Planar waveguide solar concentrator with couplers fabricated by laser-induced backside wet etching

Nikai Zhang

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A Thesis

entitled

Planar Waveguide Solar Concentrator with Couplers Fabricated by Laser-Induced Backside Wet Etching

by

Nikai Zhang

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Engineering

Dr. Daniel Georgiev, Committee Chair

Dr. Anthony Johnson, Committee Member

Dr. Sarit Bhaduri, Committee Member

Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo

December 2013
Solar radiation can be converted directly into electricity by using the photovoltaic effect, which represents the principle of operation of solar cells. Currently, most solar cells are made of crystalline silicon and have a conversion efficiency of about 20% or less. Multi-junction solar cells, made of III–V compound semiconductors, can have efficiencies in excess of 40%. The main factor that prohibits such high-efficiency technologies from wider acceptance is the cost. An alternative approach to using large-area expensive solar cells is to employ lower cost optics and concentrate the solar radiation to smaller cell area, which is the basic principle of solar concentrators.

In this thesis, we consider a solar concentrator module that consists of a combination of a lens array and a slab waveguide with etched conical holes on one side of the waveguide, which are aligned with the lenslets. Sunlight coming through each of these lenslets is focused on the backside of the waveguide, where a coupling structure (an etched cone) is fabricated. This coupler changes the propagation direction of the incident light in such a way that light is guided through total internal reflection (TIR) within the
glass slab and eventually reaches a solar cell, which is properly mounted on the side of the slab.

The concept of this concentrated photovoltaic (CPV) system is based on a planar light guide solar concentrator module, proposed earlier by another group. This project builds on the original idea by including the following substantial modifications. The lens array is to be made of solid glass by a mold technology and provided to us by our industrial partner, Libbey, Inc., as opposed to silicone on glass technology, in which the lenses are made out of silicone and sit on a glass substrate. The coupling structures are cone-shaped holes etched directly into the solid glass waveguide, as opposed to coupling structures that are formed by addition of polymeric layer and consequent patterning. The fabrication of the etched holes in the glass is proposed to be based on a self-aligned process using a laser-induced backside etching (LIBWE) method, which is discussed in this project and its feasibility is examined.

The role of different parameters to the concentration level and the optical efficiency of the CPV system are studied by simulations in ZEMAX (which is a leading optical analysis/design software) using non-sequential ray tracing. The optical efficiency of this design under different light concentration level is studied and discussed. The main contributions of this research consist of a new design of a waveguide-based CPV system which can be made entirely of glass by a low-cost glass fabrication method, and a feasibility study in terms of critical fabrication steps and optical performance.
Acknowledgements

I would like to thank my advisor Dr. Daniel Georgiev for his guidance and support during my research. Dr. Georgiev is a passionate and responsible advisor, mentor and friend. I also would like to thank Dr. Anthony Johnson and Dr. Sarit Bhaduri for serving on my committee.

I am grateful to Libbey, Inc. for supporting my researches and providing the funding, and especially to Andrew Walsh for his help, opinions, and encouragement.

A special thanks to my fellow students Nanke Jiang, Ruozhu Duan, David Goodrich, not only for their helps in my research but also for the friendships making my experience at the University of Toledo more enjoyable. I would also like to express my appreciation to current and former staff members of the Electrical Engineering and Computer Science Department and Mechanical Industrial and Manufacturing Engineering department including: Tom Jacob, Christina Hennen, Sandra Stockard, Lisa Byers, and John Jaegly for their help and friendship during my time at the Univ. of Toledo.

Finally and most importantly, I would like to express my deepest gratitude to my parents and my girlfriend, whose love, support and encouragement made all this possible.
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List of Abbreviations

CNC .......................Computer Numerical Control
CPV .......................Concentrated Photovoltaic
CTE .......................Coefficients of Thermal Expansion
CTJ .......................Concentrating Triple Junction

DPSS .....................Diode Pumped Solid State

FLATCON ...............Fresnel Lens All-glass Tandem-cell Concentrator

HPC .......................Holographic Planar Concentrator

LESAL ....................Laser Etching at a Surface Absorbed Layer
LIBWE ....................Laser Induced Backside Wet Etching
LIPAA .....................Laser-induced Plasma Assisted Ablation
LSC .......................Luminescent Solar Concentrator

MJ ..........................Multi Junction

OPL .......................Optical Path Length

PV ..........................Photovoltaic

RB ..........................Rose Bengal

SEM .......................Scanning Electron Microscopy

TIR ..........................Total Internal Reflection
List of Symbols

<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{geo}$</td>
<td>Concentration Ratio</td>
</tr>
<tr>
<td>$C_{eff}$</td>
<td>Effective concentration Ratio</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>$T_g$</td>
<td>Glass transition temperature</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Half acceptance angle</td>
</tr>
<tr>
<td>$\eta_{optics}$</td>
<td>Optical efficiency</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Density</td>
</tr>
<tr>
<td>$K$</td>
<td>Degrees Kelvin</td>
</tr>
<tr>
<td>$n$</td>
<td>Refraction index</td>
</tr>
<tr>
<td>$f$</td>
<td>Focal length</td>
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</tbody>
</table>
Chapter 1

Introduction

1.1 Overview

Solar radiation is the most important energy source on earth. Other energy sources such as wind or non-renewable resources come indirectly from solar energy. On a sunny day, there are about 1,000 W of power incident on 1m$^2$ of earth surface. Learning to directly make use of solar energy is beginning to help us reduce the stronger and stronger demand of fossil-based energy. What is more, as a clean energy source, solar energy does not produce any greenhouse gas and pollution (excluding those created during the solar cell fabrication), which makes it more favorable and also more urgent to be implemented as widely as possible.

Solar radiation can be converted to thermal energy and electricity. Concentrated solar power (CSP) systems use mirrors or lenses to concentrate sunlight over a larger area to a smaller receiver which then converts light to heat. This heat can be directly used to heat buildings or to drive a steam turbine which is connected to an electrical power generator. However, CSP systems are more efficient for a large scale of space. Unlike CSP systems, solar cells directly turn solar radiation into electricity by using the photovoltaic (PV)
effects. PV systems can be applied to either large areas or small areas like roofs of buildings.

Crystalline silicon solar cells and thin film solar cells dominate the current PV market. Despite the reported highest efficiency of about 25% for silicon cells in lab research [1], the current silicon cells on the market have efficiency of about 15%. Solar cells are expensive to make and their manufacturing process can cause significant environmental pollution. Concentrated Photovoltaic (CPV) systems offer several benefits compared with conventional flat PV devices. First, the efficiency is higher; modules with 30% conversion efficiency are available [2]. Second, smaller semiconductor material usage not only reduces the cost but also helps reduce the manufacturing process pollution. Third, CPV systems have higher efficiency for hot and sunny locations.

In this thesis, we consider a CPV design, based on a planar light guide solar concentrator module, originally proposed by a group in UCSD [3]. This CPV system consists of three main elements: a micro-optic lens array, a common flat waveguide and etched holes as couplers on the backside of the waveguide. The principle of operation is as follows. First, light incident on the aperture of the lens array is focused onto the couplers on the back side of the waveguide. Second, these couplers change the light propagation direction to insure most of the light is then guided within the waveguide volume by TIR. Finally, the light reaches the edges of the waveguide and is absorbed by the solar cells attached to the edges. Compared to the original design, the novelties in the fabrication of this CPV structure are that (1) the etched couplers are obtained by directly structuring the slab waveguide (as opposed to adding the patterning additional polymer and metal layers), and (2) the couplers (etched conical holes) are formed by laser-induced
backside etching technology (LIBWE) on the backside of the waveguide. Self-alignment of each lenslet and hole is achieved by using this approach. High optical efficiency and acceptance angle are verified by the optical analysis/design software packages such as ZEMAX and Photopia, which use non-sequential optical ray tracing. The proposed module has a low profile, a relatively low mass and a reasonable high concentration ratio and optical efficiency, as well as a substantial mass manufacture potential.

1.2 Background on CPV Systems

The design of a CPV system requires the consideration of many different factors and constrains. Usually, the most important factors are cost and efficiency. Ideally, the goal is optimizing all the parameters to obtain the highest possible efficiency at the lowest price. However, in some cases, parameter requirements are contradictory. Attempting to improve the performance based on one parameter may not help because of adverse changes in other parameters. There are a number of tradeoffs which one needs to make in designing and fabricating a CPV system. Some common optical design considerations are introduced next.

1.2.1 Concentration Ratio

The concentration ratio is defined as the ratio between the area of the primary concentrator and the cell area.

\[
C_{geo} = \frac{\text{Input Area}}{\text{Output Area}}
\]  

(1.1)

Based on their concentration ratios, CPV systems are generally divided into low concentration systems (<10X), medium concentration systems (10X to 100X) and high
concentration systems (>100). Usually, the higher the concentration ratio, the more cell area is reduced, and more significant, most generally, is the larger cost reduction. However, sometimes higher concentration ratio means higher complexity. Additional parts like heat sink and tracking systems are required for high concentration CPV systems. In our design, the theoretical concentration ratio is flexible according to different goals. However, it is more suitable for medium concentration system.

There is an upper limitation of concentration ratio on the basis of the second principle of thermodynamics [4]. In two dimensional CPV systems, the maximum geometric concentration is related by the input radiation cone angle by:

\[
C_{\text{max}} = \frac{n}{\sin \theta}
\]  (1.2)

In three dimensions, the maximum concentration is defined by:

\[
C_{\text{max}} = \frac{n^2}{\sin \theta}
\]  (1.3)

Here, \( n \) is the index of refraction of the concentration material, and \( \theta \) is the half-angle of acceptance. The sun has an angular extent (or size) of \( \pm 0.26^\circ \) [5]. According to Eq. 1.2 and Eq. 1.3, the maximum concentrations for a 2D line focus CPV system is 220, and for a 3D point focus CPV system, it is 48,562.

### 1.2.2 Acceptance Angle

Acceptance angle is the maximum angle at which incoming sunlight can be captured by a solar concentrator. For an ideal concentrator, light with incident angles less than or equal to acceptance angle will be absorbed; for incident angles larger than the acceptance angle, the light will be lost. However, in practice, the real acceptance angle is defined as
the angle for which power collection drops to 90% of its maximum. Figure 1-1 shows the angular aperture of sunlight and the acceptance angle. \( \theta_s \) is the sun angular aperture of about \( \pm 0.26^\circ \), and \( \alpha \) is the half acceptance angle.

The acceptance angle is seen as a measure of how precise a tracking is needed. Usually, the smaller the acceptance angle, the more precise the tracking system needs to be; thus the system becomes more expensive. There are a number of factors that can decrease the acceptance angle such as the imperfections in the system or some aberrations of the lens. Therefore, it is very important to design a concentrator with the widest possible acceptance angle.

*Figure 1-1: Angular aperture of sunlight and its effect on the acceptance angle [6].*
1.2.3 Optical Efficiency and Effective Concentration

Optical efficiency, $\eta_{\text{optics}}$ of a CPV system is the percentage of light entering the optical system that reaches the solar cells. The design principle is to make optical efficiency as high as possible. However, due to different types of loss, for example, Fresnel loss or material absorption loss or light entering the system but is not collected by solar cell etc., optical efficiency can't be 100%. The optical efficiency defines how well the system uses the light entering the receiving aperture.

The effective concentration, $C_{\text{eff}}$ if defined by the product of concentration ratio $C_{\text{geo}}$, and optical efficiency $\eta_{\text{optics}}$. The product of the effective concentration and the incident irradiance (about 1,000 watts per sunny square meter) determines the actual incident irradiance on the solar cells.

$$C_{\text{eff}} = C_{\text{geo}} \cdot \eta_{\text{optics}} \quad (1.4)$$

1.2.4 Irradiation Uniformity

Real optic may not produce a uniform illuminated spot on the solar cell. For example, RXI system (in which ‘R’ represents refraction, ‘X’ represents reflection, and ‘I’ means total internal reflection) will have 20,000 suns in the center of the solar cell under 1200 average concentration level [7]. Irradiance uniformity is a measurement of the light distribution across the surface of the solar cell. Previous studies have shown that non-uniform illumination decreases the open circuit voltage and the fill factor and therefore the whole efficiency of the solar cells [8,9].

In addition to these adverse effects on the traditional single junction solar cells, non-uniform illumination on multi-junction solar cells leads to other problems. Tunnel
diodes of multi-junction (MJ) cells used in CPV limit the maximum irradiance and concentration level over the cell [10]. In addition, MJ cell efficiency may decrease because of the current mismatch between junctions [11]. Furthermore, the non-uniform light distribution will cause temperature gradient over the solar cell. For multi-junction solar cell, the gradient will be three dimensional. Every point of the solar cell will be at a different temperature. The band gap will decrease as the temperature increase. Thus the hottest spot will absorb more light, which will further increase the current mismatch. For non-uniform Gaussian light distribution, drop in both open voltage and efficiency are observed when compared to the performance of uniformly illuminated cells [12]. In addition to improve the efficiency and the overall performance, uniform distribution also assures the long term usage and concentrator reliability. However, for a given concentration ratio and angular acceptance specification, improving the uniformity may increase the system complexity and cost.

1.2.5 Étendue

Nonimaging optics studies the transfer of light radiation between a source and target. Unlike traditional imaging optics, there is no requirement of point-to-point mapping from object to target. Instead, the optimal optical radiation transfer from the source to the target is desired. The most important concept of nonimaging optics is étendue. In general, étendue is represented as a four dimensional quantity given by $n^2dx dy dL dM$, where $x$ and $y$ are spatial coordinates and $L$ and $M$ are the $x$ and $y$ direction cosines. Étendue characterizes how spread light is in area and angle. Étendue is conserved as light travels through optical system with perfect refractions or reflections.
1.3 Types of CPV systems

1.3.1 Low Concentration Systems (<10X)

Some companies are pursuing low concentration CPV systems. Table 1.1 lists some of these companies, the type of the system and their locations [13]. In this field, the main goal is to reduce the cost of the semiconductor material not the efficiency, thus most systems are fixed without tracking systems. All these systems use silicon photovoltaic cells.

Table 1.1: Summary of low concentration CPV companies.

<table>
<thead>
<tr>
<th>Company</th>
<th>Types of System</th>
<th>Location</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxxun</td>
<td>Luminescent</td>
<td>Eindhoven, Netherlands</td>
<td></td>
</tr>
<tr>
<td>KD Solar Co.</td>
<td>Holographic, 3X</td>
<td>Kyunggi-Do, Korea</td>
<td><a href="http://www.kdsolar.com">http://www.kdsolar.com</a></td>
</tr>
<tr>
<td>Prism Solar</td>
<td>Holographic, Si cells</td>
<td>Lake Katrine, NY, USA</td>
<td><a href="http://www.prismSolar.com">http://www.prismSolar.com</a></td>
</tr>
<tr>
<td>Technologies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solaria</td>
<td>Linear trough, 2X-3X,</td>
<td>Fremont, CA, USA</td>
<td><a href="http://www.solaria.com">http://www.solaria.com</a></td>
</tr>
<tr>
<td>Stellaris</td>
<td>Static, 3X,</td>
<td>North Billerica, MA, USA</td>
<td><a href="http://www.stellarissolar.com">http://www.stellarissolar.com</a></td>
</tr>
<tr>
<td></td>
<td>“see-through”, Si cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sun Power</td>
<td>Reflective, 7X, Si cells</td>
<td>San Jose, CA</td>
<td><a href="http://us.sunpowercorp.com">http://us.sunpowercorp.com</a></td>
</tr>
</tbody>
</table>

As we can see from the table, there are different technologies applied to the low concentration CPV field. The simplest system is the V-trough reflector which directs light onto receiver using flat mirrors [14,15]. Prism Solar Technologies uses highly efficient bifacial silicon solar cells that convert light hitting both front and back surfaces of the solar cell to electricity. Figure 1-2 shows a schematic of the Prism’s Holographic planar concentrator (HPC). Bifacial cell and holographic are put between two glass plates. Light hitting the bifacial cell will be converted to electricity as normal. When light hit the holographic film, they are diffracted and propagate within the glass by TIR until they
reach the cell. The bifacial HPC configuration uses 72% less silicon than a standard module and lowered the cost of a solar installation to below $1.00/w [16].

Figure 1-2: Prism’s Holographic Bifacial Concentrator Module [17].

1.3.2 Medium Concentration Systems (10X to 100X)

Some companies see medium concentration system as less risky than high concentration CPV systems. Using silicon PV cells and low-accuracy trackers may be perceived as safer and simpler to implement. The main difference from low concentration system is that medium concentration systems are allowed to use slightly more expensive and efficient solar cells to pursue higher module efficiency. Medium concentration systems are generally divided into two groups: parabolic troughs and those using Fresnel optics in the form of lenses or mirrors. Table 1.2 shows a list of companies that have developed medium concentration systems [13].

Reflective parabolic trough system uses a trough to focus solar energy to a line, where solar cells are mounted. Some companies like Absolicon Solar uses water cooling to cool the solar cell. While cooling the cell, the water is also heated. Therefore the system also operates as a solar heater. The combination of electricity and heat generation on the same system makes it possible to achieve higher efficiency [18]. The tracking is achieved by rotating the entire concentrator around a single axis. These systems have small
field-of-view in the tracking direction but have large field-of-view in the non-tracking direction.

Table 1.2: Summary of medium concentration CPV companies.

<table>
<thead>
<tr>
<th>Company</th>
<th>Types of System</th>
<th>Location</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolicon Solar</td>
<td>Reflective trough, 10X, Si cells, thermal hybrid</td>
<td>Harnosand, Sweden</td>
<td><a href="http://www.absolicon.com/">http://www.absolicon.com/</a></td>
</tr>
<tr>
<td>Banyan Energy</td>
<td>Flat-plate, TIR, 10X, Si cells</td>
<td>Berkeley, CA</td>
<td><a href="http://www.banyanenergy.com/">http://www.banyanenergy.com/</a></td>
</tr>
<tr>
<td>CPower</td>
<td>Point focus reflective, 25X-30X, Si cells</td>
<td>Ferrara, Italy</td>
<td><a href="http://www.cpower.it/">http://www.cpower.it/</a></td>
</tr>
<tr>
<td>Entech</td>
<td>Linear Fresnel lens, Si cells, thermal hybrid</td>
<td>Fort Worth, TX, USA</td>
<td><a href="http://www.entreprise.com">http://www.entreprise.com</a></td>
</tr>
<tr>
<td>Whitfield Solar</td>
<td>Fresnel lens, 40X, Si cells</td>
<td>Reading, UK</td>
<td><a href="http://fn-solar.com/">http://fn-solar.com/</a></td>
</tr>
<tr>
<td>Zytech Solar</td>
<td>Reflective, 4X-150X Si modules</td>
<td>Zaragoza, Spain</td>
<td><a href="http://www.zytech.es/">http://www.zytech.es/</a></td>
</tr>
</tbody>
</table>

Linear Fresnel reflectors offer more possibilities for tracking other than rotating the whole concentrator system. Tracking can be achieved by the following technologies: two-axis tracking [19], tracking the sun by moving the mirrors [20] or moving the PV receiver [21]. As for linear Fresnel lenses CPV systems, there are several advantages of applying them to solar concentrators: they can be produced in large sizes; their aspect ratio can be large if one want to design a compact concentrator system; they can be very thin therefore the cost of the optical material and the mechanical load of the supporting structure are reduced.
1.3.3 High Concentration Systems (>100X)

High concentration systems are not only the dominant CPV technology nowadays but also the hottest research direction within all CPV systems. Fig 1-3 is the historical summary of champion cell efficiencies from NREL. From the picture, we can see there are several multi-junction cells with reported efficiencies higher than 40%. The current record efficiency is 43.5% by Solar Junction [22]. Table 1.3 shows a list of companies developing high concentration CPV systems [13].

![Figure 1-3: Historical summary of champion cell efficiencies for various PV technologies. Figure of NREL [23].](image-url)
### Table 1.3: Summary of high concentration CPV companies.

<table>
<thead>
<tr>
<th>Company</th>
<th>Types of System</th>
<th>Location</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abenqoa Solar</td>
<td>Lens, pedestal</td>
<td>Madrid, Spain</td>
<td><a href="http://www.abengoasolar.com">http://www.abengoasolar.com</a></td>
</tr>
<tr>
<td>Amonix</td>
<td>Lens, Pedestal, 500X</td>
<td>Torrance, CA</td>
<td><a href="http://amonix.com/">http://amonix.com/</a></td>
</tr>
<tr>
<td>GuascorFoton</td>
<td>Lens, pedestal</td>
<td>Ortuella, Spain</td>
<td><a href="http://www.fotonhc.com/">http://www.fotonhc.com/</a></td>
</tr>
<tr>
<td>Isofoton</td>
<td>Lens, pedestal</td>
<td>Malaga, Spain</td>
<td><a href="http://www.isofoton.com">http://www.isofoton.com</a></td>
</tr>
<tr>
<td>Suncore Photovoltaic Technology</td>
<td>Lens, pedestal</td>
<td>Fujian, China</td>
<td><a href="http://www.suncorepv.com">http://www.suncorepv.com</a></td>
</tr>
</tbody>
</table>

Proper optical and thermal design and high precision tracking are basic requirements for correct operation of a HCPV system. Lenses and mirrors are used to achieve such high concentration. Cooling system must help to release the heat on the solar cell to keep it working with high efficiency. Two-axis tracking system with high precision makes sure most of the direct incident sunlight hitting the solar cells.

For concentration factor below 400x, lower cost backside contact silicon cell is more suitable than III–V cells for economical consideration. Fig 1-4 is the relationship between
efficiency and concentration for Emcore’s concentrating triple junction (CTJ) cell [24]. As we seen in the picture, at concentration level of about 400, the efficiency is the highest. Although we can pursue higher concentration for lower cost system and concentration factor above 1000X make sense economically. However, high concentration level may decrease the III–V cell efficiency and lifetime. Therefore concentrator factor at 400-1000 is appropriate for III–V solar cells on the considerations of economy, efficiency, lifetime and safety.

![Efficiency vs. concentration characteristic of Emcore’s CTJ Photovoltaic cell.](image)

1.3.3.1 Fresnel Type

The most widely used high concentration CPV design is the Fresnel type refractive point-focus concentrator. Comparing to conventional lens, Fresnel lens reduces the usage of the material and make the whole system thinner and lighter. Light absorption will decrease because light transfer with shorter optical path length in thinner lens. Fresnel
lenses are typically injection molded with plastics such as PC or PMMA or formed by silicone on glass. All these fabrication methods lead to low cost and high volume.

Some companies use Fresnel lens as the primary focus element to focus sunlight directly to solar cell. Fig 1-5 is the scheme of a FLATCON (Fresnel Lens All-glass Tandem-cell Concentrator) module developed at Fraunhofer Institute of Solar Energy. The module is made completely out of glass and hermetically sealed. Fresnel lenses are made of silicone via a stamp process on the backside of the top glass. By doing this, Fresnel surfaces are protected because they are isolated by the outside environment like dust or water. Under 500 concentration level, module efficiency of 30% is achieved [25].

![Figure 1-5: Scheme of a FLATCON module [26].](image)

However, the use of Fresnel lenses alone without secondary optic like the FLATCON technology will produce a quasi-Gaussian profile with about 2500X concentration in the center of the solar cell under 500X average concentration as in Figure 1.6 [39]. The highly non-uniform distribution will demand a specially adapted grid design for the solar
cell. Usually, to solve this problem, some companies combine Fresnel lens with some secondary optics. Secondary optics has the following purposes: additional concentration, increasing the acceptance angle of the system, and improving the uniformity of the light distribution over the solar cell.

![Figure 1-6: Calculated intensity profile of a Fresnel lens used in FLATCON technology. Whereas the average concentration factor is 500, and the center concentrator is 2500 in a 2mm diameter cell [39].](image)

Secondary optics can be either reflective or refractive. Truncated cone and truncated pyramid are the most common reflective surfaces. They can be easily made by rolling or bending the metal sheet. Refractive elements include CPCs and different dome shape designs. The secondary refractive optics are usually made of glass to assure the long lifetime. Previous researches have studied the influence of different kinds of secondary optics to the optical efficiency, acceptance angle, and uniformity [27, 28].

Based on these studies, reflective surface usually have higher optical efficiency but small acceptance angle. Refractive optics may decrease efficiency a little because of the additional Fresnel loss but have higher acceptance angle. Larger acceptance angle system
may have the largest non-uniform light distribution. In the real system, all the parameters must be considered together: cost, efficiency, acceptance angle, uniformity. There is no design can optimize all the parameters. Tradeoffs have to be made to design the most appropriate secondary optics for a particular CPV system.

1.3.3.2 Reflective Type

Reflective concentrators use one or two reflective surfaces to concentrate solar energy to the solar cell. The advantages of reflective systems are that they can avoid chromatic aberration, so the primary concentration can be much higher than Fresnel systems.

Figure 1-7: The Micro-Dish with secondary reflector and homogenizer [29].

One example is the micro-dish CPV developed by SolFocus in California as in Fig. 1-7. This System has a micro-dish, a secondary reflector and a homogenizer to focus the sunlight 650 times on a 1cm$^2$ III–V solar cell. One module includes 20 micro-dish units and one system consists of 36 modules mounted on a dual-axis tracker. The panel
efficiency is 29% and the system efficiency is 27% according to [30]. The energy
difference between panel efficiency and system efficiency comes from the losses through
inverter and the tracking system energy consumption.

Australia Company Solar Systems has developed CPV dish system for more than 20
years. As seen in Fig. 1-8, the dish consists of 112 area of 1.6 m\(^2\) curved mirrors which
are all mounted on a parabolic dish frame tracker. The receiver is a dense array module
that packs high efficiency triple junction solar cells closely into a 36cm\(^2\) actively cooled
package. This system is similar to a solar thermal power plant. Solar systems have
already installed 1.3MW in Australia and have a manufacture capacity of 5MW per year.

![Image](image_url)

*Figure 1-8: Solar Systems CS500-5 [31].*

One important factor of the cost effective CPV system design is the aspect ratio.
Thinner module will reduce the weight and make the tracking easier. Next chapter, planar
waveguide serves as concentrators is introduced. By combing non-imaging optics design
and waveguide, it is possible to design a compact CPV module with high efficiency and
large aspect ratio.
Chapter 2

Waveguide Concentrators

2.1 Waveguides

Waveguides are physical structures that confine light in a high index medium surrounding by lower index medium using TIR. The critical angle is the angle of incidence above which total internal reflection occurs. For angles larger than the critical angle, light will be reflected perfectly. Usually, waveguides are widely used in two areas: optical fiber and backlight. However, despite the wide use in these areas, there are not many practical concentrator systems using waveguides. The main advantage of waveguides in CPV system is the high aspect ratio, which reduces the material usage, volume and weight and can make accurate tracking easier and inexpensive. Also, the uniformity of light output distribution by using waveguide helps the system to get higher efficiency and longer lifetime.

2.2 Luminescent Solar Concentrators

The traditional solar concentrator has the advantage of reducing the semiconductor usage by focusing the incident sunlight onto smaller areas. The luminescent solar concentrator (LSC) concept preserves this advantage while trying to avoid its’
disadvantages: the need for direct sunlight, tracking and the large sizes. The first LSC module used a solution of laser dye between two glass sheets [32]. The first publication on luminescent solar collectors in the open literature is in 1976 by Levitt and Weber [33]. Figure 2-1 shows a schematic of LSC.

Luminescent solar concentrator generally consists of a dye layer dispersed in a transparent waveguide. As seen in the Figure 2-1, when incident light (①) hit on the top surface, some light is reflected due to Fresnel loss (②), some light is transmitted into the waveguide. A fraction of the transmitted light will just escape from the bottom surface of the waveguide without being absorbed (④) because of the limited absorption range of the dyes. The others will be absorbed by dyes (③) and fluorescence is emitted in lower energy. Fluorescence is emitted kind of isotropic. So when the incident angle is larger than the critical angle, they will do TIR in the waveguide as (⑥) and finally reach the solar cell (⑧), when the angle is smaller than the critical angle, the light will escape...
from the waveguide (\(^7\)). However, some of fluorescence will hit the fluorophor modules again during the propagation and get re-absorption (\(^5\), \(^6\)) if the absorption spectrum overlaps the emission. Fluorescence can also be absorbed by host material and lost (\(^10\)). Finally, due to limited emission quantum yield (\(^9\)), some of the absorbed photos are not re-emitted but instead lost as heat and vibrations.

The efficiency of LSC is low compared to other CPV systems because of losses mentioned above. The most significant problem is still identifying the optimal luminophore with a broad spectral absorption, high absorption efficiency over the whole absorption spectrum, a high luminescent efficiency, a high photostability, a matching spectrum of the emitted photos to the PV cell and good solubility in the host material \([34]\).

Before LSC could become a commercially viable technology, the luminophore issue will need to be solved.

### 2.3 Morgan Solar Light Guide Solar Panel

CPV company Morgan Solar applies waveguides to CPV system in some innovative ways. The first Morgan Solar light guide solar panel module comprises two parts: a light-insertion stage 102 and an optical waveguide 104 as in Figure 2-2. Light hitting on the light-insertion stage will be reflected at surface 110 towards the optical waveguide through aperture 116. The material of 114 is usually air to make a total internal reflection possible at the interfaces. After light reach the waveguide, they will propagate towards surface 132 where solar cell is attached by TIR of surface 120 and 124. By extruding this cross-section, we can get a 20-50X concentration CPV system requiring a single axis
tracker. By revolving the cross-section, we can get a 500-1000X concentration CPV system requiring a dual axis tracker with about 1° half acceptance angle.

**Figure 2-2: Cross-section view of a first embodiment of a LGSP 100 of Morgan Solar [35].**

By making some modifications on either light-insertion stage or waveguide of the original module, Morgan Solar proposes several different modules. Cassegrain optics and Winston cones can be applied to the light-insertion stage [35]. By using Winston cones as the light-insertion stage, non-tracking CPV system is possible because of the large acceptance angle. Winston cone and flat faced taper shape are also applied to the end of the waveguide to further increase the concentration ratio. Another modification is as Figure 2-3. In this design, the waveguide is designed as a stepped shape and the lenslets are tilted, so that light will hit on the couplers and be captured by the waveguide.

In all these designs, the waveguide is either tapered or stepped to make sure the TIR will always happen within the waveguide and reduce the possibilities of light leakage when light hit on the couplers. Although these designs provide a much flatter CPV module than traditional reflective or refractive CPV module, it will be difficult and
expensive to manufacture them. These designs will require both complicated light insertion optics and tapered or stepped waveguide, which all need expensive molding technology to make. Also, the only possible material for these designs is plastic, which degrades very fast under high concentrations because of both UV degrading and IR heating. Plastic waveguide may not be able to maintain the efficiency of the CPV system after long term use.

![Figure 2-3: Morgan Solar stepped light guide solar panel [35].](image)

2.4 Planar micro-optic solar concentrator and dimpled planar waveguide solar concentrator

Planar micro-optic solar concentrator was proposed by Karp and Ford from the University of California at San Diego (UCSD). This is the prototype that is most closely related to this thesis research. This module consists of an array of lenslets made of injection molded plastic, a slab waveguide made of glass, and a corresponding array of reflective prismatic features made of SU-8 (a photoresist polymer material) and aluminum as in Figure 2-4. Light which is incident on the lenslets will be focused on the
prismatic features coated with aluminum. These prismatic mirrors redirect the light into the waveguide which then propagate by TIR until reaching the edge of the waveguide.

One of the innovative advantages of this design is the self-alignment ability of the lenslets and the corresponding injection prismatic elements. The processes are shown as Figure 2-5. First, micro prisms made of SU-8 are molded across the entire back surface of the planar waveguide. After that, the lens array is mounted on top of the waveguide and the device is exposed to UV radiation. Then an aluminum coating is deposited over the entire back layer using DC magnetron sputtering. Because SU-8 is a negative photoresist, after the UV exposure, one can remove the uncured parts and the cured parts will become couplers corresponding to their lenslets. Lenslet and injector misalignments are eliminated because the lenslets are used to define both the couplers and to collect solar energy. Even if some lenslets have some mismatch or tilt problems, the corresponding coupler will mismatch or tilt accordingly and therefore together they are aligned.

Figure 2-4: Exploded perspective of the planar micro-optic solar concentrator [36].
Although Karp and Ford claim that a roll-to-roll process makes this module possible for large scale manufactured. In reality, there are several problems that need to be solved. Firstly, if a large concentration ratio is needed, a large aperture is required. In their case, spin coating SU-8 on a large surface evenly is troublesome, and so is the sputtering of aluminum on the entire back surface. Secondly, there are several heating and baking processes while forming the SU-8 and removing the uncured parts, which is complicated and also would affect the quality of the fabricated structures. Thirdly, SU-8 is cured by UV-light, which would experience a different refraction index of sunlight, and therefore it will not perform exactly the same way because the system is actually working under sunlight. Size difference of the couplers affects the efficiency significantly as will be shown later. Finally, reflectivity of the metallic coating is only about 85%, which waste a large amount of the light.
Another version of this design, the dimpled planar waveguide solar concentrator was proposed by a group at the University of Rochester [37]. This module consists of four parts: lenslets, couplers, bypass elements, and waveguide. The material choice is somewhat similar to the planar micro-optic solar concentrator of UCSD. However, there are several differences. First, instead of adding prismatic reflective structures on the backside surface, a thin polymer layer with some couplers oriented inward are coated on the back surface of the waveguide which redirect light by TIR. A master tool made by laser-writing lithography is used to replicate the dimple pattern into a polymer-on-glass layer. Secondly, there are bypass elements which prevent light hitting the couplers again when propagating in the waveguide. Higher efficiency will achieved by adding this part.

Figure 2-6: Schematic of the general dimpled lightguide model (top) and the injection and bypass prism (bottom) [37].
However, this method loses the self-alignment capability and needs very precise matching of the individual lenslet and the dimple part. The master making process of laser-writing lithography is complex and expensive and time consuming, which may not be favorable in mass production.

Both of these two methods use additional polymer materials on the bottom side of the waveguide, which may be a problem for long-time proper usage of CPV system under natural environment. The reasons are as follows. First, the adhesion of the polymer material to the waveguide may decrease after long term use. Second, the differences in coefficients of thermal expansion (CTE) will cause the polymer layer to expand or warp. Third, the optical properties of polymers in general deteriorate with time and the problem is worse when the material is exposed to relatively high light intensity as in PV systems of this type. If the coupler can’t redirect light to the waveguide, the whole system will perform worse. In the next chapter, I describe a version of the planar waveguide solar concentrator made entirely of all glass, which will eliminate many of the disadvantages described above.
Chapter 3

Planar Waveguide Solar Concentrator with Couplers Fabricated by LIBWE

3.1 Concepts

CPV systems are supposed to work in the sunniest places for a long period of time. The material choices in CPV systems are of crucial importance to their lifetime and efficiency. Besides high optical transmission, materials must have long lifetime under environments such as long-time exposure to sunlight, large changes in temperature, and large changes in humidity.

The design, considered in this thesis will allow having all optical parts of the CPV system made of glass at a relatively low cost. There are several advantages of using glass in CPV systems. First, plastic material like PC and PMMA will degrade under UV light irradiation, which is inevitable upon normal solar cell operation. Yellowing problems will occur and cause lower optical efficiency after a limited period of time. Second, because of the concentration of sun flux, the temperature at the focal spot on the backside of the waveguide may be very high, and any photoresist or polymer used in planar micro-optic and dimpled planar waveguide solar concentrator designs may start to soften or even peel off the waveguide if the temperature is high enough. If this situation happens, the whole system will work at a very low efficiency. Third, all glass ensures similar coefficients of
thermal expansion (CTE). As mentioned before, in planar micro-optic and dimpled planar waveguide solar concentrators, dissimilar materials are cemented with each other. Even very small differences in CTE can cause the material stack to warp or even delaminate.

Therefore, instead of adding any additional layer on the backside of the waveguide, we try to directly etch a cone in it. The cones serve as the couplers which redirect the focused light to the waveguide by TIR. The fabrication of such etched cones could likely be done by using various fabrication methods, but the method we focus on is laser-induced backside wet etching (LIBWE). By using this process, we not only can fabricate the holes but also preserve the very desirable self-alignment feature of the original design.

Next, I will discuss how each part of this module is designed and simulated in detail.

3.2 Components Design

3.2.1 Lens Array

Sunlight is first concentrated by an array of lenslets. There are three parameters to consider when designing each lens element:

the shape of the surface, aperture and focal length. To maximize the optical efficiency, the lenslets must fill up the total areas of the input aperture of the waveguide concentrator. Shapes like rectangles and hexagons can satisfy this requirement.

Figure 3-1: Hexagonal spherical lens array built in SolidWorks.
In this case, we choose hexagonal spherical lens for easy manufacture as shown in Figure 3-1.

The aperture size defines the spacing of the etched couplers and thickness of the waveguide concentrator. We choose the aperture size for 3mm to make it possible to be made in glass in a low-cost way. Smaller size may be better to further decrease the thickness of the waveguide concentrator. However, making such small micro lens array at a large scale in glass may be beyond the state-of-the-art, or may be too expensive.

In the planar waveguide solar concentrator, the lenslets are usually on one side of the concentrator while the etched couplers on the other side. Therefore the focal length of the lens array defines the approximate thickness of the concentrator. The focal spot is on the back side of the waveguide, whose size is also affected by the focal length \( f \). For a given acceptance half-angle \( \theta \), \( 2f \tan \theta \) calculates the aberration-free focal spot size. Each lens has its own concentration factor expressed by Eq.3.1, which is also the maximum concentration of the CPV system. Because focal length has such significance to the CPV system, choosing an appropriate f-number for the waveguide concentrator is important.

\[
C_{lens} = \frac{1}{4(f / \# \cdot \tan \theta)^2}
\]  

Marginal rays traces from the edge of the entrance pupil and define the largest angle that must be coupled to the waveguide. F-number (sometimes called focal ratio, f-ratio) of an optical system is the ratio of the lens's focal length to the diameter of the entrance pupil. For small f-number, the thickness of the concentrator is smaller and the ideal focal spot size is smaller. However, the incident cone angle to the coupler is larger. In this case, it may be hard to ensure all angles result in TIR in the waveguide. For this reason, some of the light near the marginal rays may be lost as seen in Figure 3-2. On the other hand,
for large f-number as in Figure 3-3, the concentrator is thicker and the etched coupler areas are larger. Thus the possibilities of the light propagating in the waveguide and hitting the couplers again will be higher. When light hit the couplers during their propagation along the waveguide, they will tend to escape from the waveguide and will not be captured by solar cells.

Figure 3-2: Schematic of waveguide CPV of f/1 (left); enlarged schematic of light hitting the etched cone (right). Light near the marginal ray will not be able to do TIR because the angle to the surface normal is smaller than critical angle (shown as red rays). These light will escape from the bottom side of the waveguide.
Figure 3-3: Schematic of waveguide CPV of f/2 (left); enlarged schematic of light hitting the etched cone (right). Even light near the marginal rays will be able to do TIR along the waveguide.

The simulation of different f-number vs. efficiency at concentration level of 75 in ZEMAX is shown as Figure 3-4. From this simulation, we can see for f-number below 2, the efficiency is very low. One reason is that light near marginal rays is not collected. The other reason is for low f-number, the spherical aberration is large, and therefore the spot size will be much larger than ideal (i.e., the diffraction-limited ideal lens spot) and the decoupling loss will be much higher. The appropriate range for f-number chooses of this design is therefore from 2 to 5.
3.2.2 Material

The refraction index contrast between the cladding layer and the waveguide must ensure that the marginal rays undergo TIR in the waveguide. If we use an air gap as the cladding layer, common glass like soda lime or BK7 glass can support angles in excess of 40 degrees. If we use higher refraction index glass such as F2, we can use some low-index claddings such as fluoropolymers. In our design, we will use air gap to ensure TIR and use lower cost glass (such as soda lime) to reduce the total cost of the design.

For both the lens array and the waveguide, we use glass for the following reasons. First, CPV systems are usually used in places where sunlight is abundant. To maintain the efficiency of the system in a long time, the system has to be able to go through daily

Figure 3-4: The efficiency under different f-number at concentration level of 75.
thermal cycling and water exposure. Glass certainly is much better than plastic in tough environment. Second, glass has higher transparency than polymer or plastic products over visible and near infrared wavelengths. Although polymer waveguide are much cheaper, they tend to absorb near infrared and UV light [38], which restrict making the most of the solar energy. Finally, from a global economics point of view, if we assume such PV will supply about 20% of the world’s electricity by 2025, the electricity yield is about 100GW per year. The yield will stress the glass market by 10%. If the lenses are made on thick PMMA substrate, it would need 1.5 times the total current world production of acrylic [39]. Also, taking account acrylic coming from oil, the perspectives are not promising for plastic in the long term.

3.2.3 Couplers Design
The etched couplers match the focal spots of the lenslets and redirect sunlight at angles which are larger than the critical angle for TIR. Previously, diffusers were used as couplers to simply scatter the incident light to the waveguide [40]. But in this case, the angles of the scattering light are not controlled. A large portion of the light will not be coupled into the waveguide. Luminescent Solar Concentrators have a similar problem because fluorescent dyes absorb and re-emit light similarly to scatters. Gratings and holograms have shown the capabilities of precise angular control of the diffracted light previously [41][42]. However, diffraction has a strong wavelength dependence, which makes it not suitable for sunlight. Simple specular surface like aluminum coated mirror can simply tilt the entire cone of focused sunlight into the waveguide. However, mirrors always have some absorption losses. For these reasons, it is beneficial to make some
etched holes on the backside of the waveguide as couplers to tilt the light by TIR, which don't have absorption losses. As in Figure 3-5, the focused light will undergo TIR twice at the edge of the etched hole and the bottom of the waveguide and will then propagate in the waveguide.

*Figure 3-5: Light is focused on the couplers and propagate along the waveguide by TIR (simulated in Zemax).*

For the etched cone, we need to define the bottom size and the cone apex angle. The bottom size is about the focal spot size. If it is larger, the acceptance angle of the system will be larger. On the other hand, larger coupler size means the total area of the couplers are larger thus the chances of decoupling of already coupled light are higher. For example, as in Fig 3-6, when light hits the coupler during propagation, it will do TIR at the air-glass boundary and get out of the system from the top surface of the lens array. As in Fig 3-7, light will comes out from the bottom surface of the waveguide.
Figure 3-6: Light escape the waveguide from the top surface.
The cone apex angle of the coupler defines the angles than insure TIR and also the optical light path in the waveguide. To illustrate the constraints of the coupler cone apex angle, we consider a light guide with a refraction index of 1.52 and air cladding refraction index of 1. The critical angle is 40.5°. Taking f/3 lenslet for example, the angular distribution is about ±10°. To maintain TIR of all angles, the maximum cone apex angle is 79° (2 * (90° − 40.5° − 10°)), and the minimum angle is 40.5°. When the cone apex angle is small, rays tends to have longer optical path length (OPL) as in Figure 3-8. Thus the chance of light hitting couplers again is higher. Also, because waveguide have the absorption coefficient, longer OPL means larger light absorption by the waveguide. The simulation of efficiency vs. angle is shown as in Figure 3-9. The result shows that at apex cone angle of about 80°, the efficiency is the highest.
Figure 3-8: Light hitting different apex angle cones (upper: 50°; lower: 70°). For a small angle, light has longer optical path length and hits the waveguide surface more often than in the large apex cone angle case.

Figure 3-9: Efficiency at different cone apex angles at the concentration level of 75.
3.2.4 Self-Alignment Process

The positions of the couplers are very important to correct operation of the whole system. The etched coupler should be exactly at the focal spot of each small lenslet. However, in general it is very difficult to control each coupler's position precisely over a large area. The size of each coupler is just about 100 $\mu m$. Even small mismatches will strongly decrease the efficiency of the CPV system. So we want to use a self-aligned technology to make the holes and align them with each lenslet at the same time. This laser-induced backside wet etching is compatible with the self-alignment requirement.

We use high-pulse energy green laser light at a wavelength of 532nm and focus it on the back side of the waveguide by using the lens array. The wavelength of green laser is in the middle of sunlight's spectrum, so the size of the focal spot would be similar to the size operation under sun light. The laser will be focused on the backside of the waveguide which is in contact with an absorbing liquid. After proper number of pulses laser shot, etching will occur at exactly the focal positions. Because of the Gaussian distribution of the laser fluence, the etched shape would be close to a cone. By controlling the fluence and the number of pulses, the etching depth can be controlled.

3.2.5 Solar Cells

The concentration ratio of this system is flexible. For different concentration ratio, different solar cells can be used. For high concentration systems, III–V multi-junction solar cells can be used. Although they are expensive, the small solar cell area needed in a high concentration ratio system would make it more cost-effective. For low and medium concentration ratio, silicon cells can be used. For example, there is a type of solar cells
called sliver cells, which typically have a length of 5-12cm, a width of 0.2-2mm, and a thickness of 20-100 $\mu m$. The very thin sliver cells are also perfectly bi-facial, and have 20% efficiency at one sun [43].

![Figure 3-10: Slivers solar cells, each 1mm wide and 50 $\mu m$ thick [43].](image)

### 3.3 Simulation Results

We use ZEMAX non-sequential module to simulate the CPV system design. Source file simulates sunlight from 0.4-1.6$\mu m$ with $\pm 0.26^\circ$ field angles. The lenslets are plano-convex shape and made of soda lime glass. The waveguide is rectangular shape and is also simulated as glass with etched holes on the backside of it. Between waveguide and lens array is 1mm thick air cladding layer. Lens aberrations, Fresnel reflections, material absorption and dispersion are considered in the optical simulations.
3.3.1 Designs

The design simulated a soda-lime glass lens array and a soda-lime glass waveguide with 1mm air cladding. Both lens array and waveguide are squares. The length of the waveguide is varied to get different concentration level. The thickness of the waveguide is simulated at 1mm and 2mm. Couplers are air cones with $80^\circ$ cone apex angle and different bottom size.

3.3.2 Performance

We simulated f/3 air cladding system under different concentration level separately for $80\mu m$ and $150\mu m$ coupler size in Figure 3-11. The geometric concentration level is defined as the ratio of the input to output areas. For this CPV system, the input aperture is the top surface of the waveguide defined by square of the waveguide length. The output apertures are the four edges of the waveguide whose area is length by thickness. Therefore, the geometric concentration ratio of this system is the waveguide length divided by four times of the waveguide thickness, Eq.3.1.

$$C_{geo} = \frac{\text{waveguide length}}{4\times\text{waveguide thickness}}$$  \hspace{1cm} (3.2)

As seen in the picture, for $80\mu m$ cone, the system has about 88% efficiency at 30X, and has about 85% efficiency at 200X. For $150\mu m$, the system has about 88.5% efficiency at 100X, and has about 79% efficiency at 200X. Under both circumstances, efficiency decreases as the concentration level grows. There are several reasons leading to this result. First, the increase of the waveguide size increases the optical path length (OPL). The reflection and material absorption loss will be higher for longer OPL. Second, as light travel longer in the waveguide, the chances that light decoupling will also be
higher. Also, we can see from the picture that as the concentration level increases, the
optical efficiency of 150 $\mu m$ cone decrease much faster than the 80 $\mu m$ one. That’s
because as the OPL become larger, the decoupling loss will be the main loss mechanism.
For larger coupler area, the decoupling loss is much higher than smaller ones under high
congestion level.

Figure 3-11: Efficiency at different concentration levels.
3.3.3 Output Characteristics

After concentrated into the waveguide, light finally propagates towards the output edges where the solar cells are mounted. Figure 3-12 is the output of one section of the solar cell. The intensity is quite uniform across the whole solar cell area as we can see from Figure 3-12.

![Figure 3-12: Uniform intensity distribution across the solar cell.](image)

3.3.4 Angular Acceptance

The angular acceptance of the concentrator depends on the size of the focal spot comparing to the size of the cone. When the size of the cone is exactly the size of the focal spot, the concentrator works on the highest efficiency but also requires the most accurate tracking. When the coupler size is larger, the acceptance angle is increased but
the decoupling loss may increase as in Figure 3-11. Figure 3-13 shows different optical efficiency when angled sunlight is incident to the CPV system under two different cone sizes. Acceptance angle is defined as the angle for which power collection drops to 90% of its maximum. We can see for 80 μm cone, the half acceptance angle is 0.15°; and for 150 μm cone, the half acceptance angle increases to 0.5°. For lower concentration level, increasing the cone size will increase the acceptance angle without affecting the optical efficiency too much. However, under high concentration levels, increase the cone size will enlarge the acceptance angle on the cost of decreasing the optical efficiency.

![Figure 3-13: Normalized efficiency vs. Angles for different cone radius at concentration level of 75.](image)

Figure 3-13: Normalized efficiency vs. Angles for different cone radius at concentration level of 75.
Chapter 4

Light Couplers Fabricated by Laser-induced Backside Wet Etching

4.1 Background

For the purpose of our design, we need to be able to etch high aspect-ratio reasonably smooth structures on the surface of the glass with enough depth control. There are three major groups of techniques used for glass etching: mechanical, dry and wet. Mechanical methods use traditional drilling methods like diamond drilling or ultrasonic drilling. However, by using mechanical methods, smooth surface are difficult to obtain at this small scale. Dry etching techniques include plasma etching and laser etching. Wet chemical etching uses hydrofluoric-based solution to etch glass by chemical reactions.

Deep reactive ion etching is one expensive and complicated dry etching technology. A mask is usually needed for the etching process. The processes for the preparation of a Ni mask are as in Figure 4-1. First Cr and Cu are sputter-deposited on the glass as the adhesion and seed layers. Second, SU-8 photoresist is spin-coated on the Cr/Cu layer, and the patterns are formed by UV photolithography. Then Ni layer is electroplated as the hard mask. After that, the unwanted SU-8 photoresist and Cr, Cu parts will be removed using different etch solutions. After this preparation, different chemistries plasma can be used to etch the glass. The disadvantages of deep reactive ion etching are the low etch
rate with the range of several tens to hundreds of nm/min [45] and cleaning process of the equipment usually is required after each 10 μm depth etch [46].

![Deep reactive ion etching process of glass](image)

**Figure 4-1: Deep reactive ion etching process of glass.**

Laser ablation has been used to etch diffractive and refractive micro-structures on polymer surfaces [47,48]. However, transparent glass can’t be etched this way because of their low absorption for normal nanosecond laser radiation. Either F\(_2\) laser (λ=157nm) whose photon energies exceed the band gap of the transparent material or femtosecond laser can be applied to ablate transparent material [49], but the cost is high and the surface quality is relatively poor for optical purpose.

Similar to deep reactive ion etching, mask is also needed for wet chemical etching. Differently, liquid etchant like buffered hydrofluoric acid (HF) or buffered oxide etching (BOE) are used instead of plasma. Different mask materials are studied for wet chemical etching. AZ 4620 positive photoresist is used as the mask, and a depth of 36 μm is got with a 0.9 μm min\(^{-1}\) etching speed [50]. Metal masks, such as Cr/Cu [51], and Cr/Au
[52] is reported, and get 100 $\mu m$ depth etching in 15 minutes and 250 $\mu m$ depth etch in 40 minutes respectively. Another commonly used mask material for glass etching is silicon. PECVD amorphous silicon and LPCVD polysilicon/amorphous mask can stand a 200 $\mu m$ depth etching in 30 min. Multilayer masks are used to get better etching results. Cr/photoresist glass etching mask is reported in [53], and 100 $\mu m$ depth in soda lime glass is achieved. The deepest reported etching through a 1mm-thick Pyrex glass uses a multiple layer mask of low stress amorphous silicon/silicon carbide/photoresist [54]. The main disadvantage of wet chemical etching is the hydrofluoric-based solution is toxic to human beings. Photoresist mask alone is not enough for our requirement of the etch depth. The other masks are not transparent and very complicated to make. Also, for our purpose, we can’t only etch the backside of the waveguide without affecting the sidewalls of the waveguide.

All these methods seem difficult to fulfill all the needs in this waveguide CPV design. Next, a new method called laser-induced backside wet etching which is a hybrid laser etching methods will be introduced.
4.2 The Basics of LIBWE

There are several material-assisted backside laser etching technologies: laser-induced plasma assisted ablation (LIPAA) [55], laser etching at a surface absorbed layer (LESAL) [56] and laser-induced backside wet etching as in Fig 4-2. LIPAA puts a metal target behind the glass to generate plasma under laser radiation. The charged plasma induces defects in the glass and enhances the absorption of laser to reach the purpose of etching. LESAL uses a thin layer of organic solvent on the back side of the glass to absorb laser. However, the thickness of the absorbed layers causes the low etch rate and the rate saturation.

Laser-induced backside wet etching (LIBWE) was invented in 1999 by Yabe and Niino [58]. Compared to direct laser ablation, LIBWE technology use conventional
nanosecond pulse lasers and has low etching threshold fluence and small roughness of the etched surface. Different types of laser systems (UV laser, green light laser and infrared laser) can be applied to LIBWE by using different absorbing solutions, usually organic dye solution[59,60,61], liquid metal is occasionally used [62,63]. Also, different types of glass such as fused silica, optical crystals, Pyrex, BK7 and soda-lime glass have been etched with high precision.

4.2.1 LIBWE Using UV nanosecond-pulse laser

The most widely used LIBWE technology utilizes UV ns laser with a wavelength shorter than 270nm. Fused silica glass is the most-studied material of this technology because of its certain properties: high transparency in a wide wavelength range, high chemical and thermal stability and simple chemical structure. To extend the available etching glasses, such as Pyrex (from Corning Inc.) or D263 borosilicate glass (from Schott Inc.) which have nearly 90% transparency at wavelength around 360nm [64], longer wavelength UV laser either XeF-excimer laser (351nm) or diode pumped solid state (DPSS) 3rd harmonic Nd:YAG laser (355nm) were used to etch these glasses [65,66]. However, Soda lime glass cannot be processed by UV LIBWE because of its opacity in the UV range. Organic dye solutions are usually used as absorbing liquids. Different solutions with different concentration have been researched. Some commonly used solutions are pyrene in toluene, or pyrene in acetone.

The mechanism of LIBWE is illustrated in Fig 4-3 (a) and (b). After the laser beam passes through the glass, it is strongly absorbed by the organic solution within a very thin region. The volume of the region is defined by the spot size of the laser beam and the
optical penetration depth which is only a few micrometers in the liquid. This strong absorption results in a high density of excited dye molecules. During and after the laser pulse, these excited molecules return to the ground state by losing energy either by emission of photons or by non-radiative relaxation. Through the latter mechanism, the energy of the excited molecules is turned into heat, which heats the liquid (which in turn heats the solid). There can be a temperature jump from 20°C to 2500°C within the ns laser pulse as shown in Fig 4-3 (b), which is high enough to melt or even boil the glass surface. However, the actual temperature at the glass-liquid interface depends largely on the laser fluence. For small laser fluence, the temperature may be below the glass melting/softening point; for large laser fluence, the temperature may be above the glass vaporization point. The best etching conditions at the interface in terms of etching roughness are at temperatures between the glass softening point and the vaporization point. After the absorption of the laser energy, the temperature decays within the first microsecond.

The fast temperature jump and cooling also result in an explosive evaporation of the solution, which induces high pressure shock waves that travel through the solution in all
direction. The shock waves’ magnitude is thousands times higher than atmospheric pressure and move with a velocity of several kilometers per second [68]. The shocks waves which propagate towards the material may help to remove the molten material (or any mechanically “etched” material, i.e., through the shock wave) from the glass surface. Also, according to [68], the shocks transfer towards the liquid forms bubbles in solution as shown in Figure 4-4 a). The bubble grows and reaches a maximum size when the pressures and temperature inside the bubble and those of the surrounding liquid are equalized. Because the bubble formation time is much smaller than the time delay between two laser pulses, without additional thermal energy, the pressure of the bubble starts to decrease. Finally, the bubble collapses and generates a liquid jet, which also causes a pressure jump transferring towards the glass surface might be large enough the remove the molten material as shown in Figure 4-4 b). However, the first pressure jump may play the key role in removing the molten material. The second pressure jump caused by the bubble collapse is smaller than the first one. Also, when this pressure jump occurs, the temperature of the glass interface may have been cooled.

![Figure 4-4: a) Laser induced bubble forming in solution, b) collapse of laser induced bubbles.](image)

To summarize the above described mechanism, LIBWE is believed to involve two main processes: a temperature jump and a pressure jump. The strong absorption of the
laser pulse energy at the glass-liquid interface can lead to the melting or boiling of the glass surface and generating strong shock waves and laser induced bubbles. The pressure jump created by the shock waves and collapse of laser induced bubbles helps to remove the etched material debris.

4.2.2 LIBWE Using infrared nanosecond-pulse laser

Compared to excimer UV lasers, IR lasers at 1064nm wavelength have a much higher and stable power output, and yet they are more affordable. Also, glass such as soda lime glass which strongly absorbs UV light can be processed by LIBWE using IR lasers. Aqueous copper sulphate solution (CuSO$_4$) is used as the absorbing liquid to absorb 1064nm IR laser light. This approach eliminates the need of toxic chemicals such as acetone or p-xylene in other LIBWE methods.

There are two explanations of the mechanism of IR LIBWE using aqueous CuSO$_4$. According to [61], copper is first deposited on the glass surface because of the absorption of laser light by the copper sulphate solution. The copper deposited on the glass also starts to absorb the laser pulses and heats up. At high laser fluence, the deposited copper can be boiled off and produce a recoil force which removes the molten material. After that, the deposition process of copper starts again and the etching continuous. The other explanation [69] is similar to the mechanism of UV LIBWE. During the experiment, the 1064nm pulses are absorbed by the Cu$^{2+}$ ions at the glass-liquid interface. Because of the Coulomb interaction, these Cu$^{2+}$ ions are attracted by the polar glass surface. The absorbed energy is mostly transformed to heat and then influences on the soda lime glass
surface. The first mechanism plays a major role on salinized surface and the second mechanism applies to untreated glass surface.

4.2.3 LIBWE Using visible-light nanosecond-pulse laser

The most suitable laser light for our application would be from the visible range and specifically the green 532 nm line (the 2\textsuperscript{nd} harmonic of the Nd:YAG laser), because the wavelength of green light laser is close to the central spectrum of sunlight, making sure the refraction index and the focused spot size will be similar to the condition under sunlight. Also, we can use soda lime or borosilicate glasses as waveguide to lower the cost of the system. Finally, the visible laser and the relating optical equipment are more economical and easier to deal with.

The mechanism of visible LIBWE is similar to UV LIBWE. Absorbing liquids are used to absorb the laser radiation, which then leads etching of the glass. However, 532nm photons contains only one half of the energy of 266nm photons, so higher photon flux is required to etching the glass using green laser. For UV LIBWE, a lot of researchers have successfully made crack free etching to fused silica [64-66]. For visible LIBWE, there is limited published information about it [60,75]. In our case, we are using soda lime glass, which has a coefficient thermal expansion of $8.5 \times 10^{-6}/K$ compared to fused silica of $0.59 \times 10^{-6}/K$ and borosilicate glass of $3.3 \times 10^{-6}/K$ at 20\degree C [70]. The residual stresses caused by thermal cycling of glass are likely to result in microcracking according to [71]. Because of the higher coefficient of thermal expansion and lower strength, it may be easier to generate cracks in using soda lime glass than in borosilicate or silica glasses. Also, once the cracks start forming, the large thermal expansion will increase the density
of the cracks, and the high pressures and high temperatures associated with laser driven shock waves may further spread these cracks.

There are many parameters that may influence the etching surface quality during LIBWE process. A proper laser fluence should assure the temperature on glass surface between the melting and boiling temperature for both higher etching speed and quality. The etched material itself of course has large influences too. High thermal conductivity may cause lower temperature of the heating zone and re-solidification may happen. This is one reason for nonuniform etching. Also, as mentioned before, high thermal expansion coefficient may result in larger number of cracks. According to previous research, a lot of parameters such as laser spot size, pulse repetition rate, different laser wavelength, and concentration variation of the absorbing liquid, and solvent affect the etching speed and etching quality [72]. To etch a smooth desired hole without cracks, all these parameters need to be considered, controlled, and optimized. Our experimental work on LIBWE of soda lime glass by using visible ns laser is presented below.
4.3 Experimental

4.3.1 Experimental Setup

The experimental setup is shown in Figure 4-5. For this experiment, a Q-switched high-energy Nd:YAG laser system (Continuum Powerlite 8010) serves as the green light laser source. This laser can emit different wavelengths from UV to IR. The pulse repetition rate for this laser is up to 10 Hz. The wavelength in this experiment is 532nm. The pulse duration is 25ns, and pulse energy of 75mJ to 500mJ. A beam expander is used to expand the beam and thus obtain a lower intensity at a relatively uniform intensity distribution over a relatively large area. A mask and a projection lens shape the laser beam profile for machining and focus it onto the backside of the waveguide.

![Figure 4-5: Schematic set up of the laser workstation (a pump can be added for refreshing the absorbing liquid).]
4.3.2 Variations of the LIBWE methods

LIBWE can be used in various applications such as in the fabrication of microfluidics for analytical chemistry and biochips or in the fabrication of three dimensional structures [73]. Laser micro processing can be performed by direct focusing, by imaging a mask, or by the interference of laser beams. By applying specific masks and using a high precision computer numerical control (CNC) work stage, the fabrication of 3D structures with high precision and small roughness is possible. Two methods relevant to our project are discussed below.

a) Stationary mask projection method

In this method, masks containing the desired shape are irradiated by the laser beam. By the imaging lens, the shape is imaged on the glass liquid interface. After a few laser shots, etching will occur at desired locations. This method can be used for etching a large area with repetitive elements. Figure 4-6 and Figure 4-7 shows attempts to etch straight channels on the glass substrate by using slit masks of 0.5mm and 2mm width respectively (i.e., a long rectangular opening in an opaque material).

![Figure 4-6: SEM image of the a 25 μm width etched channel.](image)
As seen in Figure 4-7, the depth of the channel becomes deeper as more pulses of laser proceed on the glass. However, the depth of the structure is not uniform over the entire length as seen in Figure 4-6. Usually, for mask projection method, homogenizing optics is used to insure uniform laser fluence over the entire imaged area for smooth etching. However, in our case, we just want to test the feasibility of this method and we didn’t use homogenizing optics.

*Figure 4-7: Optical microscopy images of straight channels etched on glass substrate using LIBWE technology for 5, 10, and 20 pulses respectively under the same fluence from top to bottom.*
b) Direct focusing method

The couplers on the back side of the waveguide of our CPV system design would be made by this method. The lens array would directly focus the laser beam onto the glass liquid interface. The somewhat non-uniform Gaussian-like distribution within the focal spot is expected to help in obtaining an etching with a shape close to a cone. Besides the holes, microfluidic channels can also be made by direct focusing method. Instead of stationary etching, scanning the laser spot along a designed path will help to obtain microfluidic channels of desired shapes as shown in Fig 4-8. The etch depth and quality are obviously dependent on the scan speed and all other laser and geometry parameters.

![Figure 4-8: Schematic of laser micro-fabrication methods: a) Stationary mask projection method, b) Direct focusing method [74].](image)
4.3.3 Etch Chamber

A simple chamber, made of teflon, was designed and fabricated as shown in Figure 4-9. Teflon is chosen because of its good chemical resistance for a wide range of chemicals. The absorbing liquids are filled into the cavity up to the rim. The glass sample to be etched is then mounted on top and seals the cavity by four screws and a cover. For large area processing, a pump can be added to ensure the flow of the light absorbing liquid. This allows the continuous replenishment of the active solution, which is in the immediate vicinity of glass surface that is being etched, as well as filtering, and cooling.

Figure 4-9: A photo of the etch chamber.

4.3.4 The Choice of Glass and Etching Solution

For this study, we choose to use soda lime glass as the waveguide etching material because it is inexpensive and can be reasonably stable in terms of its optical properties, and can be processed by existing technologies at our partner, Libbey Inc., Toledo, Ohio. The optical transmission dependence on the wavelength for a typical soda lime glass
composition is shown in Figure 4-10. It has high transmission for visible light. Table 4-1 contains some important material properties for soda lime glass.

![Soda lime Glass graph](image)

**Soda lime Glass**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index</td>
<td>$n$</td>
<td>1.518</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>2.44 g/cm³</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>$C_p$</td>
<td>0.72 J/(g K)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$\kappa$</td>
<td>1.05 W/(m K)</td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>$T_g$</td>
<td>573°C</td>
</tr>
<tr>
<td>Compressive strength</td>
<td></td>
<td>325 Mpa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td></td>
<td>33 Mpa</td>
</tr>
<tr>
<td>Thermal Expansion</td>
<td></td>
<td>9μm/m-K</td>
</tr>
</tbody>
</table>

Before etching, the following steps to clean the sample are performed:

1. Place the sample in a beaker with detergent solution and put them to an ultrasonic treatment for 10 minutes
2. Rinse with distilled water
3. Place the sample in a beaker with ethanol and put them to an ultrasonic treatment for 5 minutes

4. Dry the sample with compressed air

In this LIBWE process, organic dye and organic solvents are mixed as liquids to absorb the incident laser radiation. Different combinations as Rose Bengal (RB) in acetone, Oil-red-O in ethanol, have been tested for this experiment with different concentrations up to levels at which the solution becomes saturated. Rose Bengal is a common xanthene dye with a molecular formula of $C_{20}H_{24}I_4Na_2O_5$ and molecular weight of 1017.64. The concentration of the saturated RB/acetone solution is 1.2mM [60]. Oil-red-O has a molecular formula of $C_{26}H_{24}N_4O$ and molecular weight of 408.49. The concentration of saturated Oil-red-O in ethanol and p-xylene are 17.13mM and 66mM [77] respectively. Because of the larger concentration of Oil-red-O in p-xylene, it can be used to etch borosilicate glass with a higher melting point. However, compared to p-xylene, acetone is a much safer chemical. And in our case, we use soda lime glass as the waveguide. Thus we mainly use Rose Bengal in acetone as our etching solution.
4.4 LIBWE Etching Results

After the all the preparations of the experiment, we applied different number of pulses at different fluence levels to the glass substrate in order to establish what laser parameters are likely to produce desirable etching. Figure 4-11 a) to d) show the top view SEM images of the etched holes after 1, 3, 5 and 10 pulses with a laser fluence of 5.85J/cm². From these pictures, we can see as more laser pulses hit on the glass substrate, the area and the depth of the etched holes grows larger gradually. The hole size in picture d) is about 80 μm, which perfectly matches our design.

Figure 4- 11: Top view SEM images of etched holes at the fluence of $\phi=5.85\text{J/cm}^2$ for a) 1 pulse, b) 2 pulses, c) 5 pulses, d) 10 pulses.
Figure 4-12 shows the difference between holes array mask etching with etching solution flow (i.e., by using a pump) and with static etching solution (no pumping). It can be seen that after when there is a continuous flow of the etching solution, the holes have more regular shapes and sizes and develop somewhat less severe cracking. The main reason for this improvement is that the flow of the absorbing (etching) liquid insures that fresh liquid (i.e., unaffected by the intense laser irradiation) is in contact with the etched glass surface before each next laser pulse. In addition, the removal of any debris from the previous pulse may be helping significantly.

![Figure 4-12: Optical microscopy images of holes array etching without pump (left) with pump (right) under.](image)

Figure 4-13 is a cross-sectional view SEM image of an etched hole cut from near its middle. The shape of the etched hole is almost conical. The apex angle of this is about 110°, which is larger than the desirable 80°. However, because and cross section surface is not at the exactly at the middle of the hole. The actual apex angle may be closer to the desired angle. Also, even if the hole is shallower than the desired one, we can always etch deeper hole by adding more pulses. Figure 4-14 shows two other etching holes with different apex angles. By using different number of laser pulses, holes with different
cross-sectional profile can be got. With enough number of pulses, very deep holes can be obtained as seen in Figure 4-15.

Figure 4-13: The cross-sectional view SEM image of one etched hole at the fluence of $\phi = 5.85 \text{J/cm}^2$ for a number of pulses. One can see what appears to be median crack formation around the etched region.
Figure 4-14: Optical microscopy images of the cross-sectional view of etching holes with different apex angle: 60° (upper) 120° (below).

Figure 4-15: Optical microscopy image of cross-sectional view of a very deep hole.
However, although the size and shape of the etched holes match the design, the surface quality observed from the SEM image leaves much to be desired. The surface is uneven as shown in Figure 4-13. In Figure 4-16, although the surface seems much smoother but there are some cracks around the etching hole when large number of pulses or large fluence is applied.

![Figure 4-16: Top view SEM image of one etched hole with smoother surface however also with cracks.](image)

There are many parameters in LIBWE which influence the final result in terms of the of the etched hole profile: laser fluence, pulse number, the spot size of the laser beam, pulse repetition rate, different absorbing solutions and glass material itself, and the wavelength of the radiation matters as well. Also smooth surfaces without cracks satisfying optical quality have been made by others as in Figure 4-17 [78, 79].
In our case, the reasons that we do not obtain smooth cone surfaces may be as follows. One reason is the laser pulse-to-pulse energy instability, which is relatively high in our case due to the laser pumping flash lamps approaching their lifetime limit. Once a larger-fluence pulse creates a crack, the crack would absorb the laser energy more efficiently, which makes it more likely direct laser ablation and results in further crack formation and thus a lower quality surface. The instability also make the etching un-uniform. The second reason may be the glass itself. The glasses we use are most common soda lime micro slides. The transmission of the glass may be low, intrinsic defects of the glass may absorb the laser flux directly and cause the cracks during etching. Higher quality optical glass may help to get better results. Other glasses like borosilicate with lower thermal expansion coefficient may also help to reduce the cracks during etching. The third reason may involve the etching solution. Based on the literature, Oil-red-O in p-xylene is likely the best etching solution for our case [77]. However, due to the safety concern, we are not able to use this etching solution in our lab. Optimizing the above factors may help to get better quality holes. The ultimate goal is controlling
these parameters such as laser fluence and pulses numbers, to obtain the desired shape and depth of the smooth hole within a given number of pulses.

Although we did not use lens array to etch holes array on waveguide, the single lens and hole pair proves that this LIBWE fabrication of self-aligned coupler is possible. This alignment of the lenslet and coupler is critically important for several reasons. First, even a little misalignment will cause a certain fraction of the light not to reach the coupler’s desired location and thus it will be wasted. Therefore the efficiency of the system would be lower. Second, if the radius and/or the height of the lenslets varie significantly (due to fabrication accuracy limits), the coupler will change its size according to each corresponding lenslet size variation because of the self-alignment property of the fabrication. Without the self-alignment, even ±5% of the lens height variation would cause about 25% optical efficiency decrease, and ±10% of the lens height variation would even cause around 55% optical efficiency decrease according to our ZEMAX simulations.

If our smoother surface of the laser etched conical coupler were to be obtained by improvements in the process (which appears to be possible by investing in equipment, and optimization of the laser parameters, materials and chemicals), this will become a one-step etching self-aligned process, which is not only very convenient but also cost-efficient. For our green light laser, with proper homogenization optics, it is possible to etch one square foot area waveguide in less than 20 minutes at the maximum power of 5W. Figure 4-18 shows incoherent irradiance vs. center line coordinate values of the spot for four different wavelengths: diode pumped solid state (DPSS) 3rd harmonic Nd:YAG laser (355nm), sunlight, the green 2nd harmonic line of the Nd:YAG laser at 532nm and
the IR fundamental laser line of the Nd:YAG laser at 1064 nm, simulated in ZEMAX using the designed single lenslet of the lens array.

![Incoherent irradiance vs. spatial coordinate value for four different wavelengths.](image)

*Figure 4-18: Incoherent irradiance vs. spatial coordinate value for four different wavelengths.*

As seen in Figure 4-18, 532nm green light laser irradiance basically matches the sunlight irradiance over all the positions. For 355nm UV laser, the focusing spot is much larger than under sunlight situation. However, the focusing spot size of IR laser is only a little larger than sunlight focusing spot, and the irradiance over the line is similar. In this case, as discussed in chapter 3, the cone size will also be a little larger than expected. However, this may help to increase the acceptance angle of the system on the basis of not largely affecting the optical efficiency. If we use IR LIBWE, the time consuming is even less because of higher IR laser power output. Also, the etching solution of IR LIBWE is
much safer than other etching method and IR laser machine is less expensive. Considering these properties of IR laser, IR LIBWE is also very promising for this application.

Figure 4-19 is the final schematic setup of the planar waveguide solar concentrator with couplers fabricated by LIBWE. Both the lens array and the waveguide are made of soda lime glass with the size of 10cm × 10cm. The thickness of the lens array and waveguide is 6mm and 2mm respectively. A frame support made of metal helps to maintain 1mm distance between the lens array and the waveguide as designed. For single lenslet, the radius is 3.353mm and the aperture is 3mm. The concentration level for this design is 12.5 and the simulated optical efficiency in Zemax is about 88%. The solar cells will be attached to the side walls of the waveguide. The total transfer efficiency will be the product of the optical efficiency and the cell efficiency. For this medium concentration CPV system, silicon cells are favorable economically. As seen in the picture, this design is not only convenient, but also very compact and robust.

*Figure 4-19: schematic setup of the planar waveguide solar concentrator with couplers fabricated by LIBWE.*
Chapter 5

Conclusions and Suggestions for Future Work

5.1 Summary

Chapter 1 introduces the current applications of solar energy, the development of solar cells, and some common design considerations for concentrator photovoltaic design. Overviews of different CPV manufactures developing concentrators from low concentration to high concentration ratio were provided. Also, chapter 1 provides examples of CPV systems of different concentration ratio and design. Accordingly, advantages and disadvantages of different CPV concentration ratio design are discussed.

Chapter 2 introduces the concept of waveguides and waveguide concentrators. Other types of waveguide concentrators are described, including the luminescent solar concentrators, the Morgan Solar light guide solar panel, the planar micro-optic solar concentrator and the dimpled planar waveguide solar concentrator. There are some innovative advantages of these designs. However, they also present some challenges. Our planar waveguide solar concentrator made by LIBWE is based on the module of the planar micro-optic solar concentrator, proposed earlier by a different group. This new design keeps the self-alignment capability of the original design, but eliminates the
disadvantages like multiple steps processing, reflective loss, and poor polymer longevity outdoor of the original design and is able to make the couplers of the system in only one step.

Chapter 3 provides details on the design of different components including the lens array and the couplers in Zemax and Solidworks. According to the simulation results, the best design has a lenslet with a plano-convex f/3 lens with a hexagonal shape. The coupler having a cone shape with 80° apex angle offers the highest efficiency. A 1mm thin air layer acts as the cladding layer between the lens array and waveguide. This design has an efficiency of 87% under 100 concentration level and still have an efficiency of 81% under 500 concentration. According to the different Zemax simulations: uniform light outputs coming from the waveguide surfaces were achieved; the efficiency of the system will decrease because of the decoupling loss as the concentration level increases; increasing the coupler bottom size will increase the acceptance angle at the cost of efficiency.

Chapter 4 introduces different approaches to etch glass for the formation of the waveguide coupler structures, most importantly, the laser-induced backside wet etching (LIBWE) method. Using this method, couplers on the waveguide can be made in one step. Also, the alignment of each lenslet and coupler is ensured by the mechanism of this method. A Q-switched high-energy Nd:YAG laser serves as the green light laser source. Soda lime glass slides were etched using saturated Rose Bengal/Acetone solution as the absorbing liquid using both stationary mask projection method and direct focusing method. By using visible light LIBWE technology, we are able to get the desired cone size and shape. However, the surface quality didn’t meet the optical quality. Using a
flowing etching/absorbing solution helps in obtaining better quality etching. However, the formation of cracks and relatively rough surfaces are still the main problems that need to be solved. The reason for this relatively low quality etched hole surfaces are likely related to laser instability and other laser parameters, as well as insufficient optimization of the glass material and etching solution combination. Although we are not able to obtain the desired quality of these etched structures, our results indicate that the design and the proposed fabrication process are feasible. It is not only convenient for its one-step processing procedure, but also it eliminates the high precision manufacturing of the lens array and alignment process because of its self-alignment ability, which is likely to lead to significant cost saving. It is also clear, that this a desirable, compact and robust which highly aesthetically acceptable due to its low profile.

5.2 Suggestions for future work

An important future task would be to work on improving the etching process in order to obtain smooth surfaces by optimizing all the parameters of laser station and with the absorbing/etching solutions.

Other glasses such as borosilicate can be used as the waveguide using and a 355nm UV laser can be employed to obtain better quality etching [65]. Also, IR LIBWE using CuSO₄ as absorbing liquid should be tested. Another possible research work is trying to also make the lens array by LIBWE (as opposed to fabricating it by molding) as in Figure 5-1 [80]. Potentially, lower cost of high performance micro lens array made of glass may be achieved by this technology. This will allow that both the lens array and the waveguide with cones as the couplers are all made by glass using LIBWE technology.
Figure 5-1: Image of the quartz microlens array fabricated by LIBWE and projection of a diffractive gray tone phase mask (DGTPM) [80].
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