principal planes of the MLAs is denoted by \(s\), and the distance between the principal plane of the plano-convex MLA and the entrance of the eye is denoted by \(d\). The focal length and pitch of the plano-concave MLA are denoted by \(p_{cc}\) and \(f_{cc}\), respectively, while those of the plano-convex MLA are denoted by \(p_{cv}\) and \(f_{cv}\), respectively.](image-url)
2.2.2 Parameters for the physical model

The physical parameters for the physical (thick lens) model of the coupled plano-concave and plano-convex MLAs within the imaging system are shown in Figure 2.4.

The system includes the microdisplay, the coupled plano-concave and plano-convex MLAs, and a representative human eye, and its physical parameters are described here from left to right. The microdisplay is the first element, and it has a (horizontal) width of 8.1 mm and (vertical) height of 6.0 mm. The distance between the microdisplay and the planar surface of the plano-concave MLA is denoted by $l_0$. The thickness of the plano-concave MLA is denoted by $t_{cc}$, where this dimension spans from its planar surface to its curved surface, being defined at the deepest points of the concave microlenses. The distance between the curved surface of the plano-concave MLA to the planar surface of the plano-convex MLA is denoted by $l_1$. The thickness of the plano-convex MLA is denoted by $t_{cv}$, where this dimension spans from the planar surface to the curved surface, being defined at the highest points of the convex microlenses. The distance from the curved surface of the plano-convex MLA and the entrance of the eye is denoted by $l_2$.

Since the introduced MLAs are comprised of curved and periodic microlenses, it is also necessary to define physical parameters for the curvature and periodicity of the microlenses. For microlenses within the plano-concave MLA, the centre-to-centre pitch is $p_{cc}$, the radius of curvature is $R_{cc}$, the diameter is $d_{cc}$, and the contact angle is $\alpha_{cc}$. For microlenses within the plano-convex MLA, the centre-to-centre pitch is $p_{cv}$, the radius of curvature is $R_{cv}$, the diameter is $d_{cv}$, and the contact angle is $\alpha_{cv}$. Note that the contact angles defined here can be expressed in terms of the radii of curvature and diameters, but they are included as explicit variables to aid upcoming discussions on surface energy. All of the physical parameters will be referred to later in simulations, via Zemax OpticStudio®, and the development of the fabrication process.
2.3 Analyses of the coupled microlens arrays

In this section, the coupled MLAs are analysed by way of the elementary model. The analysis introduces the basic imaging characteristics of coupled MLAs and lays the foundation for the design work in the upcoming section via the elementary and physical models.

The elementary model is implemented with ray transfer matrices [19]. For such matrices, a light ray is characterized by a column vector that includes its distance from the horizontal optical axis, as the top element, and its angle with respect to the horizontal optical axis, as the bottom element, with a ray directed up and to the right being positive. With such column vectors, the effects of a single optical element can be quantified by a matrix, and the effects of an entire optical system can
be quantified by a compound matrix, which is generated by simple multiplication of the matrices for the optical elements.

Ray transfer matrices make use of the $xyz$-axes and the input and output planes that are shown in Figure 2.5 for a generalized lens. The planes are orthogonal to the optical axis, which runs along the $z$-axis, and the intersection of the ray with each plane defines the input and output position of the ray. The input ray is at a distance of $y_{in}$ from the optical axis and is at an angle of $\theta_{in}$ with respect to the horizontal. Similarly, the output ray is at a distance of $y_{out}$ from the optical axis and is at an angle of $\theta_{out}$ with respect to the horizontal. With such a configuration, the optical element is said to modulate the input ray in forming the output ray. The relationship between the input and output rays is defined by

$$\begin{bmatrix} y_{\text{out}} \\ \theta_{\text{out}} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} y_{\text{in}} \\ \theta_{\text{in}} \end{bmatrix},$$  

(1)

where the coefficients of the $2\times2$ matrix, $A$, $B$, $C$, and $D$, are defined for a given optical element. While such ray transfer matrices are straightforward to define for a simple optical element, like a conventional lens, the $2\times2$ matrix that is defined cannot easily encompass the net effects from the hundreds or thousands of periodic microlenses within an MLA. This is because each microlens would need its own matrix.

![Figure 2.5. Schematic showing the input and output rays that define a ray transfer matrix of a generalized lens. The input ray strikes the input plane at a distance of $y_{\text{in}}$ from the optical axis and makes an angle of $\theta_{\text{in}}$ with respect to the horizontal; the output ray strikes the output plane at a distance of $y_{\text{out}}$ from the optical axis and makes an angle of $\theta_{\text{out}}$ with respect to the horizontal.](image)
Given the challenges of working with periodic optical elements, Lindlein developed an innovative technique to characterize the effects of periodic optical elements with a compressed ray transfer matrix [20]. Its definitions are shown in Figure 2.6. The definitions include the aforementioned distances from the optical axis, $y_{in}$ and $y_{out}$, and angles with respect to the horizontal, $\theta_{in}$ and $\theta_{out}$, for the respective input and output rays. The definitions also include the spatial shift $\Delta y$ as the distance from the optical axis to a given optical element and the angle $\Delta \theta$ as the angular rotation of the given optical element in the clockwise direction. This formulation leads to a $3 \times 3$ ray transfer matrix of the form

$$\begin{bmatrix}
y_{out} \\
\theta_{out} \\
1
\end{bmatrix} = \begin{bmatrix} A & B & \Delta y \\
C & D & \Delta \theta \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix} y_{in} \\
\theta_{in} \\
1
\end{bmatrix}, \quad (2)$$

where the coefficients $A$, $B$, $C$, and $D$ are the elements of the aforementioned $2 \times 2$ matrix for the given optical element.

![Figure 2.6](image)

Figure 2.6. Schematic showing the input and output rays that define the ray transfer matrix of a microlens in an MLA. The input and output rays strike the input plane at a distance of $y_{in}$ and $y_{out}$ from the optical axis and make an angle of $\theta_{in}$ and $\theta_{out}$ with respect to the horizontal, respectively. The microlens of interest is a distance of $\Delta y = N_{cc/ev} p_{cc/ev}$ off the optical axis, where $N_{cc/ev}$ is an integer and $p_{cc/ev}$ is the pitch of the MLA, and is rotated by $\Delta \theta = 0$. 
Lindlein’s technique can be tailored to the purposes of this study by applying it to a periodic array of microlenses. The MLA has rotational symmetry between the $y$-axis, in the plane of the page, and the $x$-axis, perpendicular to the plane of the page, so the cross-section shown in Figure 2.6 is an adequate representation of the full MLA. Within this figure, the given light ray and microlens are shown in dark grey with the microlens having a spatial shift of $\Delta y = N_{cc/cv} p_{cc/cv}$, where $N_{cc/cv}$ is an integer for the plano-concave (subscripted cc) or plano-convex (subscripted cv) MLA, and $p_{cc/cv}$ is the pitch for the plano-concave (subscripted cc) or plano-convex (subscripted cv) MLA. The rotation here is $\Delta \theta = 0$ because the microlenses lie within a plane.

The 3×3 ray transfer matrix for the given microlens in the MLA can be defined as a compound matrix that is built up from three elementary ray transfer matrices. The first elementary matrix characterizes a spatial shift of the given microlens and its ray by $-N_{cc/cv} p_{cc/cv}$ down along the $y$-axis to centre the microlens on the optical ($z$-) axis. This is expressed by the ray transfer matrix

$$
\begin{bmatrix}
1 & 0 & -N_{cc/cv} p_{cc/cv} \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}.
$$

(3)

Here, the $A$, $B$, $C$, and $D$ coefficients in the top left corner form a 2×2 identity matrix that yields no net effect on the ray, the element $-N_{cc/cv} p_{cc/cv}$ in the top right corner implements the spatial shift, and the 0 in the middle of the rightmost column indicates no angular rotation. The second elementary matrix characterizes the effects of a single microlens on the ray while the microlens is centred on the optical axis. This can be expressed by the ray transfer matrix

$$
\begin{bmatrix}
1 & 0 & 0 \\
-\frac{1}{f_{cc/cv}} & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}.
$$

(4)

Here, the $A$, $B$, $C$, and $D$ coefficients in the top left corner form the well-known 2×2 matrix of a lens with a focal length of $f_{cc/cv}$ [18], which can apply to the plano-concave MLA (subscripted cc) or the plano-convex MLA (subscripted cv), while the 0 values at the middle and top of the rightmost column indicate no spatial shift or angular rotation. The third elementary matrix characterizes a spatial shift of $N_{cc/cv} p_{cc/cv}$ for the given microlens and ray up along the $y$-axis to bring them to their original position. This can be expressed by the ray transfer matrix
As before, the $A$, $B$, $C$, and $D$ coefficients in the top left corner form a $2 \times 2$ identity matrix that yields no net effect on the ray, the element $N_{cc/cv}P_{cc/cv}$ in the top right corner implements the spatial shift, and the 0 in the middle of the rightmost column indicates no angular rotation.

The compound ray transfer matrix for the given microlens in the MLA is constructed as the product of the elementary matrices in (3), (4), and (5), with the appropriate order of operations on the input ray. This gives a compound ray transfer matrix of

\[
\begin{bmatrix}
 y_{\text{out}} \\
 \theta_{\text{out}} \\
 1
\end{bmatrix}
= \begin{bmatrix}
 1 & 0 & N_{cc/cv}P_{cc/cv} \\
 0 & 1 & 0 \\
 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
 1 & 0 & 0 \\
 -\frac{1}{f_{cc/cv}} & 1 & 0 \\
 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
 1 & 0 & -N_{cc/cv}P_{cc/cv} \\
 0 & 1 & 0 \\
 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
 y_{\text{in}} \\
 \theta_{\text{in}} \\
 1
\end{bmatrix},
\]

(6)

Since $N_{cc/cv}$ is any integer, spanning negative to positive infinity, this last result can characterize the effects of any microlens in either MLA. Moreover, two of these compound matrices can be assembled together to characterize the effects of a coupled MLA.

The plano-concave and plano-convex MLAs that are coupled to form the imaging system must generate a virtual image at infinity for the human eye. Since the image is virtual, it should be formed to the left of the MLAs, i.e., at negative infinity along the $z$-axis. This can be realized by considering the relationship between the coupled plano-concave and plano-convex MLAs and the object and virtual image in the manner shown in Figure 2.8. In this figure, the distance between the object and the principal plane of the plano-concave MLA is denoted by $f$, the separation between the principal planes of the plano-concave and plano-convex MLAs is denoted by $s$, and the distance between the principal plane of the plano-concave MLA and the virtual image that is formed is denoted by $v$, which will ultimately approach infinity. The object is treated as a point source of light with rays emanating in all directions. Two of its rays are traced through the figure.
The rays diverge at the plano-concave MLA and then partially converge at the plano-convex MLA. The converging rays can be extrapolated backwards, in the negative z-direction, to have their point of overlap define the position and size of the virtual image.

![Figure 2.7](image)

**Figure 2.7.** Schematic showing the real and virtual rays traced through the elementary (thin lens) model of the coupled MLAs. The object is shown in black, and the virtual image is shown in red. The distance between the object and the principal plane of the plano-concave MLA is denoted by \( f \), the separation between the principal planes of the MLAs is denoted by \( s \), and the distance between the principal plane of the plano-concave MLA and the virtual image is denoted by \( v \). The input ray leaves the object at a distance of \( y_in \) from the optical axis and makes an angle of \( \theta_in \) off the horizontal; the output ray exits the plano-convex MLA at a distance of \( y_out \) from the optical axis and makes an angle of \( \theta_out \) off the horizontal. Real light rays are shown as solid red lines, and virtual light rays are shown as dotted red lines.

A compound ray transfer matrix can be formed for the coupled MLAs shown in Figure 2.7. To do this, ray transfer matrices are multiplied together to describe the light ray propagation over a distance of \( f \), refraction by the plano-concave MLA, propagation over a distance of \( s \), and refraction by the plano-convex MLA. These ordered operations yield a compound ray transfer matrix for the coupled MLAs of

\[
M = \begin{bmatrix}
1 & 0 & 0 & 0 \\
\frac{1}{f_{cv}} & 1 & \frac{N_{cv}P_{cv}}{f_{cv}} & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix} \begin{bmatrix}
1 & s & 0 \\
0 & 1 & 0 \\
\frac{1}{f_{cc}} & 1 & \frac{N_{cc}P_{cc}}{f_{cc}} \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
1 & f & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}.
\]  

\( (7) \)
Here, the first and third matrices from the left come about from (6) for the plano-convex and plano-concave MLAs having integers of $N_{cv}$ and $N_{cc}$, respectively. The second and fourth matrices from the left come about from assigning 0 values at the middle and top of their rightmost columns, for no spatial shift or angular rotation, and the insertion of the well-known $2 \times 2$ matrix in the top right corner for propagation over a distance of $s$ and $f$, respectively [18].

The compound ray transfer matrix for the coupled MLAs is formed by multiplying the above four matrices together and simplifying the result to a $2 \times 3$ matrix. (The non-square form for this latter matrix is allowed because the input and output rays are column vectors with the top two elements defining characteristics and the bottom element being 1.) The complete relationship between the input and output rays and the compound ray transfer matrix for the coupled MLAs is

$$
\begin{bmatrix}
Y_{\text{out}} \\
\theta_{\text{out}} \\
1
\end{bmatrix} = M
\begin{bmatrix}
Y_{\text{in}} \\
\theta_{\text{in}} \\
1
\end{bmatrix}
= \begin{bmatrix}
M_{11} & M_{12} & M_{13} \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
Y_{\text{in}} \\
\theta_{\text{in}} \\
1
\end{bmatrix},
$$

where

$$M_{11} = 1 - \frac{s}{f_{cc}},$$

$$M_{12} = fM_{11} + s = f - f \frac{s}{f_{cc}} + s,$$

$$M_{13} = \frac{N_{cc}p_{cc}}{f_{cc}} s,$$

$$M_{21} = \frac{s}{f_{cc}f_{cv}} - \frac{1}{f_{cc}} - \frac{1}{f_{cv}},$$

$$M_{22} = fM_{11} + 1 - \frac{s}{f_{cv}} = f \left( \frac{s}{f_{cc}f_{cv}} - \frac{1}{f_{cc}} - \frac{1}{f_{cv}} \right) + 1 - \frac{s}{f_{cv}},$$

$$M_{23} = \frac{N_{cc}p_{cc}}{f_{cc}} + \frac{N_{cv}p_{cv}}{f_{cv}} - \frac{N_{cc}p_{cc}d}{f_{cc}f_{cv}}.$$
It is the ultimate goal of this work to find the values of the physical parameters in (9)-(14) that can make (8) realize the three design criteria introduced in Section 2.1. To this end, we recognize that the following equations must hold:

\[ y_{\text{out}} = M_{11}y_{\text{in}} + M_{12}\theta_{\text{in}} + M_{13}, \]
\[ \theta_{\text{out}} = M_{21}y_{\text{in}} + M_{22}\theta_{\text{in}} + M_{23}. \]

Since the light starts from a single point source, \( y_{\text{in}} \) is a constant and \( \theta_{\text{in}} \) can vary from 0 to 180˚. Moreover, the output rays can be extended backwards, in the negative \( z \)-direction, to converge at a single point to define the virtual image at a distance of \( v \) from the principal plane of the plano-concave MLA. Thus, according to Figure 2.7, \( y_{\text{out}} \) and \( \theta_{\text{out}} \) must obey the relationship

\[ y_{\text{out}} + v\tan\theta_{\text{out}} = C_1, \]

where \( C_1 \) is a constant. We can assume that \( \theta_{\text{out}} \) is sufficiently small so that \( \tan\theta_{\text{out}} \approx \theta_{\text{out}} \) and then substitute (16) into the approximate form of (17) to give an explicit expression for \( y_{\text{out}} \) in terms of \( y_{\text{in}} \) and \( \theta_{\text{in}} \). This expression can be equated to (15) to give

\[ (M_{11} + vM_{21})y_{\text{in}} + (M_{12} + vM_{22})\theta_{\text{in}} + (M_{13} + vM_{23}) = C_1. \]

Since \( y_{\text{in}} \) is a constant, the sum of the second and third terms in (18) must also be equal to a constant, \( C_2 \), according to

\[ (M_{12} + vM_{22})\theta_{\text{in}} + (M_{13} + vM_{23}) = C_2. \]

The expressions for \( M_{12}, M_{13}, M_{22}, \) and \( M_{23} \), in (10), (11), (13), and (14), respectively, can then be substituted into (19) to give

\[ \left[ (fv+1)\left( f - f - \frac{s}{f_{cc}} + s \right) + v \left( 1 - \frac{s}{f_{cv}} \right) \right] \theta_{\text{in}} \quad \text{and} \quad \left[ N_{cc}P_{cc} \left( \frac{s}{f_{cc}} + \frac{v}{f_{cc}} - \frac{sv}{f_{cc}f_{cv}} \right) + N_{cv}P_{cv} \frac{v}{f_{cc}} \right] = C_2. \]

The left side of (20) has two noteworthy functions in brackets. The first function, being the coefficient of \( \theta_{\text{in}} \), it must be equal to zero so that the remainder of the equation can be true for any value of \( \theta_{\text{in}} \). The second function, being a constant, must also be equal to zero so that the remainder of the equation can be true for any values of \( N_{cc} \) and \( N_{cv} \).
To define the relationship between $N_{cc}$ and $N_{cv}$, we can consider two light rays passing through the MLAs. The first ray propagates through the $a$th microlens on the plano-concave MLA, giving $N_{cc} = a$, and then propagates through the $a$th microlens on the plano-convex MLA, giving $N_{cv} = a$. The second ray also propagates through the $a$th microlens on the plano-concave MLA, giving $N_{cc} = a$, but then propagates through the $b$th microlens on the plano-convex MLA, giving $N_{cv} = b$. As such, we can only meet these conditions, and make the second function in (20) be equal to zero, with $N_{cc} = N_{cv}$. This equality allows the integers to be factored out of the second function in (20) and leaves two expressions relating the physical parameters of the coupled MLAs:

\[
(fv+1)\left(f - f\frac{s}{f_{cc}} + s\right) + v\left(1 - \frac{s}{f_{cv}}\right) = 0, \tag{21}
\]

\[
\left(\frac{s}{f_{cc}} + \frac{v}{f_{cc}} - \frac{sv}{f_{cc}f_{cv}}\right)p_{cc} + \frac{v}{f_{cv}}p_{cv} = 0. \tag{22}
\]

A coupled MLA that adheres to (21) and (22) can be analysed according to the light rays shown in Figure 2.8. In this figure, the solid black circle is a point source of light representing an object point. (It can be visualized simply as a pixel on the microdisplay.) The distance between this solid black circle and the principal plane of the plano-concave MLA is $f$. The light rays emanating from the solid black dot diverge as they pass through the plano-concave MLA, and this creates a virtual image point at a distance of $u$ to the left of the principal plane of the plano-concave MLA. This image point, shown as a solid yellow circle, can be treated as an object point for the plano-convex MLA because this MLA causes the output rays to converge. The output rays can then be extrapolated backwards, in the negative $z$-direction, to define an image point for the overall coupled MLA at a distance of $v$ to the left of the principal plane of the plano-concave MLA. This image point is shown as a solid red circle in the figure.

Some key relationships between the physical parameters can be defined using the above definitions for object and image points. According to the thin lens equation [18], stating that the sum of the reciprocals of the object and image distances equals the reciprocal of the focal length, the functionality of the plano-concave and plano-convex MLAs is set by two equations:

\[
\frac{1}{f} + \frac{1}{u} = \frac{1}{f_{cc}}, \tag{23}
\]
Figure 2.8. Schematic showing the object and images generated by the plano-concave MLA (left) and plano-convex MLA (right). The black dot at a distance of $f$ to the left of the plano-concave MLA represents a single pixel on the microdisplay, which can be regarded as a point light source. The yellow dot at a distance of $u$ to the left of the plano-concave MLA is the image of the black dot, which acts as an object for the plano-convex microlens. The red dot at a distance of $v$ to the left of the plano-concave MLA is the virtual image of the yellow dot and the virtual image generated by the overall coupled plano-concave and plano-convex MLAs.

\[
\frac{1}{s-u} + \frac{1}{v} = \frac{1}{f_{cv}}.
\]

(24)

These equations can be combined to give

\[
\frac{ff_{cc}}{f - f_{cc}} = s - \frac{vf_{cv}}{v - f_{cv}},
\]

(25)

as an expression that must be met by the physical parameters along with (21) and (22) to give the desired functionality. Equations (21), (22), and (25) can then be simplified to give the following:

\[
f = \frac{[vs - (s + v)f_{cv}]f_{cc}}{vs - (s + v)f_{cv} - vf_{cc} + f_{cc}f_{cv}},
\]

(26)

\[
\frac{p_{cv}}{p_{cc}} = \frac{vs - (s + v)f_{cv}}{vf_{cc}},
\]

(27)
Lastly, we recall that the coupled MLAs must function with the relaxed eye, with a virtual image at infinity. Thus, \( v \) is taken to infinity in expressions (26), (27), and (28) to give the following three finalized relations for the physical parameters of the coupled MLAs:

\[
\frac{1}{f} = \frac{p_{cv} - p_{cc}}{p_{cv} f_{cc}} + \frac{f_{cc} f_{cv}}{\left[ v s - (s + v) f_{cv} \right] f_{cc}}.
\]  

(28)

We note here that equations (29), (30), and (31), for the aforementioned condition of \( N_{cc} = N_{cv} \), can only yield imaging if the pitches of the plano-concave and plano-convex MLAs in equation (31) differ from each other. The differing pitches produce radiating displacements between the centres of the plano-concave and plano-convex microlenses, with the magnitude of the displacements growing as the microlenses become increasingly far from the centre of the MLAs. Such a condition is shown in Figure 2.9. Figure 2.9(a) shows the outlines of the plano-convex microlenses in solid black and outlines of the plano-concave microlenses in dashed red. Figure 2.9(b) shows the centres of these plano-convex and plano-concave microlenses as black and red dots, respectively. It is apparent here that the displacements between the paired microlenses are roughly symmetric with respect to (and grow in magnitude with their distance from) the centre of the MLA. This radiating pattern creates the desired convergence or divergence of light rays as they pass through the MLAs, in the same manner seen for light rays passing through a conventional lens. Clearly, such convergence or divergence can only happen if the pitches of the plano-concave and plano-convex MLAs differ.
Figure 2.9. Schematics (as top views) of the coupled MLAs. In (a), the schematic shows outlines of the plano-concave microlenses (dashed red) and plano-convex microlenses (solid black). In (b), the schematic shows plano-concave and plano-convex microlenses as red and black dots, respectively. The outlines and dots have displacements between paired microlenses that radiate out from the centre of the coupled MLAs. It is these radiating displacements that have the coupled MLAs function in a similar manner to a conventional lens.

We also note here that six physical parameters, $p_{cc}$, $p_{cv}$, $f_{cc}$, $f_{cv}$, $s$, and $f$, are present within the three relations (29), (30), and (31), and so the system is underdetermined. Thus, it becomes necessary to choose certain physical parameter values and solve for the remaining physical parameter values while optimizing the functioning of the coupled MLAs according to the aforementioned three design criteria. The selection and optimization is carried out in the following section.

2.4 Design of the coupled microlens arrays

In this section, values for the physical parameters of $p_{cc}$, $p_{cv}$, $f_{cc}$, $f_{cv}$, $s$, and $f$ are set for optimal functioning of the coupled MLAs. The optimization is performed according to the three design criteria: Criterion I has the coupled MLAs project an image of the microdisplay into the relaxed eye focused at infinity with an FOV $\alpha$ between $15^\circ$ to $25^\circ$; Criterion II has the image projected by the coupled MLAs be an accurate reproduction of the microdisplay with a resolution of 30 cycles/mm or greater; Criterion III has the coupled MLAs be implemented with a flat form factor having the sum of its focal length and separation between its MLAs being less than 23.4 mm.
The optimization starts by choosing the physical parameter values for the plano-convex MLA. The values are chosen based on the ease of fabrication and resulting uniformity of the MLA, as discussed in the following chapter. As such, the pitch and radius of curvature of the microlenses are chosen to be \( p_{cv} = 440 \, \mu m \) and \( R_{cv} = 497 \, \mu m \), respectively. The corresponding focal length can be found from the radius of curvature and refractive index of the polymer microlens. However, the plano-convex microlens has a fairly large numerical aperture, and is thus fairly thick, so its focal length cannot be accurately found by the simple lensmaker’s formula. Instead, a Zemax simulation is carried out on the plano-convex microlens, shown in Figure 2.10, to define a focal length of \( f_{cv} = 943 \, \mu m \) for the given radius of curvature of \( R_{cv} = 497 \, \mu m \).

The optimization process continues by assigning values for the remaining four physical parameters of \( p_{cc}, f_{cc}, s, \) and \( f \) in (29), (30), and (31). Given that there are four physical parameters and three equations, yielding infinitely many solutions, it is necessary to identify the optimal solutions. Tradespace analyses are used for this. Such analyses have proven to be an effective tool to identify optimal solutions in systems with many physical parameters [21].

![Figure 2.10. Schematic showing a plano-convex microlens with its principal plane and focal length of \( f_{cv} \) for a radius of curvature of \( R_{cv} \). The beam radiates from the focal point on the optical axis at a distance of \( f_{cv} \) to the left of the principal plane, passes through the microlens, and exits the microlens parallel to the optical axis.](image)

Criterion I, relating to the \( FOV_A \) of the coupled MLAs, is considered first via the tradespace analysis in Figure 2.12(a). The \( FOV_A \) values are shown in the figure as a colourmap versus the negated focal length of the plano-concave MLA, \( -f_{cc} \), on the left axis, and the focal length between
the microdisplay and plano-concave MLA’s principal plane, \( f \), on the bottom axis. The FOV\(_A\) values are computed in units of degrees from (12), (16), and (29), which together give

\[
\text{FOV}_A = 2 \max(\theta_{\text{out}}) = \frac{2 f_{cc}(3\text{ mm}) 180^\circ}{f_{cv}(f - f_{cc})\pi},
\]

where the dimension of 3 mm is half of the microdisplay’s width and the function \( \max(\cdot) \) denotes the maximum value of its argument. We see here that small FOV\(_A\) values are obtained when \(-f_{cc}\) is small and \(f\) is large, large FOV\(_A\) values are obtained when \(-f_{cc}\) is large and \(f\) is small, and the allowed values of the FOV\(_A\) for Criterion I, being between 15º and 25º, exist between these extremes. To meet Criterion I with some room for error, FOV\(_A\) values in the range of 20º ± 0.5º are targeted here. The region of the figure that yields this FOV\(_A\), and thus captures allowable values of \(-f_{cc}\) and \(f\), is shown as a linear band enclosed by two black lines. The linear trend for this band suggests that the two physical parameters can be selected by keeping their ratio at \(-f_{cc}/f = 0.058 \pm 0.001\).

Criterion II, relating to the resolution of the coupled MLAs, is linked to the separation between the principal planes of the MLAs, for reasons that will be seen shortly, and is considered next via the tradespace analysis in Figure 2.12(b). The figure shows this separation, \( s \), as a colourmap versus the negated focal length of the plano-concave MLA, \(-f_{cc}\), on the left axis, and the focal length between the microdisplay and plano-concave MLA’s principal plane, \( f \), on the bottom axis. Colours are not shown in the white regions at the bottom and left of this figure because the overall thickness of the microlenses in these regions would need to be larger than their radius of curvature and such structures are unphysical. The calculation of the \( s \) values in the figure proceeds as follows. As a first step, the values of \( s \) are computed for a system with no physical (i.e., air) gap between the plano-concave and plano-convex MLAs, according to

\[
s = \left[ t_{cc} - f_{cc}(n_{cc} - 1)t_{cc} \right] + \left[ R_{cc}(1 - \cos \alpha_{cc}) \right] + \left[ \frac{f_{cv}(n_{cv} - 1)t_{cv}}{n_{cv}R_{cv}} \right],
\]

where \( n_{cc} = 1.4 \), \( t_{cc} = 700 \mu\text{m} \), \( R_{cc} \), and \( f_{cc} \) are the refractive index, thickness, radius of curvature, and focal length of the plano-concave MLA, respectively, and \( n_{cv} = 1.524 \), \( t_{cv} = 131.8 \mu\text{m} \), \( R_{cv} = 497 \mu\text{m} \), and \( f_{cv} = 943 \mu\text{m} \) are the refractive index, thickness, radius of curvature, and focal length of the plano-convex MLA, respectively. The physical parameter \( \alpha_{cc} = 36^\circ \) is the contact angle of the plano-concave microlens, and its value is defined by measurements of the contact angle for the
employed ultraviolet- (UV-) curable optical polymer, Norland Optical Adhesive (NOA) 65, that is applied on a glass substrate to act as a mold for the plano-convex MLA. (The details of the fabrication are given in the following chapter.) The thickness of the plano-concave microlens, \( t_{cc} = 700 \ \mu m \), is chosen to have its material, polydimethylsiloxane (PDMS), be sufficiently flexible and have a short curing time. The thickness of the plano-convex microlens, \( t_{cv} = 131.8 \ \mu m \), is the sum of the thickness of the glass substrate, being 100 \( \mu m \), and the sag of the plano-convex microlens, being \( R_{cv} - \left[ R_{cv}^2 - (d_{cv}/2)^2 \right]^{1/2} \). In (33), the first, second, and third terms correspond to the distance from the principal plane of the plano-concave microlens to the deepest point of its curved surface, the sag of the plano-concave microlens, and the distance from the planar surface of the plano-convex microlens to its principal plane, respectively. These three terms are shown in Figure 2.12 as the respective dimensions “A”, “B”, and “C”. Using (29) and \(-f_{cc}/f = 0.058\) from above, along with the lensmaker’s formula \( R_{cc} = f_{cc}(n_{cc} - 1) \) for the plano-concave microlens, we can state that the separation between the principal planes of the MLAs is \( s = 0.94f_{cc} + f_{cv} = 340 \ \mu m \). As a second step, the separation is increased to accommodate a baffle between the MLAs. The baffle is an opaque metal layer with an array of microholes having the same periodicity as the plano-concave MLA, onto which it is butted up against. Such a baffle, if appropriately implemented, can improve the resolution of the coupled MLAs because its microholes preferentially pass light propagating through the microlenses and block light propagating between the microlenses. The net effect is minimized distortion in the image. To accommodate this baffle, the separation, \( s \), between the principal planes of the MLAs is adapted to allow for a physical gap of 25 \( \mu m \) to 50 \( \mu m \) between the MLAs. With this in mind, Figure 2.12(b) displays a curved band as the region that establishes a physical gap between the MLAs of 25 \( \mu m \), corresponding to \( s = 365 \ \mu m \) and denoted by the top black line, to a physical gap between the MLAs of 50 \( \mu m \), corresponding to \( s = 390 \ \mu m \) and denoted by the bottom black line. The figure also shows the aforementioned linear band, and so the region in which the linear and curved bands intersect identifies the values of \(-f_{cc}\) and \( f \) that establish the allowable values of the FOV_A and separation, \( s \), between the principal planes of the MLA.

Criterion III, relating to the flat form factor, is considered next via the tradespace analysis in Figure 2.12(c). The figure shows the overall length of the display, \( f + s \), as a colormap versus the negated focal length of the plano-concave MLA, \(-f_{cc}\), on the left axis, and the focal length between the microdisplay and plano-concave MLA’s principal plane, \( f \), on the bottom axis. The aforementioned regions of permissible FOV_A and \( s \) are displayed by way of the linear and curved bands between black lines, respectively. To meet
this criterion, it is desirable to have the overall length of the display be minimized, and this is done by selecting the smallest value of $f$ within the region of overlap for the linear and curve bands. As such, a value of $f = 10$ mm is selected for the focal length between the microdisplay and plano-concave MLA’s principal plane. As a result, the separation between the principal planes of the plano-concave and plano-convex MLAs is $s = 390$ µm, giving a physical gap of $50$ µm, and the focal length for the plano-concave array is $f_{cc} = -638$ µm. The radius of curvature of the plano-concave MLA is then estimated by the lensmaker’s formula for a thin lens [16: Hecht], which gives $R_{cc} = -(n_{cc} - 1)f_{cc} \approx 267$ µm.

![Figure 2.11](image.png)

Figure 2.11. Schematic of coupled plano-concave and plano-convex microlenses showing the dimensions “A”, “B”, and “C” as the three terms in (33). These terms correspond to the distance from the principal plane of the plano-concave microlens to the deepest point of its curved surface, the sag of the plano-concave microlens, and the distance from the planar surface of the plano-convex microlens to its principal plane, respectively.
Figure 2.11. Tradespace analyses for optimization of the coupled MLAs. The physical parameters of the MLAs are varied to optimize the (a) FOV, (b) separation, s, between the plano-concave and plano-convex MLAs, and (c) overall display length, \( f + s \). The three characteristics being optimized are shown as colormaps versus the negated focal length of the plano-concave MLA, \(-f_{cc}\), and the focal length between the microdisplay and plano-concave MLAs, \( f \). The linear band between black lines encloses values of \(-f_{cc}\) and \( f \) that yield the desired FOV of \( 20^\circ \pm 0.5^\circ \). The curved band between black lines encloses values of \(-f_{cc}\) and \( f \) that yield a separation, s, in the desired range from 365 \( \mu \)m to 390 \( \mu \)m.

It should be noted that the values quoted here for the radii of curvature are only estimates, because they are subject to the thin lens approximation in the lensmaker’s formula. With this in mind, the values can be checked and adjusted, if necessary, by way of ray-based simulations with Zemax OpticStudio® software. In the simulations, each pixel on the microdisplay is treated as a point source of rays. The rays propagate through the coupled plano-concave and plano-convex MLAs and into the relaxed eye, within which they focus on the retina. It is found that the values of all the physical parameters from the above tradespace analyses of the coupled MLAs bring about the desired focusing on the retina—with the exception of the radius of curvature of the plano-concave MLA, which must be adjusted (slightly) to \( R_{cc} = 247 \mu \)m. All of the finalized physical parameter values are shown in Table 2.1.

The functionality of the coupled plano-concave and the plano-convex MLAs is shown in Figure 2.13. The figure shows a cross-sectional view of light rays at a wavelength of 555 nm propagating out from the
centre (red rays), interior (blue rays), and edge (green rays) of the microdisplay, through the coupled MLAs, and onto the retina of the human eye. The human eye model used by the Zemax software and shown in this figure simulates the eye in its relaxed state. It is apparent from the displayed ray-tracing simulation that the coupled MLAs can effectively project images onto the retina of the relaxed eye.

A close-up image of the light rays passing through the coupled plano-concave and plano-convex MLAs in the ray-based simulations is shown in Figure 2.14. The displayed image is centred about the optical axis. The means by which the coupled MLAs function like a conventional lens can be seen here. The plano-concave and plano-convex microlenses function in pairs, with the pairs near the optical axis producing semi-collimated beams that are roughly parallel to the optical axis and pairs further from the optical axis producing semi-collimated beams that are directed toward the optical axis. In this way, the entire system of coupled MLAs directs the light rays to a point—like a conventional lens.

Table 2.1. Optimized values for physical parameters of pitch, diameter, radius of curvature, and focal length for plano-concave and plano-convex MLAs.

<table>
<thead>
<tr>
<th></th>
<th>Pitch</th>
<th>Diameter</th>
<th>Radius of curvature</th>
<th>Focal length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plano-concave MLA</td>
<td>$p_{cc}$ = 466 µm</td>
<td>$d_{cc}$ = 300 µm</td>
<td>$R_{cc} = 247$ µm</td>
<td>$f_{cc} = -600$ µm</td>
</tr>
<tr>
<td>Plano-convex MLA</td>
<td>$p_{cv}$ = 440 µm</td>
<td>$d_{cv}$ = 350 µm</td>
<td>$R_{cv} = 497$ µm</td>
<td>$f_{cv} = 943$ µm</td>
</tr>
</tbody>
</table>

Figure 2.13. Ray-tracing simulations of the coupled plano-concave and plano-convex MLAs projecting an image of the microdisplay into the human eye. The figure shows light rays emanating from the microdisplay, passing through the coupled MLAs, and focusing onto the retina of the human eye.
Figure 2.14. A close-up view of the light rays passing through the coupled plano-concave and plano-convex MLAs. The left MLA is plano-concave, and the right MLA is plano-convex.

Given that the optimized values for the physical parameters of the coupled MLAs have been identified, it is now necessary to analyse their imaging performance in terms of resolution. This is done with the image analysis tools that are available in the Zemax OpticStudio® software. The “geometric MTF analysis” function in the software is used with this tool because the features of the MLAs are sufficiently large with respect to the diffraction limit. The imaging resolution of the optimized structure is analysed by way of its modulation transfer function (MTF). The MTF quantifies the ability of the imaging system to resolve spatial frequencies from alternating bright and dark bands with varying cycles/mm [22]. The ability to resolve the bands at a high spatial frequency is indicative of good imaging quality. The MTF takes the form of a curve showing the modulation depth, spanning from 0 to 1, as a contrast ratio between the absolute difference of observed luminance values of the bright and dark bands to the sum of the luminance values of the two bands as a function of the spatial frequency in cycles/mm. (Further details on the MTF are given in Chapter 4.)

It was mentioned earlier in this work that the resolution of the coupled MLAs is related to the fraction of light that passes through the microlenses and thus yields the desired image of the
microdisplay. With this in mind, the MTF analyses are carried out for three distinct systems: the first has the rays pass only through the microlenses of the coupled MLAs (and thus contribute to imaging); the second has the rays pass only through the gaps between the microlenses of the MLAs (and thus do not contribute to imaging); the third has the rays pass through both the microlenses and the gaps between the microlenses of the coupled MLAs.

The MTF results for the first configuration of the coupled MLAs, with the rays passing only through the microlenses, are shown in Figure 2.15(a). The figure shows the modulation depth versus the spatial frequency in cycles/mm. It is apparent from the MTF curve that the modulation depth is highest for the low spatial frequencies, as one expects, and it decreases for the higher spatial frequencies. In this case, the MTF curve spans continuously up to a spatial frequency of 30 cycles/mm. Such a result is indicative of strong imaging performance. A representative colour photograph for this system having been generated by the Zemax OpticStudio® software is shown in Figure 2.16. Figure 2.16(a) shows the applied image on the microdisplay. Figures 2.16(b) shows the resulting image that is formed on the retina for the resolution of 30 cycles/mm that is established by the coupled MLAs when the rays pass only through the microlenses. As comparisons, Figures 2.16(c) and (d) show the images that would be resolved on the retina if the system had resolutions of only 20 cycles/mm or 10 cycles/mm, respectively. It is apparent from these results that the coupled MLAs with rays passing only through the microlenses, yielding a resolution of 30 cycles/mm, gives the best imaging performance.
Figure 2.15. The MTF results from ray-tracing simulations of the coupled plano-concave and plano-convex MLAs with rays propagating (a) only through the microlenses, (b) only through the gaps between the microlenses, and (c) through both the microlenses and gaps between the microlenses.
Figure 2.16. Imaging results from ray-tracing simulations of the coupled plano-concave and plano-convex MLAs showing (a) the image on the microdisplay and images resolved on the retina for MTF results with a resolution of (b) 30 cycles/mm (being that obtained with rays passing only through the microlenses), (c) 20 cycles/mm, and (d) 10 cycles/mm.

The MTF results for the second configuration of the coupled MLAs, with the rays passing only through the gaps between the microlenses, is shown in Figure 2.15(b) as the modulation depth versus the spatial frequency in cycles/mm. It is apparent from this MTF curve that the modulation depth spans continuously only up to approximately 0.5 cycles/mm—although there are discrete peaks with finite modulation depths above this value. These discrete peaks, referred to as spurious resolution because they arise after the MTF has already reached zero, are due to the diffraction of the beam’s wavefronts as they pass through the periodic gaps between the microlenses. It can be concluded that such light rays passing between the microlenses do not contribute to imaging and only lead to blurriness in the image.

The MTF results for the third configuration of the coupled MLAs, with the rays passing both through the microlenses and through the gaps between the microlenses, is shown in Figure 2.15(c) as the modulation depth versus the spatial frequency in cycles/mm. It is apparent from this MTF
curve that the modulation depth spans continuously only up to approximately 20 cycles/mm. As one would expect, the resolution of this system is between that of Figures 2.15(a) and (b) because its performance is between the ideal performance seen in Figure 2.15(a) and the poor performance seen in Figure 2.15(b).

Ultimately, it can be concluded that the design for the coupled MLAs should incorporate a means to preferentially pass the light propagating through the microlenses and block the light propagating through the gaps between the microlenses. This will be accomplished by the introduction of a baffle, i.e., a two-dimensional array of micro-holes, which passes light propagating through the microlenses and blocks light propagating through the gaps between the microlenses. With such a baffle, the coupled MLAs should be capable of imaging with a resolution of 30 cycles/mm. The following chapter looks at the fabrication and implementation of the complete structure.
Chapter 3: Fabrication of the coupled microlens arrays

The coupled MLAs that were designed in the prior chapter are implemented in this chapter to have them function as Gabor lens that meets the three design criteria.

Several fabrication processes have been proposed in the past to fabricate MLAs. Some key examples include the micro-compressing process proposed by Moon et al. [23], the UV proximity printing process proposed by Lin et al. [24], the excimer laser drilling process proposed by Shin et al. [25], and the thermal reflow process proposed by Yang et al. [26]. Of these, the thermal reflow process is the most common, but it does not allow for sufficient tunability of the microlenses within the MLAs. It is for this reason, and the fact that the coupled MLAs required for this work must be fine-tuned to have them function optimally, that the thermal reflow process is not employed here. A tunable dispensing process is developed instead to realize the precise shapes and sizes of the needed microlenses.

The tunable dispensing process is introduced in this chapter. The process applies a plasma pre-treatment on a glass substrate followed by dispensing and curing of microdroplets on the substrate to form microlenses across a plano-convex MLA. The plano-convex MLA is then used as is or as a mold to cast the plano-concave MLA. The following sections show the relevant motivation, sub-systems, and characterizations of the tunable dispensing process.

3.1 Motivation for the tunable dispensing process

As mentioned earlier, the thermal reflow process is the most commonly used fabrication process for the MLAs. The process involves the four steps, being photolithography, reflow, casting, and curing, as shown in Figure 3.1(a).
In the photolithography step, a layer of positive photoresist is spin-coated onto the substrate. The photoresist-coated substrate is then covered by a mask that is transparent for all but an array of opaque circles. It is then exposed to UV light for approximately 10 seconds, and then the mask is removed. The photoresist-coated substrate is then dipped into developer, which washes away the regions of photoresist that were not protected by the opaque circles on the mask. This leaves an array of photoresist cylinders that is subjected to the thermal reflow step.

In the reflow step, the substrate with the photoresist cylinder array is placed on a hot plate for 30 seconds. The temperature of the hot plate is approximately 130ºC, which is the typical melting point of photoresist. The resulting heating has the photoresist cylinders reflow into spherical caps. The transformation is shown in Figure 3.1(b). Following the reflow, the substrate is removed from the hot plate, and the spherical caps solidify into an array of spherical caps. These spherical caps can be used as is, in the form of a plano-convex MLA, or used as a mold to fabricate a plano-concave MLA, as described in the following step.

In the casting and curing steps, the plano-convex MLA is used as a mold to cast a plano-concave MLA out of PDMS polymer. The PDMS polymer is prepared as a mixture of prepolymer solution to curing agent at a ratio of 5:1. The mixture is poured onto the plano-convex MLA mold in a container, and the PDMS-coated mold is then left in an oven at a temperature of 60ºC for 2 hours.
This fully cures the PDMS polymer. In the end, the PDMS polymer is peeled off of the mold to reveal the fabricated plano-concave MLA.

The above-described thermal reflow process is widely used for MLA fabrication. It is capable of fabricating MLAs with high quality, excellent reproducibility, and good optical performance. However, it does have some disadvantages.

The major disadvantage of the thermal reflow process is that it does not allow for a great deal of tunability in the characteristics of the fabricated microlenses. This is due to the fact that the surface profiles of the microlenses are defined strictly by the interfacial surface tensions, which are themselves defined by the chosen materials. In this way, it becomes difficult to fine-tune the surface profile to achieve the needed radius of curvature (and its related contact angle). A second disadvantage of the thermal reflow process is its cost. The process requires a long fabrication cycle time in a cleanroom facility, and this leads to a high fabrication cost [27].

Given the above challenges for the thermal reflow process, a tunable dispensing process is introduced in this thesis for the fabrication of the MLAs. This fabrication process is capable of controlling the surface profile of the fabricated MLAs with specialized treatments while maintaining excellent quality for the microlenses. The tunable dispensing process is described in the following section.

3.2 Sub-systems for the tunable dispensing process

The tunable dispensing process that is introduced here for MLA fabrication is made to directly dispense polymer onto a glass substrate and cure these microdroplets into the form of the desired microlenses. Such a process can be fully-automated with real-time control to create the needed plano-convex MLAs.

The polymer that is used in the process is from the family of UV-curable NOA polymers. These polymers are advantageous because they exhibit minimal expansion and contraction during curing. Moreover, the polymers in this family differ greatly in terms of viscosity, refractive index, and glass adhesion characteristics. This allows for an easy selection of the polymer with the best characteristics.
The proposed tunable dispensing process is denoted in Figure 3.2. The selected optical polymer is deposited into the syringe, and air is removed, to allow the polymer flow freely out of the needle tip. The syringe is then connected to a pneumatic dispenser that applies controllable pressure. The pressure forces the optical polymer out of the needle tip and onto the glass substrate to form a roughly spherical microdroplet. The surface profile of the dispensed microdroplet can then be characterized by its contact angle with the substrate, $\theta$, which is defined by Young’s Equation:

$$\gamma_{sg} = \gamma_{sl} + \gamma_{gl} \cos \theta. \tag{37}$$

In this equation, $\gamma_{sg}$, $\gamma_{sl}$, and $\gamma_{gl}$ denote the surface energies of the solid-gas (glass-air) interface, the solid-liquid (glass-polymer) interface, and the gas-liquid (air-polymer) interface, respectively.

It is worthwhile to note that the surface energies in (37) can be tuned if there is a need to change the contact angle and alter the shape of the microdroplet. A particularly effective way to do this is with an oxygen plasma pre-treatment of the glass surface. The oxygen plasma transfers energy to the glass substrate and increases its surface energy [28]. Based on (37), the term $\gamma_{sg}$ increases, which in turn increases $\cos \theta$ and decreases $\theta$. The proposed tunable dispensing process makes use of this plasma pre-treatment to adjust the shape of the dispensed microdroplet.

Figure 3.2. Schematic of the proposed tunable dispensing process using a syringe and needle tip to form a microdroplet on a glass substrate. The surface profile of the microdroplet is defined by its contact angle of $\theta$, which is itself defined by the surface energies of the solid-gas (glass-air) interface, $\gamma_{sg}$, the solid-liquid (glass-polymer) interface, $\gamma_{sl}$, and the gas-liquid (air-polymer) interface, $\gamma_{gl}$. 
The employed MLA fabrication system is shown in Figure 3.3. It uses LabVIEW-based control to dispense the UV-curable polymer microdroplets from the syringe via a needle tip and onto the glass substrate. The system is composed of four sub-systems: a pneumatic sub-system, an actuation sub-system, a curing sub-system, and a monitoring sub-system. The relevant details of these four sub-systems are given in the following subsections.

![Figure 3.3. Schematic of the MLA fabrication system for fabricating plano-convex MLAs. The system is composed of the pneumatic sub-system, actuation sub-system, curing sub-system, and monitoring sub-system.](image)

### 3.2.1 Pneumatic sub-system

The pneumatic sub-system was developed to apply precise dispensing pressures over precise dispensing times in the MLA fabrication system. The dispensing pressure ranges from 0 psi to 60 psi, and the dispensing time ranges from milliseconds to seconds. These ranges allow the user to tune the volume of the dispensed optical polymer. The pneumatic sub-system is implemented with a Nordson EFD Ultimus™ V High Precision Dispenser, which is operated by way of the LabVIEW pneumatic control module shown in Figure 3.4. This module allows the user to apply the desired dispensing pressure over the desired dispensing time, and it can be fully automated for the fabrication of MLAs with large numbers of microlenses.
3.2.2 Actuation sub-system

To ensure that there is suitable reproducibility of the dispensed microdroplets across each array, it is necessary to implement an actuation sub-system with 3-D motion. The actuation sub-system that was assembled for this makes use of three single-axis 25-mm motorized actuators (MTS25/M-Z8, Thorlabs). The three actuators are configured to provide orthogonal ($x$, $y$, and $z$) motion of the stage holding the glass substrate. The syringe and needle tip remain stationary during the process. The decision to move the glass substrate, rather than the syringe and needle tip, is a subtle but important point. It was done to allow for the implementation of an especially rigid mount for the syringe and needle tip, which are preferentially sensitive to vibration. A photograph of the actuation sub-system is shown in Figure 3.5(a). The actuation system can be controlled by the LabVIEW-based actuation control module shown in Figure 3.5(b) or the Thorlabs-based actuation control module shown in Figure 3.5(c). Both actuation control modules can be easily integrated with the pneumatic control module.

Figure 3.4. The pneumatic control module in the pneumatic sub-system. Values of the dispensing pressure and dispensing time, for the dispenser, can be set and controlled in real-time via this LabVIEW module.
To reduce backlash and vibrations produced by the actuation system during the dispensing process, the LabVIEW control algorithm was implemented with three sub-modules:

- A **backlash correction sub-module** was applied because it was noticed that there could be a few microns of backlash after each pass along the x-, y-, or z-axes, and such backlash would accumulate. (Backlash manifests itself within a motor when one of its gears changes its direction of rotation but there occurs a small lag in the reversed rotation of its companion gear.) The backlash correction sub-module corrects this issue. With each pass along the x-, y-, or z-axes, the sub-module would move the motorized stage an extra distance, called the backlash scale, to compensate for the lag in the system. This can greatly reduce the translational error caused by backlash and can greatly improve the precision of pitches in the fabricated MLAs.

- A **dwell time control sub-module** was implemented to provide a delay during and between dispensing of microdroplets. This delay minimizes the effects of the vibration caused by the application of pressure to the syringe.

- A **velocity and acceleration control sub-module** was implemented because it was noticed that excessive velocity or acceleration could introduce vibration within the system. The sub-module allows the user to vary the velocity and acceleration to minimize the effects of vibration.
To promote reproducibility in the fabrication of large MLAs, the actuation sub-system was implemented with a sufficiently stable and adjustable MLA dispensing platform. The platform was 3-D printed with a high-resolution 3-D printer having a resolution of 6 µm, and it is shown in Figure 3.6(a). The platform firmly holds the glass substrate within a recessed square and is adjusted via a kinematic mirror mount (KS1, Thorlabs). Such adjustability is critical, because it allows the glass substrate to be levelled for suitable reproducibility during the dispensing. A photograph of the MLA dispensing platform and its mount is shown in Figure 3.6(b).

![Image](image1.png)

Figure 3.6. The (a) designed MLA dispensing platform and (b) its integration within the actuation sub-system. The platform has a 25 × 25 mm² recessed square, as shown in (a), to hold the glass substrate. The platform is integrated with a kinematic mirror mount in the manner shown in the photograph of (b).

3.2.3 Curing sub-system

The pneumatic and actuation sub-systems are controlled in a manner that forms the desired periodicity and surface profile of microlenses in the MLAs. However, careful attention must also be paid to the effects of gravity and surface wetting during microdroplet dispensing. These effects, which manifest themselves over prolonged timescales, can alter the surface profile of the microlenses across a given MLA and thereby sacrifice the reproducibility. Since the optical polymer used in the MLA fabrication system is liquid, its contact area on the glass substrate can slowly increase over time, which decreases the polymer-substrate contact angle and increases the focal length. In the extreme of having the diameter of the microlens equal the pitch, the neighbouring microlenses will merge with each other and the MLA will become unusable.
To mitigate the above challenges due to the prolonged effects of gravity and surface wetting an \textit{in situ} curing sub-system was developed. The sub-system applies UV illumination during the dispensing process such that the dispensed microdroplets cannot undergo significant deviations from their as-dispensed profiles. The sub-system is implemented with a UV LED module (M365FP1, Thorlabs) having a nominal wavelength of 365 nm, which is ideal for curing of NOA [29]. The module is connected to a multimode fibre (FT400UMT, Thorlabs) having a numerical aperture of 0.39 and core diameter of 400 µm. The fibre delivers 9.8 mW of UV optical power to cure a typical microlens within one second. The module is mounted on a heat sink to promote thermal dissipation and allow the unit to operate continuously for many hours.

The \textit{in situ} curing sub-system is ultimately integrated with the pneumatic and actuation sub-systems to form the system shown in Figure 3.7. The end of the fibre is aligned to cure the desired microdroplet while not illuminating the needle tip, which can clog its interior. To do this, the end of the fibre is aligned to cure the previous microdroplet from the one being dispensed.
3.2.4 Monitoring sub-system

Given that the diameter and pitch are critical physical parameters for the MLAs, with tight tolerances, a monitoring sub-system is integrated into the MLA fabrication system for real-time monitoring. This sub-system uses a microscope to view the polymer dispensing process with a field of view of 0.3 mm to 1.4 mm. The monitoring sub-system is shown in Figure 3.8.

The monitoring sub-system must provide a means by which the needle tip can be observed, to prevent it from being driven onto the substrate, and it should be capable of achieving the necessary focusing on the needle tip with large background lighting. This is done by carefully adjusting the spacing between the dispensing platform (i.e., where the glass substrate lies) and the illumination source as well as controlling the power level of the illuminating light source. With these adjustments to the system, it is possible to create a clear image of the needle tip and the dispensed microdroplets with the employed camera (Thorlabs MVL6X12Z). A representative image is shown in the inset of Figure 3.10. It is worth noting that the images show the needle tip and its reflection on the glass substrate, and these features together can be used to level the dispensing platform. In essence, the space between the needle tip and its reflection are monitored as the substrate is moved to ensure that their spacing does not change. This was found to be a critical
point for the operation of the system, because poorly-levelled glass substrates were found to cause drifting in the characteristics of the dispensed microdroplets across large MLAs.

![Image](image1.png)

**Figure 3.8.** A photograph of the monitoring sub-system with its camera in the bottom left. A representative image of the needle tip and microdroplets is shown in the inset.

3.2.5 Integration of the sub-systems as the microlens array fabrication system

The developed sub-systems are integrated together to form the MLA fabrication system, which is fully automated via a LabVIEW user control interface. The interface, shown in Figure 3.9, is composed of two main parts. The first part is the Thorlabs actuator control module. It is used to actuate the motorized dispensing stage with the glass substrate along the x-, y-, and z-axes. This part is shown on the left side of the figure. The geometrical features for the MLA, e.g., pitch, size, and location of the MLA, as well as the actuation parameters of the actuators, e.g., velocity, acceleration, dwell time, and backlash corrections, can all be controlled with this module. The module can also monitor the position of the individual motorized actuators. The second part, being the Nordson pneumatic control module for the dispensing steps of the microdroplets, is shown on the right side of the figure. This module is used to configure the process parameters. The desired surface profile of the fabricated microlenses can then be achieved by applying the appropriate dispensing pressure and time. Operation details are summarized at the bottom of this interface.
Once the sub-systems are integrated, the system is used to fabricate and characterize a wide variety of plano-convex MLAs. A representative plano-convex MLA is shown as an optical microscope image and a scanning electron microscopic (SEM) image in Figures 3.10(a) and (b), respectively. A profilometer is then used to quantify the MLA parameters. Figure 3.11 shows a profilometer curve for five microlenses within a plano-convex MLA. The data from the
profilometer is implemented into R code to extract the diameter and sag of each microlens, and these parameters are used to calculate the radius of curvature. The radius of curvature is the key parameter for the microlens, because it is this curvature that dictates the focal length. Ultimately, the radius of curvature should be sufficiently close to the value defined by the design and sufficiently uniform across the plano-convex MLA.

![Figure 3.11. Profilometer curve for five microlenses within a representative plano-convex MLA.](image)

3.3 Characterizations of the tunable dispensing process: Plano-convex microlens arrays

The tunable dispensing process has many factors that contribute to the surface profile, reproducibility, and quality of the fabricated MLAs. It is important to identify these factors and ultimately control the extent to which they affect the fabricated MLAs. With this in mind, characterizations were carried out to test the influence of these factors on the fabricated MLAs and use this knowledge to develop an appropriate recipe to produce the desired MLAs. The following subsections present details on characterizations of the NOA optical polymer as well as the process parameters, including the velocity and acceleration, dwell time, dispensing pressure, and dispensing time.
3.3.1 Characterization of the Norland Optical Adhesive

As mentioned in the former sections, the selected optical polymer is from the NOA family. These NOA polymers are transparent liquids that become cured when exposed to a sufficient level of UV fluence, i.e., radiant exposure. The curing time of the NOA can be remarkably fast if the UV light has a suitable wavelength and intensity.

The members in the NOA family differ greatly in terms of the viscosity, refractive index, physical characteristics, and glass adhesion. The characteristics are summarized in Table 3.1 for the four considered NOA optical polymers.

Experiments were carried out to test the capabilities of these polymers in forming microdroplets, and it was ultimately found that NOA 65 is the best choice. It has an intermediate viscosity of 1200 cps, which was sufficiently low to allow it to be dispensed at a relatively low pressure and sufficiently high to promote reproducibility. It has minimal oxygen inhibition, so its surfaces are not tacky when fully cured. It also has the smallest refractive index of 1.52, which is beneficial for the integration with the glass substrate whose refractive index is 1.52. The NOA 65 is cured by UV light according to the transmission and absorption spectra shown in Figure 3.12. It is apparent from this figure that transmission decreases and absorption increases as the wavelength drops below 400 nm. With this fact in mind, and knowledge of the wavelengths that are readily available from commercial LEDs, a GaN LED with a wavelength of 365 nm is chosen to cure the NOA 65.

Table 3.1. Characteristics of the four considered NOA optical polymers, including the viscosity, refractive index, physical characteristics, and glass adhesion characteristics. The data shown here is from Norland Products Inc.

<table>
<thead>
<tr>
<th>NOA type</th>
<th>Viscosity (cps)</th>
<th>Refractive Index</th>
<th>Physical Characteristics</th>
<th>Glass Adhesion features</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>300</td>
<td>1.56</td>
<td>Tough</td>
<td>Good</td>
</tr>
<tr>
<td>61</td>
<td>300</td>
<td>1.56</td>
<td>Tough</td>
<td>Excellent</td>
</tr>
<tr>
<td>65</td>
<td>1200</td>
<td>1.52</td>
<td>Flexible</td>
<td>Good</td>
</tr>
<tr>
<td>68</td>
<td>5000</td>
<td>1.54</td>
<td>Flexible</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
3.3.2 Characterization of the velocity and acceleration

In this subsection, the diameters and deviations of the dispensed microlenses are characterized with respect to the velocity and acceleration of the translation stage. In general, it is beneficial to have the velocity and acceleration be sufficiently high to allow an MLA to be fabricated in a short period of time. However, it is also important to have the velocity and acceleration be sufficiently low to prevent deviations of the microlens characteristics during the fabrication.

To characterize the microlens diameter and its deviation, a MATLAB-based imaging detection algorithm is used. The algorithm does this by carrying out four steps: first, it loads the original image of the MLA; second, it converts the original image to a grayscale image; third, it identifies the individual microlenses according to the pixel brightness and a defined threshold; fourth, it outputs the centre and diameter of each microlens and encircles the microlens in a final image for inspection. (The last step allows the user to judge whether the program correctly recognizes the microlenses.) An example of the algorithm’s implementation is shown in Figure 3.13. Figure 3.13(a) shows images for the four steps of the imaging detection algorithm; Figure 3.13(b) shows an expanded view of the final image with the recognized microlenses encircled in blue.
The characterizations are carried out by monitoring deviations in the diameters of the microlenses while varying the velocity and acceleration of the actuators in the actuation sub-system and keeping the dispensing pressure (4.8 psi) and time (0.18 seconds) fixed in the pneumatic sub-system. Nine different velocity and acceleration combinations are used for the dispensing, with three MLAs fabricated for each combination, and then the images are captured with an optical microscope (Zeiss Discovery Stereoscope). The results for the 27 plano-convex MLAs, containing 7102 microlenses in total, are shown in Table 3.2. The data in this table is generated by calculating the mean and standard deviation for each combination of velocity and acceleration and quoting the standard deviation in the table as a percentage of the mean. Such a percentage is indicative of the uniformity of the microlenses in each MLA.

It is apparent from Table 3.2 that the most uniform plano-convex MLAs can be generated with the actuators moving with a velocity of 0.5 mm/s and an acceleration of 0.5 mm²/s. Such conditions keep the standard deviation of the diameter at approximately 3.5%. This standard deviation is deemed to be acceptable—given that further reductions in the velocity and acceleration would bring the overall MLA fabrication time to an unnecessarily long duration. For the remainder of this thesis, a velocity of 0.5 mm/s and an acceleration of 0.5 mm²/s are used for the implementation of the actuation sub-system.

Figure 3.13. Microlenses in an MLA shown as (a) the four individual images for the corresponding four steps of the imaging detection algorithm and (b) the final image produced by the algorithm with the recognized microlenses encircled in blue.
Table 3.2. Standard deviations of the diameters (as a percent of the mean) for microlenses within MLAs with nine different combinations of velocity and acceleration of the actuators.

<table>
<thead>
<tr>
<th>Acceleration (mm²/s)</th>
<th>Velocity (mm/s)</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
<td>3.5%</td>
<td>4.7%</td>
<td>4.5%</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>4.2%</td>
<td>4.9%</td>
<td>5.0%</td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>5.0%</td>
<td>4.7%</td>
<td>4.7%</td>
</tr>
</tbody>
</table>

3.3.3 Characterization of the dwell time

In this subsection, the diameters and deviations of the dispensed microlenses are characterized with respect to the dwell time. The dwell time is the waiting time after each microlens is dispensed. Too short of a dwell time can yield poor uniformity in the MLAs because the stage may vibrate during dispensing. However, too long of a dwell time can yield gravity-induced deviations in microlens diameters across the MLA and unnecessarily prolong the fabrication time.

The dwell time is characterized for plano-convex MLAs being fabricated with dwell times of 1, 2, 3, 4, and 5 seconds. (It is found that dwell times beyond 5 seconds yield little changes.) The aforementioned optimal actuator velocity of 0.5 mm/s and acceleration of 0.5 mm²/s are used in the characterization with a fixed dispensing pressure of 4.8 psi and dispensing time of 0.18 seconds. In total, 1679 microlenses are characterized, with approximately 340 microlenses per MLA, and the resulting images are processed by the aforementioned imaging detection algorithm. The mean and standard deviation of the diameters are calculated, and the results are shown in Figure 3.14. The figure shows the standard deviation of the microlens diameter as a percentage of the mean versus the dwell time. The results show that a dwell time at or above 3 seconds yields a standard deviation below 3.2%. Such a standard deviation is deemed to be acceptable in this work, and so a dwell time of 3 seconds will be used for the implementation of the actuation sub-system in the remainder of this thesis. (Longer dwell times unnecessarily increase the fabrication time.) The slight increase in the standard deviation as the dwell time rises from 3 to 5 seconds is attributed to measurement error of the imaging processing algorithm. Representative images of the MLAs from an optical microscope (Zeiss Discovery Stereoscope) are shown for the dwell times from 1 to 5 seconds in Figures 3.15(a) to (e), respectively. Note that the velocity and acceleration could be
decreased even further, but this would need to be done with a corresponding reduction in the dwell time to keep the overall fabrication cycle time the same.

Figure 3.14. Standard deviations of the microlens diameters (as a percent of the mean) within MLAs for five different dwell times. The MLAs are fabricated with a dispensing pressure of 4.8 psi, a dispensing time of 0.18 seconds, and a pitch of 440 µm. The pneumatic sub-system is operated at a velocity of 0.5 mm/s and acceleration of 0.5 mm/s². The spacing between the needle tip and glass substrate is (0.08 ± 0.01) mm.
3.3.4 Characterization of the dispensing pressure

In this subsection, the diameters and deviations of the dispensed microlenses are characterized with respect to the dispensing pressure, being one of the process parameters in the pneumatic subsystem. It is the pressure applied within the syringe to expel the optical polymer from the needle tip and onto the glass substrate. Thus, it will greatly influence the diameter of the microlenses within the fabricated MLA.

To identify the extent to which the dispensing pressure influences the diameter of the microlenses, a characterization is carried out by dispensing plano-convex MLAs with dispensing pressures of 6.5 psi, 7.5 psi, 8.5 psi, 9.5 psi, 10.5 psi, and 11.5 psi. The dispensing time is fixed, at
0.25 seconds, because it will otherwise influence the volume of the dispensed optical polymer and the resulting microlens diameters. The pitch of the MLA is selected to be sufficiently large, at 500 µm, to prevent the dispensed microdroplets from merging with their neighbouring microdroplets if a large volume of optical polymer is dispensed. (Such merging occurs for this pitch when the dispensing pressure is greater than 12 psi.) The pneumatic sub-system is operated at the optimal actuation process parameters, i.e., a velocity of 0.5 mm/s, an acceleration of 0.5 mm²/s, and a dwell time of 3 seconds. The spacing between the dispensing needle tip to the glass substrate is fixed at (0.08 ± 0.01) mm. The error here is due to the fact that the dispensing stage is not perfectly flat over the dispensing area of 10 × 10 mm².

The results of the characterization of the dispensing pressure is shown in Figure 3.16. The figure shows the diameters of the dispensed microlenses as a function of the dispensing pressure, with representative optical microscope images in the figure insets. The diameters and their standard deviations shown here are extracted from the aforementioned imaging detection algorithm. It is seen here that the pressures of 6.5 psi, 7.5 psi, 8.5 psi, 9.5 psi, 10.5 psi, and 11.5 psi result in microlenses with diameters of (313 ± 6) µm, (343 ± 5) µm, (348 ± 6) µm, (350 ± 6) µm, (360 ± 6) µm, and (365 ± 7) µm, respectively. It is seen that the diameters grow with the dispensing pressures with a sublinear dependence, being indicative of an approach toward a saturated value, while the standard deviations of the microlens diameters remain nearly constant across the range of dispensing pressures.
3.3.5 Characterization of the dispensing time

In this subsection, the diameters and deviations of the dispensed microlenses are characterized with respect to dispensing time, being one of the process parameters in the pneumatic sub-system. The dispensing time is the duration of time for which the dispensing pressure is applied to the optical polymer in the syringe. It is similar to the dispensing pressure in that a greater dispensing time will lead to a greater volume of dispensed optical polymer and a larger microlens diameter.

To identify the relationship between the microlens diameter and the dispensing time, a characterization is carried out. The characterization uses a fixed dispensing pressure of 6.5 psi, with dispensing times of 0.18 seconds, 0.25 seconds, 0.30 seconds, and 0.35 seconds. The pitch is fixed at 500 µm to prevent merging between neighbouring microdroplets. The pneumatic sub-system is operated at the optimal actuation process parameters, i.e., a velocity of 0.5 mm/s, an acceleration of 0.5 mm²/s, and a dwell time of 3 seconds. The spacing between the dispensing needle tip to the glass substrate is fixed at (0.08 ± 0.01) mm. The results of this characterization

Figure 3.16. Microlens diameter as a function of the dispensing pressure for various MLAs. The MLAs are fabricated with a dispensing time of 0.25 seconds and pitch of 500 µm. The pneumatic sub-system is operated at a velocity of 0.5 mm/s, an acceleration of 0.5 mm²/s, and a dwell time of 3 seconds. The spacing between the needle tip and glass substrate is (0.08 ± 0.01) mm. Representative images of the MLAs are shown as insets.
are shown in Figure 3.17. The figure shows the diameters of the dispensed microlenses as a function of the dispensing time, with representative optical microscope images in the figure insets. The presented microlens diameters are $(247 \pm 5)$ µm, $(271 \pm 6)$ µm, $(285 \pm 6)$ µm, and $(293 \pm 7)$ µm for the dispensing times of 0.18 seconds, 0.25 seconds, 0.30 seconds, and 0.35 seconds, respectively. Like the characterization of dispensing pressures, the microlens diameters here grow with the dispensing times with a sublinear dependence, being indicative of an approach toward a saturated value, while the standard deviations of the microlens diameters remain nearly constant across the range of dispensing times.

3.3.6 Characterization of the surface pre-treatment

For the prior characterizations, the balance of surface energies between the NOA 65 and glass substrate is fixed—which yields a roughly constant contact angle for the dispensed microlens ranging from $35^\circ$ to $40^\circ$. However, it is possible to adjust the surface energies to produce a smaller
contact angle. This is done with the application of an oxygen plasma to the glass substrate as a surface pre-treatment [30].

The plasma pre-treatment works by increasing the surface energy of the glass substrate and thereby reducing the contact angle, according to (37). To identify the relationship between the contact angle and the dose of plasma pre-treatment, as defined by its RF power and treatment time, a characterization is carried out. The RF power and treatment times are shown in Table 3.3 along with the numbers of MLAs that are tested and the resulting contact angle of the microlenses in the stated MLAs. For all of these MLAs, the dispensing time is 0.25 seconds, the dispensing pressure is 5.5 psi, the pitch is 440 µm, the actuation velocity is 0.5 mm/s, the actuation acceleration is 0.5 mm²/s, the dwell time is 3 seconds, and the spacing between the dispensing needle tip and glass substrate is (0.08 ± 0.01) mm. The applied RF powers span from their minimum to maximum values as defined by the plasma treatment system (Plasma Etch PE-25). The applied treatment times range from 0 to 30 seconds. Note that the RF powers and treatment times are selected to produce microlenses with contact angles that span across the desired value of $\alpha_{cv} = 20^\circ$ for the microlenses in the plano-convex MLA. This contact angle corresponds to a microlens with the desired radius of curvature of $R_{cv} = 497$ µm and diameter of $d_{cv} = 350$ µm, for the plano-convex MLA, as shown in Table 2.1. Given the full span of contact angles that is seen, it can be concluded that an RF power index of 22.5 W and a treatment time of 10 seconds are needed to produce the desired contact angle of $\alpha_{cv} = 20^\circ$.

As a final point of analysis, it is worthwhile to characterize the diameter of the microlenses on the plasma pre-treated substrate as a function of the order in which they are dispensed within an array. Such a characterization would show the uniformity of the microlenses within the array and the consistency of the fabrication process. With this in mind, a representative array of plano-convex MLAs is fabricated on a plasma pre-treated substrate and its diameters are measured. The resulting diameters are shown in Figure 3.18 as a function of the order in which they are dispensed. It is clear from this figure that the diameters exhibit random scatter with respect to a roughly constant mean value. This indicates that the process exhibits little systematic error with good overall consistency.
Figure 3.18. Characterization of the diameter of each microlens within a plano-convex MLA on a plasma pretreated substrate versus its order of dispensing within the array. The results show random scatter with respect to a mean diameter, shown as a solid red line, which is indicative of little systematic error and good consistency in the process.
Table 3.3. Contact angle of microlenses within the MLAs for various RF powers and treatment times. For all of the MLAs, the dispensing time is 0.25 seconds, the dispensing pressure is 5.5 psi, the pitch is 440 µm, the actuation velocity is 0.5 mm/s, the actuation acceleration is 0.5 mm²/s, the dwell time is 3 seconds, and the spacing between the dispensing needle tip and glass substrate is (0.08 ± 0.01) mm. Each contact angle quoted here for a given MLA is an average of the contact angles for the measured microlenses within the MLA. The row corresponding to a contact angle of 20° is shown in bold.

<table>
<thead>
<tr>
<th>Oxygen plasma treatment</th>
<th>Number of tested MLAs</th>
<th>Contact angle of microlenses in the MLA (approximate, degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF power (watts)</td>
<td>Treatment time (seconds)</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>20.0</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>22.5</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>22.5</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>25.2</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>27.6</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>30.0</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>32.5</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>40.0</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>60.0</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>80.0</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>100.0</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>200.0</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>

3.4 Characterizations of the tunable dispensing process: Plano-concave microlens arrays

In the prior sections, a tunable dispensing process was developed for the fabrication of plano-convex MLAs. It made use of dispensing to produce plano-convex microlenses with a wide variety of physical parameters. In this section, the plano-convex MLAs are used as molds in a casting process to form plano-concave MLAs. The fabrication process for the plano-concave MLAs is presented by way of five steps.
The first step for the fabrication of the plano-concave MLAs involves PDMS mixing. The PDMS is generated by mixing the prepolymer base and curing agent at a ratio of 5:1. In the literature, this ratio ranges from 3:1 to 10:1 [31], but it is found through our studies that a ratio of 5:1 gives a sufficiently short curing time and sufficient flexibility for the cured structure.

The second step for the fabrication of the plano-concave MLAs involves bubble elimination. This step is important because it is found that the mixing in the prior step generates many bubbles and these bubbles diminish the quality of the resulting optical images. To eliminate the bubbles, the PDMS mixture is subjected to an ultrasonic bath (Branson 3510) [32]. The bath is applied until all of the observable bubbles are eliminated, which takes roughly 30 minutes.

The third step for the fabrication of the plano-concave MLAs involves casting. For this step, the bubble-free PDMS mixture is poured into a container within which the plano-convex MLA mold lies (face up). The thickness of the resulting plano-concave MLA is dictated by the volume of the PDMS mixture that is poured into the container, and this volume is monitored by way of the weight of the PDMS mixture. It will be shown later in this section that 1 gram of PDMS mixture and a square container (139-17, Ted Pella Inc.) with a cross-sectional area of 25.4 × 25.4 mm² yield a thickness for the plano-concave MLA of 1 mm.

The fourth step for the fabrication of the plano-concave MLAs involves curing. This is carried out via heating in an oven (Fisher Isotemp 500 Economy Vacuum Lab Oven) at a temperature of 60°C. For 1 gram of PDMS mixture in the container, the mixture is fully cured after 36 minutes.

The fifth step for the fabrication of the plano-concave MLAs involves extraction. For this step, the container holding the PDMS mixture is removed from the oven and cooled to room temperature in a fume hood. This takes approximately 30 minutes. Such cooling is important because peeling off the PDMS from its planar-convex mold at too high of a temperature results in contraction of the PDMS and shrinking of the plano-concave MLA. When the PDMS mixture is sufficiently cool, it is peeled off of its plano-convex mold and is ready for use.

First, a characterization of the firmness for the plano-concave MLAs is carried out with respect to two key process parameters—being the PDMS mix ratio between the prepolymer base and curing agent and the curing time. The results are described here. It is generally found that larger PDMS mix ratios require correspondingly long curing times to achieve the same firmness [33], and for the purposes of this study, two PDMS mix ratios are considered. The first mix ratio, at 5:1,
has been noted in the literature to be effective for PDMS-based MLAs [34]. The second mix ratio, at 10:1, is the typical mix ratio that is used in the literature. See [35] as an example. With this in mind, twelve plano-concave MLAs were fabricated out of PDMS and cured in an oven at 60°C. The MLAs with a PDMS mix ratio 5:1 were cured for times of 30, 32, 34, 36, 38, 40, 42, and 45 minutes, while the MLAs with a PDMS mix ratio of 10:1 were cured for times of 32, 60, 90, and 135 minutes.

The results of this characterization of firmness versus PDMS mix ratio and curing time are shown in Table 3.4. It can be seen from the bottom four rows of Table 3.4, for a PDMS mix ratio of 10:1, that increasing curing times increase the firmness of the PDMS. Specifically, curing times of 32, 60, and 90 minutes lead to firmness levels of liquid, soft, and soft, respectively, while a curing time of 135 minutes leads to a suitably firm PDMS structure. It can be seen from the top eight rows of the table, for a PDMS mix ratio of 5:1, that increasing curing times again increase the firmness of the PDMS but this happens at much lower curing times. Here, the curing time of 30 minutes is deemed to be too short to create a suitably firm PDMS structure, while the curing times of 40, 42, and 45 are deemed to be too long because they create PDMS structures that are too difficult to remove from their molds and are therefore susceptible to damage. Overall, curing times of 32, 34, 36, and 38 minutes are deemed to be appropriate to form plano-concave MLAs with suitable firmness. The deviation of the thickness for these MLAs is approximately 10 µm. Figure 3.19 shows a few representative optical microscope images of the resulting plano-concave MLAs.
Table 3.4. Firmness of the fabricated plano-concave MLAs for various combinations of PDMS mix ratio (of prepolymer base to curing agent) and curing time. All of the MLAs were cured at a temperature of 60°C.

<table>
<thead>
<tr>
<th>PDMS mix ratio (prepolymer base to curing agent)</th>
<th>Curing time (minutes)</th>
<th>Firmness</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:1</td>
<td>30</td>
<td>soft</td>
</tr>
<tr>
<td>5:1</td>
<td>32</td>
<td>firm</td>
</tr>
<tr>
<td>5:1</td>
<td>34</td>
<td>firm</td>
</tr>
<tr>
<td>5:1</td>
<td>36</td>
<td>firm</td>
</tr>
<tr>
<td>5:1</td>
<td>38</td>
<td>firm</td>
</tr>
<tr>
<td>5:1</td>
<td>40</td>
<td>firm*</td>
</tr>
<tr>
<td>5:1</td>
<td>42</td>
<td>firm*</td>
</tr>
<tr>
<td>5:1</td>
<td>45</td>
<td>firm*</td>
</tr>
<tr>
<td>10:1</td>
<td>32</td>
<td>liquid</td>
</tr>
<tr>
<td>10:1</td>
<td>60</td>
<td>soft</td>
</tr>
<tr>
<td>10:1</td>
<td>90</td>
<td>soft</td>
</tr>
<tr>
<td>10:1</td>
<td>135</td>
<td>firm</td>
</tr>
</tbody>
</table>

*These plano-concave MLAs became difficult to peel off their molds and are therefore susceptible to damage.

Next, a characterization of the thickness of the plano-concave MLAs is carried out with respect to the weight of the PDMS mixture. This is done to determine the weight of the PDMS mixture that is needed to produce a 1-mm-thick plano-concave MLA. For this characterization, the PDMS mix ratio is set at 5:1, the curing time is set at 36 minutes, and the curing temperature is set at 60°C. The PDMS mixtures of various weights are then poured into a container holding the plano-convex mold (face up). The container (139-17, TED Pella Inc.) is square and has an area of 25.4 × 25.4 mm². The resulting thickness of the plano-concave MLA is shown in Figure 3.20 as a function of the weight of the PDMS mixture that is used. A nearly linear trend is seen, as one might expect, and it exhibits an R-squared coefficient of 0.994. Given this trend, the appropriate weight of PDMS mixture that is to be used is 0.916 gram. Such a weight will form a plano-concave MLA with a thickness of (1 ± 0.01) mm.
Figure 3.19. Representative microscopic images of the plano-concave MLAs having been fabricated with a curing temperature of 60°C, a PDMS mix ratio of 5:1, and curing times of (a) 34 minutes, (b) 36 minutes, (c) 38 minutes, and (d) 40 minutes.

Figure 3.20. Thickness of plano-concave MLAs as a function of weights of the PDMS mixture being poured into the molding container. The container is square and it has an area of 25.4 x 25.4 mm². For these plano-concave MLAs, the PDMS mix ratio is 5:1, the curing time is 36 minutes, and the curing temperature is 60°C.
3.5 Summary

The characterizations and findings presented in this chapter pertained to the fabrication processes of plano-concave and plano-convex MLAs. The characterizations defined the values of the process parameters that yielded the optimal physical parameters for the coupled MLAs—being those identified in chapter 2 for functioning as a Gabor lens and meeting the three design criteria. The characterizations yielded the values for the process parameters shown in Table 3.5, in terms of the plasma pre-treatment to the substrate, dispensing pressure, dispensing time, actuation velocity, actuation acceleration, dwell time, needle-tip-to-substrate spacing, PDMS mix ratio, PDMS weight, PDMS curing time, and PDMS curing temperature. It is also worth noting that efforts were made to realize the values with an overarching goal to minimize the fabrication cycle time. Such efforts can improve the practicality of the developed technologies and better support their use in industry.

In light of this fact, the physical parameters of the plano-concave and plano-convex MLAs are quoted in Table 3.6 with their overall processing times of 30 and 70 minutes, respectively. These times are noticeably lower than the typical processing time needed to fabricate MLAs via the thermal reflow process, which can be in excess of 12 hours [36].

Table 3.5. Process parameter values for fabrication of the plano-concave and plano-convex MLAs.

<table>
<thead>
<tr>
<th></th>
<th>Plano-concave MLA</th>
<th>Plano-convex MLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma pre-treatment to the substrate</td>
<td>None</td>
<td>22.5 W of RF power for 10 seconds</td>
</tr>
<tr>
<td>Dispensing pressure</td>
<td>6.5 psi</td>
<td>8.5 psi</td>
</tr>
<tr>
<td>Dispensing time</td>
<td>0.35 seconds</td>
<td>0.25 seconds</td>
</tr>
<tr>
<td>Actuation velocity</td>
<td>0.5 m/s</td>
<td></td>
</tr>
<tr>
<td>Actuation acceleration</td>
<td>0.5 m/s²</td>
<td></td>
</tr>
<tr>
<td>Dwell time</td>
<td>3.0 seconds</td>
<td></td>
</tr>
<tr>
<td>Needle-tip-to-substrate spacing</td>
<td>0.08 ± 0.01 mm</td>
<td></td>
</tr>
<tr>
<td>PDMS mix ratio</td>
<td>5:1</td>
<td></td>
</tr>
<tr>
<td>PDMS weight</td>
<td>0.916 gram</td>
<td></td>
</tr>
<tr>
<td>PDMS curing time</td>
<td>36 minutes</td>
<td></td>
</tr>
<tr>
<td>PDMS curing temperature</td>
<td>60°C</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.6. Physical parameter values for the coupled plano-concave and plano-convex MLAs along with their respective processing times.

<table>
<thead>
<tr>
<th>Coupled MLAs</th>
<th>Pitch</th>
<th>Number of microlenses</th>
<th>Microlens diameter</th>
<th>Microlens radius of curvature</th>
<th>Microlens contact-angle</th>
<th>Processing times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plano-concave MLA</td>
<td>$p_{cc} = 466 , \mu m$</td>
<td>$20 \times 20 = 400$</td>
<td>$d_{cc} = 300 , \mu m$</td>
<td>$R_{cc} = 247 , \mu m$</td>
<td>$\alpha_{cc} = 38^\circ$</td>
<td>70 minutes</td>
</tr>
<tr>
<td>Plano-convex MLA</td>
<td>$p_{cv} = 440 , \mu m$</td>
<td>$20 \times 20 = 400$</td>
<td>$d_{cv} = 350 , \mu m$</td>
<td>$R_{cv} = 497 , \mu m$</td>
<td>$\alpha_{cv} = 20^\circ$</td>
<td>30 minutes</td>
</tr>
</tbody>
</table>
Chapter 4: Testing of the coupled microlens arrays

In this chapter, the imaging performance of the coupled plano-concave and plano-convex MLAs, having been designed according to the work in chapter 2 and fabricated according to the work in Chapter 3, is put to the test. The coupling of this system is critical, given that each MLA by itself would not function in a manner similar to a conventional lens. Each independent MLA would instead have each of its microlenses generate an image of a distant object within its focal plane. Figure 4.1 shows such a result. However, when the plano-concave and plano-convex MLAs are coupled together, they can perform in the manner of a conventional lens, i.e., as a Gabor lens, and generate a single image of the object.

The tests in this chapter will show if the coupled MLAs can perform as a Gabor lens that meets the three design criteria: Criterion I would have the coupled MLAs project an image of the microdisplay into the relaxed eye focused at infinity with an FOV$_A$ between 15º and 25º; Criterion II would have the image projected by the coupled MLAs be an accurate reproduction of the microdisplay with a resolution of 30 cycles/mm or greater; Criterion III would have the coupled MLAs be implemented with a flat form factor having the sum of its focal length and separation between its MLAs be less than 23.4 mm. The following sections look at such testing via the setup, procedures, results, and packaging. The final section summarizes the findings.

Figure 4.1. Optical image generated by an isolated plano-convex MLA. Each microlens in the plano-convex MLA generates a separate image of a distant object within its focal plane. The diameter of the microlenses seen here is 300 µm.
4.1 Setup

In this section, the components of the experimental setup that is used to test the resolution of the coupled plano-concave and plano-convex MLAs are introduced. A schematic of the setup is shown in Figure 4.2. It consists of a microdisplay, the coupled plano-convex and plano-concave MLAs with a physical gap of 50 µm between them, and a camera positioned within the eyebox of the coupled plano-concave and plano-convex MLAs.

A Sony EXC336A is used for the microdisplay. It has an active area of $8.14 \times 5.99 \, \mu m^2$, with pixels in an array of $1044 \times 768$, giving a pitch of 7.8 µm. The microdisplay is connected to a computer via serial control with a mini-HDMI connection. The EXC336A controller is used on the computer to control the brightness and resolution of the microdisplay. The user interface of the EXC336A is shown in Figure 4.3. The brightness of the displayed image can be adjusted by the displayed “LUMINANCE” tab using five different levels.

![Figure 4.2. Schematic of the experimental setup that is used to test the coupled plano-concave and plano-convex MLAs. An image generated on the microdisplay is captured by the coupled plano-concave and plano-convex MLAs and projected into the camera, which is focused at infinity.](image)
The plano-concave and plano-convex MLAs used in the setup are fabricated by the MLA fabrication system and casting process introduced in Chapter 3 to have the physical parameters shown in Table 3.5, within a 2% tolerance. The plano-concave MLA has a pitch of \((466 \pm 2) \, \mu\text{m}\), a microlens diameter of \((300 \pm 5.89) \, \mu\text{m}\), and a radius of curvature of \((247 \pm 4.85) \, \mu\text{m}\). The plano-convex MLA has a pitch of \((440 \pm 2) \, \mu\text{m}\), a microlens diameter of \((350 \pm 6.87) \, \mu\text{m}\), and a radius of curvature of \((497 \pm 9.81) \, \mu\text{m}\). The plano-concave and plano-convex MLAs are mounted in the setup on MLA mounts that are attached to \(xyz\)-translation stages. Each stage can be independently rotated and translated. In this way, adjustments can be made to align the MLAs and optimize the functionality. The alignment is carried out by monitoring the interference pattern from the beating of the two periodic MLAs, which manifests itself as a Moiré pattern. The alignment is optimal when the Moiré pattern is minimized. Schematics of the MLA mounts for the plano-concave and plano-convex MLAs are shown in Figures 4.4(a) and (b), respectively, and photographs of the resulting MLA rotational mounts (Thorlabs rotation mount CRM1) are shown in Figures 4.4(c) and (d).

![Figure 4.3](image_url)

Figure 4.3. The user interface of the EXC336A controller for the microdisplay. The brightness of the microdisplay can be adjusted by the “LUMINANCE” tab using five different levels.
Figure 4.4. The MLA mounts for the (a) plano-convex MLA and (b) plano-concave MLA, and photographs of the (c) plano-convex MLA and (d) plano-concave MLA.

The image from the microdisplay is projected by the plano-concave and plano-convex MLAs toward the camera in the setup. The Canon SX 720HS is selected for this camera because it has a high resolution, with a sensor having $4000 \times 3000$ pixels at a size of $7.6 \times 5.7 \text{ mm}^2$, and the ability to focus from zero to infinity. The virtual image generated by the coupled MLAs is captured by camera to define the imaging resolution of the system. The procedures to do this are given in the following section.
4.2 Procedures

The procedures to define the imaging resolution are presented in this section. The test patterns are described first, followed by details on quantifying the resolution via the MTF.

The test patterns that are applied in this work are based off one that is widely used—being the United States Air Force- (USAF-) 1951 test chart shown in Figure 4.5. The test chart conforms to the MIL-STD-150A standard and is reproduced here under the Wikimedia Creative Commons Attribution-Share Alike 3.0 Unported License. The USAF-1951 test chart contains groupings of tangential and sagittal lines, with each grouping having lines with spatial frequencies that span 0.25 cycles/mm up to 912.3 cycles/mm [37].

Figure 4.5. The USAF-1951 test chart used to characterize imaging resolution. The chart contains grouping of tangential and sagittal lines with spatial frequencies spanning 0.5 cycles/mm to 912.3 cycles/mm. The chart is used here under the Wikimedia Creative Commons Attribution-Share Alike 3.0 Unported License.

The test patterns that are used in this work are a modified form of the standardized USAF-1951 test chart. For this work, the test patterns with tangential and sagittal lines are applied as black-and-white digital images on the microdisplay. The lines are generated with differing spatial frequencies and the patterns are projected through the setup and captured by the camera to define the overall resolution. The test patterns are applied to the microdisplay with values of 0 or 255 for black or white pixels, respectively. The pixels form a spatially-periodic pattern of black and white lines with a pixel frequency of $f_p$ in pixels/cycle and a pixel pitch of $p_m$ in units of microns. The
black and white lines on the microdisplay appear with a spatial frequency of \( f_s \) in units of cycles/mm. Thus, the spatial frequency in cycles/mm, \( f_s \), can be calculated from the pixel frequency in pixels/cycle, \( f_p \), and the pixel pitch in microns, \( p_m \), according to

\[
f_s = \frac{1000}{f_p p_m}.
\]  

(38)

A sketch showing a representative black-and-white test pattern is shown in Figure 4.6. The figure shows the overall microdisplay with its \( a \times b = 1044 \times 768 \) pixels in the vertical and horizontal dimensions, respectively. For example, given a pixel pitch of \( p_m = 7.8 \) \( \mu m \) and spatial frequency of \( f_s = 7.8 \) cycles/mm being considered for testing, the pixel frequency of the black and white lines on the microdisplay would be set to \( f_p = 16 \) pixels/cycle. In other words, each black or white line would be 8 pixels wide. Such a process is used to generate black-and-white test patterns on the microdisplay with spatial frequencies from \( f_s = 0.4 \) cycles/mm to 32.1 cycles/mm. Figures 4.7(a)-(f) show test patterns for spatial frequencies of \( f_s = 4.3 \) cycles/mm, 5.3 cycles/mm, 6.4 cycles/mm, 10.7 cycles/mm, 16.0 cycles/mm, and 32.1 cycles/mm, respectively.

![Figure 4.6. Sketch of a representative black-and-white test pattern showing its pixel frequency of \( f_p \) in pixels/cycle. The pattern has \( a \) pixels in the vertical dimension and \( b \) pixels in the horizontal dimension with the pixels have a pitch of \( p_m \) in a units of microns.](image)
Figure 4. Black-and-white test patterns on the microdisplay with spatial frequencies of (a) 4.3 cycles/mm, (b) 5.3 cycles/mm, (c) 6.4 cycles/mm, (d) 10.7 cycles/mm, (e) 16.0 cycles/mm, and (f) 32.1 cycles/mm. The lower solid bar in the test patterns is used to prevent the spurious resolution, which is caused by the diffraction of the beam’s wavefronts as they pass through the periodic gaps between the microlenses.

Once a test pattern with a given spatial frequency has been applied to the microdisplay, it is projected through the coupled MLAs and its image is captured by the camera. Captured images from test patterns with differing spatial frequencies can then be used to define the system’s overall MTF and imaging resolution. This characterization follows the work in “Modulation Transfer Function in Optical and Electro-Optical Systems” [38] by defining the MTF off of the sinusoidal profiles in images captured from test patterns with differing spatial frequencies. The process can be seen in Figure 4.8. Figure 4.8(a) shows a test pattern with a particular spatial frequency in the horizontal dimension, and Figure 4.8(b) shows the resulting image captured by the camera as a profile of pixel signal values versus the horizontal dimension. Note that the profile captured by the camera is not a perfect square wave, as would result for a system with infinite resolution. The profile of its pixel signal values is sinusoidal, instead, with a minimum value of \( v_{\text{min}} \), a maximum value of \( v_{\text{max}} \), and a mean value of \( (v_{\text{min}} + v_{\text{max}})/2 \).

With such definitions for the system, the output image can be considered to be a modulated
version of the input image. For a small spatial frequency on the input image, the output image will exhibit a large swing between its minimum and maximum pixel signal values; for a high spatial frequency on the input image, the output image will instead exhibit a small swing between its minimum and maximum pixel signal values. Thus, these spatial characteristics are similar to the input/output characteristics of signals passing through a system having a low-pass transfer function. In the following section, the above definitions will be applied to imaging tests of the coupled MLAs.

![Figure 4.8](image)

Figure 4.8. Sketch of (a) a representative black-and-white test pattern being applied to the microdisplay versus the horizontal dimension and (b) its resulting image captured by the camera showing a profile of pixel signal values versus the horizontal dimension. The figures show a pixel frequency of $f_p$ in pixels/cycle and the resulting minimum value of $v_{\text{min}}$ and maximum value of $v_{\text{max}}$ in the profile of pixel signal values.

4.3 Testing

The imaging tests of the coupled plano-concave and plano-convex MLAs are presented in this section. The following three subsections give details on the alignment, processing, and results.

4.3.1 Alignment

The alignment procedure for the coupled plano-concave and plano-convex MLAs can be divided into translational and rotational alignment.

For translational alignment, the plano-concave and plano-convex MLAs are translated along the $x$, $y$, and $z$-dimensions. The translation is enabled by having the MLA mounts be fixed to $xyz$-translation stages (Thorlabs DT12XYZ) that provide a range of 12.7 mm and micron-scale resolution. The stages are adjusted to have the plano-concave MLA be parallel to and concentric
with the plano-convex MLA. In this way, the optical axis of the system passes through the centre of both MLAs.

For rotational alignment, the plano-concave and plano-convex MLAs are aligned by rotating the relative orientation of their MLA mounts. The plano-convex MLA is kept fixed while the plano-concave MLA is rotated in its rotational mount (Thorlabs rotation mount CRM1), shown in Figures 4.4(c) and (d), which has a resolution of 0.1°. The rotation of the MLA changes the number of fringes seen in the Moiré pattern generated by the coupled MLAs, and the alignment is optimal when the number of fringes is minimized.

### 4.3.2 Processing

Once the plano-concave and plano-convex MLAs are aligned, the coupled MLAs can be tested. To do this, the camera is adjusted to simulate a human eye in the relaxed state. Specifically, its focal length is adjusted to 35 mm, to simulate the FOV_A of the human eye, and its focus is adjusted to be infinity. A preliminary test is then carried out by applying an image of the letter “A” to the microdisplay. The distance between the microdisplay and coupled MLAs and the distance between the coupled MLAs and camera are then adjusted until a sufficiently clear image of the letter “A” is seen on the camera. Figure 4.9 shows the image captured by the camera when the letter “A” is applied to the microdisplay. Figure 4.9(a) shows the image without the coupled MLA; Figure 4.9(b) shows the image with the coupled MLA. It is important to note that this result is a virtual image generated by the coupled plano-concave and plano-convex MLAs without a baffle between them to block light that does not pass through the microlenses. Thus, light that is not refracted by the microlenses is captured in the image and this is seen as blurriness. The baffle will be introduced later in this work to minimize this blurriness.
Figure 4.9. The image captured by the camera when the letter “A” is applied to the microdisplay without the coupled MLA (a) and with the coupled MLA (b). This image is formed by the coupled plano-concave and plano-convex MLAs without a baffle between them.

Once a sufficiently clear image of the letter “A” is projected by the coupled plano-concave and plano-convex MLAs and captured by the camera, black-and-white test patterns are applied to the microdisplay. The test patterns are generated with the desired spatial frequencies and are projected through the coupled MLAs. The resulting images are captured by the camera and processed according to the definitions in section 4.2. Specifically, the minimum pixel signal value, $v_{\text{min}}$, and maximum pixel signal value, $v_{\text{max}}$, are extracted and assumed to be linearly proportional to the respective minimum luminance value and maximum luminance value striking the image sensor. This assumption is made valid because the auto-gain/contrast is kept off during the image capture. Thus, the modulation depth of the image, being one-half the peak-to-peak swing in luminance values divided by the mean of the luminance values, can be written in terms of the pixel signal values as

$$\text{Modulation depth} = \frac{v_{\text{max}} - v_{\text{min}}}{v_{\text{max}} + v_{\text{min}}}. \tag{39}$$

This modulation depth is computed for test patterns being applied to the microdisplay with varying spatial frequencies. The resulting distribution of modulation depth versus spatial frequency is the desired MTF for the system.

A MATLAB code is written and applied to carry out the above procedure of extracting the minimum and maximum pixel signal values, computing the modulation depths, and formulating
the overall MTF. The MATLAB code is shown in Appendix C, and representative results are shown in Figure 4.10 from the application of a tangential test pattern with $f_s = 0.8$ cycles/mm to the microdisplay. The captured image is shown in Figure 4.10(a), and the corresponding pixel signal values are shown in Figure 4.10(b) as a function of the horizontal dimension. The latter figure shows the raw data as a red curve and the finalized data as a blue curve. The finalized data is produced by bandpass filtering the Fourier transform data around the spatial frequency of the black-and-white test pattern and inverse Fourier transforming the result. Such a process rejects noise at lower and higher spatial frequencies than the spatial frequency of interest and generates an image that is similar to the raw data image—but with more clear minimum and maximum values. The minimum and maximum pixel signal values are then used to compute the modulation depth. This process of generating modulation depths is repeated for test patterns with various spatial frequencies, and the overall MTF is created by the MATLAB code.

Figure 4.10. The (a) image captured by the camera and (b) resulting pixel signal values versus the horizontal dimension for a test pattern with a spatial frequency of $f_s = 0.8$ cycles/mm. In (b), the raw data is shown as a red curve and the finalized data is shown as a blue curve that results from bandpass filtering of the Fourier transform around the spatial frequency of the black-and-white test pattern.
4.3.3 Results

The aforementioned alignment and processing procedures are carried out to test the imaging capabilities of the coupled plano-concave and plano-convex MLAs, with and without the baffle, and the results are presented in this subsection.

The MTF results of the coupled MLAs with and without the baffle are shown in Figure 4.10 as solid black circles and red crosses, respectively. The figure shows the modulation depths as a function of spatial frequency, $f_s$, for the optimized coupled MLA structure, with and without the baffle, that was designed according to Chapter 2 and fabricated according to Chapter 3 with the physical parameters shown in Table 3.6. The figure also shows a (theoretical) solid blue curve of the modulation depth versus spatial frequency for the optimized coupled MLA structure with the baffle having been generated from 61 ray-based simulations.

Two key observations can be made from the results of Figure 4.11. First, it can be seen that there is strong agreement between the experimental and theoretical MTF curves for the coupled MLAs with a baffle. The experimental results exhibit a standard deviation from the theoretical results of only 7.9%. Thus, it can be concluded that the ray-based simulations yield an accurate understanding on the functioning of the coupled MLAs. Second, it can be seen that the baffle plays an important role in blocking light that passes between the microlenses and improving the resolution of the coupled MLAs. The coupled MLAs without the baffle yield a maximum MTF of 20 cycles/mm, while the coupled MLAs with the baffle yield a maximum MTF of 30 cycles/mm. This latter result is indicative of strong imaging performance, and it suggests that the optimized coupled MLAs and baffle can function effectively as a Gabor lens in accordance with Criterion II. At the same time, Criterion I and Criterion III are met by this structure, because its FOV was measured to be equal to 18.2° and its overall length was defined by the original design at 11.4 mm.
4.4 Packaging

As a final step in the design and implementation of coupled MLAs as a heads-up display, it is necessary to create a monolithic package for the microdisplay and coupled MLAs. The work for such packaging is carried out through a partnership with Intel Corp., formally Recon Instruments Inc., and its goal is to integrate the microdisplay and coupled MLAs as a heads-up display within their Recon Jet™ eyewear. The packaging is carried out via the preparation and integration of the coupled MLAs and microdisplay, as described in the following two subsections.

4.4.1 Preparation of the coupled microlens arrays and microdisplay

The first step in preparing the coupled MLAs and microdisplay for packaging pertains to a reduction in the size of the coupled MLAs. The plano-concave and plano-convex MLAs were formed on PDMS and glass substrates, respectively, with both having a size of 25 mm × 25 mm. However, the actual plano-concave MLA, having 20×20 microlenses with a diameter of 300 µm and pitch of 466 µm, only spans an area of 9.154 mm × 9.154 mm, while the actual plano-convex MLA, having 20×20 microlenses with a diameter of 350 µm and pitch of 440 µm, only spans an
area of 8.725 mm × 8.725 mm. Thus, it is necessary to reduce the substrate sizes of the plano-concave and plano-convex MLAs, as this will make the heads-up display more compact.

The sizes of the plano-concave and plano-convex MLAs on their substrates should be made equal and have a small border to facilitate their mounting. Given these constraints, and the 8.0 mm × 6.0 mm area of the microdisplay, the sizes of the plano-concave and plano-convex MLAs on their substrates are both set at 11.0 mm × 11.0 mm.

The cutting of the substrates for the plano-concave and plano-convex MLAs is done with careful attention to their materials. The material for the plano-concave MLA substrate is PDMS, which is very flexible, so its substrate can be easily trimmed to the desired dimensions of 11.0 mm × 11.0 mm with a razor blade. In contrast, the material for the plano-convex MLA substrate is glass, which is far more difficult to cut, and the substrate is quite fragile because it is only 100 µm thick. With this in mind, a holder was designed via SolidWorks® for the cutting of the plano-convex MLA substrate, and it was fabricated with a high-resolution 3-D printer (Connex 500) having a resolution of 6 µm. The holder firmly holds the plano-convex MLA substrate in place between two layers, which prevents cracking while the substrate is cut with the razor blade. With this holder, the plano-convex MLA substrate is effectively cut to the desired size of 11.0 mm × 11.0 mm.

The second step in preparing the coupled MLAs and microdisplay for packaging pertains to the creation of a mounting bracket. This mounting bracket holds the microdisplay, plano-concave MLA, and plano-convex MLA with the correct positions and alignment, and it is made of two parts. The first part of the mounting bracket firmly holds the plano-concave and plano-convex MLAs together while parallel to each other and with the correct separation, i.e., leaving a physical gap of 50 µm to hold the baffle. The part is shown in Figure 4.12(a). It is designed in SolidWorks® and printed by a high-resolution 3-D printer (Connex 500) having a 6 µm resolution. The part has dimensions of 12.0 mm × 12.0 mm × 12.0 mm, and it has inset squares on opposing sides. The inset square on one side has dimensions of 11.2 mm × 11.2 mm × 11.0 mm, where the dimensions of 11.2 mm are selected to accommodate the width of the plano-concave MLA, and the depth of 11.0 mm is selected because it is the sum of the distance from the microdisplay to the plano-concave MLA and the thickness of the plano-concave MLA. The inset square on the opposing side has dimensions of 11.2 mm × 11.2 mm × 1.0 mm, where the dimensions of 11.2 mm are selected to accommodate the width of the plano-convex MLA, and the depth of 1.0 mm is selected to
accommodate the 131.8 µm thickness of the plano-convex MLA and offer protection. The second part of the mounting bracket holds the microdisplay. It is shown in Figure 4.12(b). The part has overall dimensions of 11.0 mm × 8.8 mm × 4.0 mm, with a rectangular slot measuring 8.1 mm × 6.1 mm × 2.0 mm. The slot houses the microdisplay, which has corresponding dimensions of 8.0 mm × 6.0 mm × 2.0 mm. Ultimately, these parts house the plano-concave MLA, plano-convex MLA, and two baffles.

The baffles are fabricated by way of a laser micromill (Oxford A series). The micromill is used to drill microholes in a 25-µm-thick aluminium foil sheet. The diameters of the microholes on the two baffles are made equal to the diameters of the plano-concave and plano-convex microlenses. An image of one of the baffles is shown in Figure 4.13(a). These baffles are then aligned onto their respective plano-concave and plano-convex MLAs under a microscope to have the microholes line up with the microlenses. The result for one baffle is shown in Figure 4.13(b).

With the coupled MLAs, the baffles, and the microdisplay implemented into their corresponding positions, and fixed by curing with NOA 65, the two parts are then glued together to form the final package.

![Figure 4.12](image.png)

**Figure 4.12.** Schematics of the mounting bracket used to firmly hold the plano-concave MLA, plano-convex MLA, and microdisplay, showing its (a) part for holding the plano-concave and plano-convex MLAs, with the baffle, and its (b) part for holding the microdisplay. The overall dimensions of the part in (a) are 12.0 mm × 12.0 mm × 12.0 mm, and the overall dimensions of the part in (b) are 11.0 mm × 8.8 mm × 4.0 mm.
4.4.2 Integration of the coupled microlens arrays and microdisplay

The plano-concave MLA, plano-convex MLA, baffle, and microdisplay are all integrated within the aforementioned mounting bracket to form a monolithic package. The package, with dimensions of 12.0 mm × 12.0 mm × 4.6 mm, is shown in the photographs of Figure 4.14. Figure 4.14(a) shows a wide image of the package with a Canadian 10-cent coin giving visual scaling; Figure 4.14(b) shows a close-up image of the package while it displays the digits “78”.

Figure 4.13. Images of (a) a baffle fabricated by the laser micromill (b) a baffle having been aligned and mounted onto the plano-convex MLA.

Figure 4.14. Photographs of the monolithic package of the heads-up display as (a) a wide image, with a Canadian 10-cent coin for visual scaling, and (b) a close-up image while it displays the digits “78”.
Following the assembly of the coupled MLAs and microdisplay within the mounting bracket, the monolithic package is mounted into Recon Jet™ eyewear. Representative photographs of the front and rear view of the fully-integrated Recon Jet™ eyewear are shown in Figures 4.15(a) and (b), respectively, and representative distant and close-up photographs of the projected images from its heads-up display are shown in Figures 4.15(c) and (d), respectively.

![Image](image_url_a)

![Image](image_url_b)

![Image](image_url_c)

![Image](image_url_d)

Figure 4.15. The fully-integrated Recon Jet™ eyewear containing the coupled plano-convex and plano-concave MLAs and microdisplay shown as a (a) photograph of the front of the eyewear, (b) photograph of the rear of the eyewear, (c) distant photograph of the projected image from the heads-up display, and (d) close-up photograph of the projected image from the heads-up display. In (c) and (d), the digits “78” are displayed.
4.5 Summary

In this chapter, the results from testing of the coupled MLAs were presented. Details were given on the setup, procedures, testing, and packaging. The setup was created to allow for translation and rotation of the coupled MLAs while they projected images of the microdisplay to a camera focused at infinity. Procedures were then developed to characterize the imaging resolution of the coupled MLAs. In doing so, modulation depths would be measured for test patterns having various spatial frequencies. The overall trend of the modulation depths would then define the MTF and set the imaging resolution in units of cycles/mm. Testing was then carried out, and it was found that the coupled MLAs with a baffle could meet all three of the design criteria for this work and establish an imaging resolution of 30 cycles/mm. This was far better than that achieved without the baffle, which gave an imaging resolution of 20 cycles/mm. Based on the results, the plano-concave and plano-convex MLAs were assembled with the baffle and mounted with the microdisplay to form a fully-integrated heads-up display for Recon Jet™ eyewear. The heads-up display gave clear images of the microdisplay and a factor of two reduction in thickness of the display, in comparison to the existing design for Recon Jet™ eyewear, which uses conventional lenses. The findings suggest that MLA technology can provide strong imaging performance in applications with tight size constraints, such as heads-up displays. Comparisons of the design criteria and complete test results of the developed heads-up display are summarized in Table 4.1.

<table>
<thead>
<tr>
<th>Design criteria</th>
<th>Test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>The design should project an image of the microdisplay into the relaxed eye, focused at infinity, with an FOV$_\alpha$ between 15º to 25º.</td>
<td>The developed heads-up display projects an image of the microdisplay at infinity, for the relaxed eye, with an FOV$_\alpha$ of 18.2º.</td>
</tr>
<tr>
<td>The design should yield an image of the microdisplay with a resolution defined by its MTF of 30 cycles/mm or greater.</td>
<td>The developed heads-up display yields an MTF with a resolution of 30 cycles/mm, using baffles between the MLAs.</td>
</tr>
<tr>
<td>The design should be implemented with a flat form factor having the sum of its focal length and the separation between its MLAs being less than 23.4 mm.</td>
<td>The developed heads-up display achieves a flat form factor, in that the sum of its focal length and the separation between its MLAs is 11.4 mm.</td>
</tr>
</tbody>
</table>
Chapter 5: Conclusions

In this chapter, the work introduced in this thesis on MLAs and heads-up display technology is summarized and conclusions are made. Future work on improving the imaging performance and compactness of the developed technology is also discussed.

5.1 Conclusions from the presented work

The work introduced in this thesis recognized the growing demand for heads-up displays in emerging eyewear for virtual reality and augmented reality systems. The heads-up displays must form magnified images into relaxed human eyes while being compact. This can be especially challenging for a conventional lens, however, because such a lens would need to balance mutually exclusive demands for a high radius of curvature and flat form factor. The work put forward here recognized this challenge and took an alternative approach by applying coupled plano-concave and plano-convex MLAs as a Gabor lens within the heads-up display. To this end, the coupled MLAs were developed to meet three key design criteria: Criterion I would have the coupled MLAs project an image of the microdisplay into the relaxed eye, focused at infinity, with an FOV\(_A\) between 15\(^\circ\) to 25\(^\circ\); Criterion II would have the image projected by the coupled MLAs yield a resolution of 30 cycles/mm or greater; Criterion III would have the coupled MLAs be implemented with a flat form factor having the sum of its focal length and separation between its MLAs be less than 23.4 mm. The work put forward in this thesis showed the design, fabrication, and testing of coupled MLAs in a heads-up display that meet these criteria.

Chapter 2 in this thesis showed the design of the coupled MLAs. The design work was carried out by optimizing the values of the physical parameters of the coupled plano-concave and plano-convex MLAs to have them function according to the above criteria. The coupled MLAs were first analysed via an elementary model that applied thin-lens approximations and aggregate parameters to enable the use of ray transfer matrices and create tractable solutions. This gave a general understanding for the functioning of the coupled MLAs. The coupled MLAs were then analysed via a physical model that characterizes the system with thick-lens equations and physical characteristics such as radii of curvature, thicknesses, diameters, etc. The analyses were carried out by ray-based (Zemax OpticStudio\textsuperscript{®}) simulations to accommodate the increased complexity of
this model. The values for the multitude of physical parameters were optimized via tradespace analyses. Ultimately, it was concluded that the coupled MLAs could be optimized and integrated with a baffle for functioning according to the three design criteria.

Chapter 3 in this thesis targeted the fabrication of the coupled MLAs that were designed in the prior chapter. A tunable dispensing process was developed to fabricate the MLAs with the necessary values and tolerances. It applied a plasma pre-treatment to the glass substrate followed by dispensing and curing of microdroplets on the substrate to form microlenses across a plano-convex MLA. The plano-convex MLA could then be used as is or used as a mold to cast the plano-concave MLA. Characterizations were carried out to identify the necessary process parameters of the plano-concave and plano-convex MLAs, including the plasma pre-treatment to the substrate (RF power and treatment time), dispensing pressure and time, actuation velocity and acceleration, dwell time, needle-tip-to-substrate spacing, and PDMS parameters (mix ratio, weight, curing time, curing temperature). Ultimately, it was concluded that the optimal coupled MLAs could be fabricated with the tunable dispensing process—with a fabrication cycle time that is substantially shorter than that of the standard thermal reflow process. The optimal plano-concave and plano-convex MLAs were then fabricated and integrated with a baffle and microdisplay for testing as a heads-up display.

Chapter 4 in this thesis presented results from testing the imaging capabilities of the developed heads-up display. It showed the development of the setup and procedures as well as results from testing and packaging. Testing revealed that the coupled plano-concave and plano-convex MLAs together with a baffle could establish the necessary resolution of 30 cycles/mm. Such a finding was in good agreement with a (theoretical) ray-based simulation of the system and was far better than the 20 cycles/mm achieved by the analogous system without a baffle. It was concluded that the coupled plano-concave and plano-convex MLAs together with a baffle could meet Criterion I, by projecting an image of the microdisplay into the relaxed eye with an FOV of 18.2°, meet Criterion II, by projecting an image with a resolution of 30 cycles/mm, and meet Criterion III, by having a flat form factor with the sum of its focal length, the thickness of the MLAs and MLA separation being 11.4 mm. The microdisplay and coupled MLAs were then integrated into a monolithic package for Recon Jet™ eyewear and the overall project was deemed to be a success.
5.2 Recommendations for future work

The proposed work can be seen as a launching point for further developments and use of MLAs. Recommendations for such future work, by refining the fabrication process and enhancing the imaging performance, are given in this section.

Refinements can be made to the fabrication process by broadening the range of the values that can be achieved for the physical parameters of the MLAs, such as the diameter and radius of curvature, and improving the uniformity of the fabricated MLAs. First, to broaden the range of parameter values, the pneumatic sub-system could be modified to operate with higher pressures and longer dispensing times with a higher gauge needle tip, having a smaller inner diameter, or even a micropipette, which can have an inner diameter as small as 10 µm. This would allow for the fabrication of especially small microlenses and open the door to other applications, such as near-field imaging [39], light-field display [40], and beam shaping [41]. However, through such work it should be noted that the microlenses would be increasingly susceptible to diffractive effects as their scale is reduced and it would be necessary to transition to wave-based (e.g., finite-difference time-domain) simulations. Second, to improve the uniformity of the fabricated MLAs, the actuation and monitoring sub-systems could be further developed. Specifically, it was noted during the presented work that the position of the needle tip in the $z$-dimension could accumulate errors during the operation and the finite tolerance in thickness across a glass coverslip could contribute to nonuniformity in the microlenses across a given MLA. To mitigate these issues, a future microlens fabrication system could use a closed-loop implementation for its actuation and monitoring sub-systems. Thus, it would use sensors and encoders to track the height between the needle tip and substrate and implement the appropriate adjustments in the $z$-dimension. This would both improve the uniformity across a given MLA and the reproducibility between multiple MLAs.

To enhance the imaging performance of the coupled MLAs, greater freedom can be allowed in the distribution of microlenses across the array. The presented MLAs used a square lattice to distribute the microlenses, and this led to confocal imaging between the coupled MLAs only along two transverse axes, i.e., two axes being perpendicular to the optical axis. If a different lattice is used, however, it should be possible to produce improved imaging performance. For example, a close-packed lattice could be used to allow for larger microlenses, and larger micro-holes in the baffle, with closer spacings [42]. This would increase the brightness of the image resolved on the
retina in proportion to fill factor. At the same time, it should be possible to analyse the imaging performance for all transverse angles around the optical axis, rather than just the two transverse axes, and modify the lattice to maximize the resolution achieved across all these angles. This would improve the clarity of the resolved image—and offer further motivation for the use of coupled MLAs in future imaging applications.
Bibliography


Appendices

Appendix A – Plano-convex MLAs fabrication procedure

Note: This Operating Procedure is given for the dispensing of a 12 × 12 mm² plano-convex MLA on a 22 × 22 mm² glass coverslip (Cat#: 72198-10 Thickness: #0). The instructions are for the fabrication system in the Integrated Optics Laboratory in The University of British Columbia’s Okanagan campus.

1. Lighting System
   a. Turn on Flashlight
   b. Turn on LED Ring

2. Motor Control System
   a. Plug in Micro-controller USB Cable to computer from T-Cube Hub
   b. Turn on USB Micro-Controller Power Supply
      i. If power was on, then ignore instruction 6.b - 6.h.
      ii. If power was off, then proceed as indicated.

3. Nordson EFD Ultimus V
   a. Switch on.
   b. Ensure that cable from the Nordson EFD Ultimus V is connected via USB.

4. PC
   a. Turn on PC.
   b. Ensure that the required peripherals are connected via USB.
      i. The Nordson EFD Ultimus V should be connected
      ii. The CMOS Camera should be connected
   c. Open Thorcam software (Now See Thorcam setup).
   d. Open LabView software (Proceed to LabView setup).

5. Thorcam Setup
   a. Select camera (C1284R13CC) from camera dropdown menu.
   b. Drag window to from primary monitor to secondary monitor.
   c. Click “Start Capture”.

6. LabView Setup

a. Click “Run” and then immediately continuously click “Stop” button until the clicking action no longer responds, and the position values appear in red digits in the MG17 Motor \( x, y, \) and \( z \), Displays.

**Note:** It is recommended to reduce the Jog Step Size and Move Step Size to prevent long sudden movements that can damage the needle tip, glass coverslip or the actuators.

b. Move the Needle Tip clear from the travel path of the Dispensing Stage.

c. Move the UV Fiber clear from the travel path of the Dispensing Stage.

d. Move any other obstructions clear from the travel path of the Dispensing Stage.

e. Click “Home/Zero” on the MG17 Motor \( x, y, \) and \( z \), Displays in LabView.

f. Place a glass coverslip on the Dispensing Stage.

h. Manually move the Needle Tip to the \((x, y)\) starting position (0,0) in the top left corner, shown as the red circle in Figure C1. Fix the “height” of the needle tip to be within the 1mm \( z \)-travel defined in step 6.g.
Figure A.1. Top and side view of the coverslip and 25mm x 25mm coverslip holder.

i. Adjust the CMOS camera so the Needle Tip and coverslip are visible.

j. Ensure that the UV \textit{in situ} Fiber is situated to cure the lenses that are directly next to the Needle Tip in the Y direction.

k. Move the Dispensing Stage to the (17, 17, z) position. Notice that, in fact, different dispensing platform has its own flat regions. These above-mentioned numbers may vary according to the setup.

l. Acquire the $z$ location ($z_0$) where the Needle Tip can be seen just above the coverslip on the ThorCam Live View. Raise the Needle Tip sufficiently to prevent contact with the coverslip while displacing around the $xy$ plane.

m. Click on “Settings” of the MG17 Motor $z$ Display and enter the desired “Backlash Correction” value (located in bottom left corner).

n. Continue to the (5, 17, z), and (17, 5, z) locations and adjust the leveling of the Dispensing Stage with the adjustment knobs until each location has the same $Z_0$ position within $\sim 50\ \mu$m. This will ensure that the Glass Cover Slip is flat enough so that all dispensed microlenses are successfully “collected” by the Dispensing Stage.
7. LabView Dispensing Operation

a. This next section will assist in entering the parameters of the MLA to be dispensed. The “Moving Interval Y” and “Moving Interval X” should be the same. Given that “Moving Intervals Y and X” are the same, the “Start Position Y” and “Start Position X” should be the same. They can be calculated by the formula below:

\[
\text{Start Position} Y = \text{Start Position} X = \frac{22 - (\text{Moving Interval} X \times \text{Array Number} X)}{2}
\]

b. Using the \( z_0 \) location as the reference, fill in the “Start Position Z” and “Moving Interval Z” values. Remember to account for the “Backlash Correction” (see 6.m) of the MG17 Z Motor.

c. Set Array Number Y = 20 and Array Number X = 20 (if you are looking for a \( 20 \times 20 \) MLA). The revised LabVIEW algorithm allows the UV fibre to have an additional 5-row motion such that UV \textit{in situ} Fiber is capable of curing rows 15-20 adequately.

d. The “Initial Dispensing Y and X” can be changed to whatever is desired, though \((5, 5)\) is recommended. Ensure that the “Initial Dispensing Position Z (mm)” matches the “Start Position Z” value. It is recommended that the “Initial Moving Interval Z” is less than the “Moving Interval Z”.

e. Set up the actuator velocity and acceleration values for MLA dispensing. In general, 0.5 mm/s and 0.5 mm/s\(^2\) are recommended for actuator velocity and acceleration, respectively. Similarly, for the actuator velocity and acceleration values during UV \textit{in situ} curing, 0.25 mm/s and 0.25 mm/s\(^2\) are desired, respectively.

f. Adjust the “Initial Dispensing Pressure” settings as desired, though the default values should be fine to use.

g. Lastly, enter the “Microlens Dispense Time (ms)” (use 180 for all NOA’s except for NOA 68, where values between 100 and 200 can be used) and the “Microlens Pressure Setting (/10)” values. Note the pressure is divided by 10.

h. Turn on the UV \textit{in situ} curing sub-system and set desired current settings to control the output UV optical power. The current setting can be adjusted by the user to better
customize the MLA properties.

i. Press “Start” and overview the 1st row of dispensing. If there are no problems then the MLA should be fine to dispense on its own.

j. When the MLA is finished dispensing, move the Dispensing Stage up to 22mm > Z > 16mm to allow for easy removal of the dispensed MLA with the glass coverslip. Place the dispensed MLA in an external UV curing box to further solidify the MLA. Reset the “Backlash Correction” to desired amount as this resets to its own default after every completed array. Insert a new glass coverslip and change any settings as desired. If finished dispensing, then proceed with the “Shutdown Checklist.”

8. Shutdown Procedure

   a. Turn off Power of the UV in situ curing sub-system
   b. Turn off and unplug the external UV curing box
   c. Turn off Nordson EFD Ultimus V
   d. Close LabView and Thorcam software on PC
   e. Put computer to sleep
   f. Turn off flashlight and LED ring
   g. Close curtain
Appendix B – Plano-concave MLAs fabrication procedure

Note: This Operating Procedure is given for the fabrication of a plano-concave MLA. The instructions are intended for fabrication in the Integrated Optics Laboratory in The University of British Columbia’s Okanagan campus.

1. PDMS Weight Measurement
   a. Put the small cylindrical container on the scale and centre it. Close the scale doors, and press tare to zero the weight as shown in Figure B1.

   ![Figure B.1. Zeroing the container weight.](image)

   b. Using either a syringe or a pipette (seen Figure B2), carefully transfer the PDMS resin into the cylindrical container.

   ![Figure B.2. Two types of liquid transfer tools: a disposable syringe (left) and a disposable pipette (right).](image)

   c. Transfer the Sylgard 184 curing agent into the cylindrical container. Typically, 5:1 or 10:1 ratio by weight is used for the resin and the curing agent. That is, for every 1 gram
of the PDMS resin, use 0.2 gram curing agent (5:1 ratio) or 0.1 gram curing agent (10:1 ratio). Be aware that different mixing ratio will require different curing time. In Figure B3, 4 grams of the PDMS resin and 0.8 gram of the curing agent were used. Use a glass stir stick to slowly mix the curing agent with the PDMS resin until the PDMS mixture becomes milky, i.e., full with lots of air bubbles.

Figure B.3. Weighting the PDMS resin and curing agent.

2. Air Bubbles Removal from the PDMS Mixture
   a. Once the PDMS mixture is prepared, one will notice lots of air bubbles are generated from stir-mixing the PDMS resin and curing agent. Cover the cylindrical container with a small piece of plastic wrap and put a lid on the container. Snap it onto the floating vessel as shown in Figure B4.

Figure B.4. PDMS container snapped onto the floating vessel.
b. Float the container and vessel in the ultrasonic bath. Turn on the timer for 30–40 minutes (Figure B5). No need to turn on the heater. Be aware that the vessel does not have enough clearance from the water level, so if the container is too heavy, it might sink.

Figure B.5. PDMS container and vessel floating in the ultrasonic bath.

c. After the ultrasonic bath, take the vessel out and separate the PDMS container. Grab a square plastic container (139-17, TED Pella Inc.) and break it into two identical pieces. Use one of them for the next step.

d. Using a pipette/syringe to transfer a couple of PDMS droplets onto the square plastic container as shown in Figure B6, and then place the plano-convex MLA coverslip right onto PDMS droplets. Use the glass stir stick to carefully and gently press the plano-convex MLA coverslip down and make sure there is no volume of air trapped in between coverslip and plastic container. Less than 0.1 gram of the PDMS should be enough. This is to ensure the plano-convex MLA coverslip stick to the bottom of the plastic container. (Notice: try to avoid putting the plano-convex MLA coverslip onto the projected numbers at the top left corner of plastic container.)
Figure B.6. A half of the square plastic container with a few droplets of PDMS deposited, before putting in the plano-convex MLA coverslip.

e. We can control the thickness of the resulting plano-concave MLA by controlling the volume of the PDMS that we pour onto the plano-convex MLA coverslip. Assuming the PDMS resin + curing agent mixture has a density of ~965 kg/m$^3$, about 0.8 g poured ON TOP of the plano-convex MLA coverslip (not accounting for the previous droplets) will produce $\sim 1 \pm 0.1$ mm thick concave MLA, in the same square plastic container in Figure B6.

f. Before curing the PDMS, one needs to make sure the poured PDMS layer is flat in the square plastic container. In order to achieve this, put the red centering piece and put the square plastic container with PDMS in the center of a Petri dish. Turn square plastic container so that the corners of the container are right against the four small red pillars at the center of the centering piece (shown in Figure B7).

g. Put the petri dish with the centred square plastic container into ultrasonic bath for about 20 minutes. This will make sure there is no air trapped in between plano-convex MLA coverslip and square plastic container as well as the flat/uniform PDMS layer on top of plano-convex MLA coverslip.
3. Curing Process

a. After 0.8 g of PDMS is flattened, take the petri dish with the centred square plastic container out of ultrasonic bath. Prepare a floating dish for curing in the Oven.

b. Take a Petri dish lid, and pour some water in the lid (Figure B8). Lid is bigger in diameter than the dish.

c. Float the Petri dish in the water-filled lid (Figure B9).

d. Put the floating Petri dish pair into the oven heated to 60°C (corresponds to ~2.8 on the dial). Cure for about 36–40 minutes.
e. After curing, cut the concave MLA with a Xacto knife by tracing the outline of the black cutting template.

Figure B.9. The dish with the centering piece and PDMS container floating on the lid.
Appendix C – MATLAB code for MTF test

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MTF test code
% %
% % Description: The following codes select the area of the imaged test patterns and calculate the modulation depths
% % Author: Weicheng (Alec) Yan, University of British Columbia, 2017.05.04
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clearvars; close all; clc;

% Read the image of the pattern and detect the size
pattern = imread('IMG_6056.JPG');
size_pattern = size(pattern);

% Crop the image with only the part of the test pattern
pattern_crop = pattern(2069:2133, 1861:2156, :);
szie_crop = size(pattern_crop);

% Save the image to visualize if correct area is selected
imwrite(pattern_crop, 'pattern_crop.jpg');

% Parameters setting
half_bandgap = 7;
pattern_width = size(pattern_crop, 1);
pattern_length = size(pattern_crop, 2);
luminance = 0;
luminance_array = zeros(pattern_width, pattern_length, 'double');
r = 0;
g = 0;
b = 0;

% Calculation of the relative luminance from the RGB of the pattern
for i = 1:pattern_width
    for j = 1:pattern_length
        if (double(pattern_crop(i,j,1))/255) > 0.03928
            r = ((double(pattern_crop(i,j,1))/255 + 0.055) / 1.055)^2.4;
        else
            r = 0;
        end
        g = 0;
        b = 0;
end
r = (double(pattern_crop(i,j,1))/255 + 0.055)/12.92;
end
    if (double(pattern_crop(i,j,1))/255) > 0.03928
    g = ((double(pattern_crop(i,j,2))/255 + 0.055) / 1.055)^2.4;
    else
    g = (double(pattern_crop(i,j,2))/255 + 0.055)/12.92;
    end
    if (double(pattern_crop(i,j,1))/255) > 0.03928
    b = ((double(pattern_crop(i,j,3))/255 + 0.055) / 1.055)^2.4;
    else
    b = (double(pattern_crop(i,j,3))/255 + 0.055)/12.92;
    end
    luminance = 0.2126 * r + 0.7152 * g + 0.0722 * b;
    luminance_array(i,j) = luminance;
end
end

% Fast Fourier transform of the luminance array
luminance_fft = zeros(size(luminance_array));
for i = 1:size(luminance_fft,1)
    luminance_fft(i,:) = fftshift(fft(luminance_array(i,:)));
end

% 1st inverse Fourier transform without filtering just to check if the
% Fourier and inverse Fourier transforms work or not.
luminance_ifft = ifft2(luminance_fft);
figure;
plot(-size(luminance_fft,2)/2:(size(luminance_fft,2)/2-1),
    abs(luminance_fft(5,:)));
title('Fourier Transform')
figure;
plot(-size(luminance_ifft,2)/2:(size(luminance_ifft,2)/2-1),
    abs(luminance_ifft(5,:)));
title('Inverse Fourier Transform without Filtering')

% Apply a bandgap filter to filter out the noise signals
luminance_fft_filter = luminance_fft;
for i = 1:size(luminance_fft_filter,1)
for j = 1:size(luminance_fft_filter,2)
    if j < size(luminance_fft_filter,2)/2-half_bandgap || j > size(luminance_fft_filter,2)/2+half_bandgap
        luminance_fft_filter(i,j) = 0;
    end
end
end

% Plot on the second inverse Fourier transform and the corresponding Fourier transform to evaluate the bandgap filter
luminance_ifft_filter = ifft2(luminance_fft_filter);
figure;
plot(-size(luminance_fft_filter,2)/2:(size(luminance_fft_filter,2)/2-1),
     abs(luminance_fft_filter(5,:)));
title('Filtered Fourier Transform')
figure;
plot(-size(luminance_ifft_filter,2)/2:(size(luminance_ifft_filter,2)/2-1),
     abs(luminance_ifft_filter(5,:)));
title('Filtered Inverse Fourier Transform')

% Plot the finalized figure with the original data (which is used in the thesis)
The original data is denoted by the blue curve while the filtered inverse Fourier transform data is denoted by the red curve, which is also the finalized data for the calculation of the modulation depth.
luminance_ifft_filter = abs(luminance_ifft_filter)/sum(sum(abs(luminance_ifft_filter)))*1000;
luminance_array = abs(luminance_array)/sum(sum(abs(luminance_array)))*1000;
figure;
plot(luminance_array(5,:),'b', 'linewidth', 2);
hold on;
plot(luminance_ifft_filter(5,:), 'r', 'linewidth', 2);
hold on;
legend('Raw data', 'Finalized data', 'location', 'north')