Dimpled Planar Lightguide Solar Concentrators

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Curriculum Vitae

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Abstract

Solar energy is an important part of the renewable energy solution and concentrated photovoltaics promise to provide a source of cost effective and clean energy. By concentrating solar energy with optics, less photovoltaic (PV) material is used, reducing cost, since many PV materials are expensive and energy-intensive to produce compared with optical components. Component and cell lifetime, weight, and scalability are critical to solar concentrator performance and a design's ability to impact the energy needs of the world. This research proposes a new type of non-imaging lightguide concentrator that transfers a large input area to a strip at one end of the device. Bounding equations are presented, defining limits of performance. Mathematical models of dimpled lightguides are developed and compared to non-sequential ray trace models. Detailed ray trace models are developed and optimized. Two prototype generations are modeled, fabricated, tested, and analyzed. In all, twenty prototypes are fabricated and tested. The highest performing prototype dimpled lightguide demonstrates an optical efficiency of greater than 70 percent, with a concentration of 53 and an acceptance angle of ± 1.0 degree.

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1 Introduction

1.1 Overview

At noon on a sunny day, about 1,000 watts of solar power is incident on one square meter of the earth. Over the course of a year, that same spot receives roughly 3,000 kilowatt-hours of energy. As the world looks toward solar as one component of a sustainable energy solution, the challenge is to capture as much of this energy as possible. In order to replace or offset a substantial portion of non-renewable electricity generation, vast areas of sunlight need to be collected. For example, the United States used roughly 4 trillion kilowatt-hours of electricity in 2008 and is projected to use 5 trillion kilowatt-hours by 2030. In order to satisfy the current total electricity demand using only solar power, approximately 15,000 square kilometers of sunny space would need to be covered with current solar technologies, assuming 10 percent conversion efficiency. While this is a large area, it is less than the area consumed by the 6 million kilometers of U.S. roadways, an area greater than 50,000 square kilometers [1-2].

Photovoltaics use semiconductor materials to convert light directly into electricity by using the photoelectric effect—more specifically, the photovoltaic effect. Focusing light to a small cell using inexpensive lenses and mirrors requires far less area of photovoltaic detector material for the same collected energy. This reduces the cost of the photovoltaic material needed per energy collected and decreases the portion of the system cost attributed to photovoltaic (PV) cells. Highly efficient, more expensive cells can thus be used—which directly impact the system cost per watt of electricity generated. Since many of the materials used in PV cells are subject to large fluctuations in price, reducing the cell's portion of the system cost also decreases the effects of supply-chain variability. Concentrated photovoltaic energy (CPV) maximizes the amount of energy collected from small patches of photovoltaics. CPV represents a small but growing segment of the solar market, and is one of the most promising—and optically interesting—technologies to address the renewable energy needs of the United States and the world.

Solar energy is used for both heat and electricity generation. Modern buildings are designed to take advantage of passive solar heating and/or cooling. The dominant solar energy generation technology

today is concentrated solar power (CSP), also known as solar-thermal energy. It uses mirrors to focus the sun onto receivers that convert light into heat. This heat can be used directly for heating buildings or manufacturing processes, or it can be converted into electricity by using a steam turbine. Since the current infrastructure associated with high-pressure steam and turbines is substantial, CSP electricity generation is only economical at very large scales. Conversely, PV cells can convert light directly into electricity. Unlike solar-thermal, photovoltaic electricity generation requires very little infrastructure. This makes PV cells practical for both large installations and much smaller ones, such as the roofs of homes and commercial buildings.

The dominant PV technologies are flat-plate silicon and thin-film technologies. Both rely on economies of scale to minimize production costs in the continued effort to make photovoltaics cost-competitive with other forms of electricity production. As a result, these low-cost approaches require vast areas of semiconductor material to generate significant amounts of energy. Despite world-record “hero” silicon cells that produce efficiencies of more than 25 percent in the laboratory, typical flat-plate modules range in efficiency from 10 to 15 percent. Alternatively, commercial CPV systems have demonstrated efficiencies as high as 30 percent, thus reducing the cost and environmental impact by using smaller areas of semiconductor [3-4].

This research focuses on a new type of nonimaging concentrator, the dimpled lightguide concentrator. This concentrator allows for significant concentration and acceptance angle in a thin, lightweight, and potentially mass-manufacturable form. The device uses four components to transfer light from its input aperture to a target plane. First, an array of focusing elements concentrates light to an array of small patches within a planar lightguide (a plate of glass or plastic, for instance). Second, injection elements within this optical medium divert the light into angles that can be guided by this planar layer. Third, this planar guiding layer carries light toward a target plane. And fourth, bypass elements divert light traveling in the guide around downstream injection elements in order to maintain high optical efficiency. Without the bypass element, introduced in this thesis, injection elements would just as easily eject light from the guiding layer as they inject light, so the introduction of bypass elements represents a critical advancement in the practical use of lightguide concentrators.

1.2 Background

The ideal solar concentrator is a dichotomy, having both the highest efficiency with the lowest cost, and maximum concentrating power with the simplest geometry. Simplicity and cost often take precedence over novel designs. Despite varying objectives, certain specifications and design considerations apply regardless of optical design form [5-6].

Geometric concentration ratio is the collected area of solar radiation divided by the area of the photovoltaic material $C_x = \text{Area}_{\text{collected}} / \text{Area}_{\text{cell}}$. Higher concentration ratios mean smaller cell areas, hence reduced cell costs. *Acceptance angle* is the amount of sky the optical system can “see” and transfer to the cell. The maximum attainable acceptance half-angle is related to the concentration ratio and given by $C_{\text{max},2D} = n_{\text{cell}} / \sin\theta_B$ for one-dimensional concentration, and $C_{\text{max},3D} = n_{\text{cell}}^2 / \sin^2\theta_B$ for two-dimensional concentration, θ_B is the half acceptance angle, and n_{cell} is the index of refraction of the material surrounding the cell. *Optical efficiency*, η_{optics} , is the percentage of light entering the optical system that reaches the PV cell. It accounts for Fresnel reflection losses, material absorption, and “rejected” light or light that entered the optical system but was ejected before reaching the cell. *Effective concentration*, $C_{\text{effective}} = C_x \eta_{\text{optics}}$, is the product of the concentration ratio, C_x , and optical efficiency, η_{optics} . The product of effective concentration and the incident irradiance (roughly 1,000 watts per sunny square meter) determines the actual incident energy on the PV cell. This is the energy the cell “sees.” *Irradiance uniformity* is a measure of the evenness of energy distribution across the surface of the cell. Some PV cells are sensitive to non-uniform illumination, resulting in non-uniform current generation across the cell.

Nonimaging optics is the study of light transfer from an extended object to an extended target. It can include an imaging condition or constraint and many nonimaging designs work well as imagers [5]. For maximum flux transfer, however, the condition of point-to-point mapping from object to target is removed [7]. The compound parabolic concentrator (CPC), first solved analytically by Winston, is a commonly known nonimaging solution [8]. The primary goal of a concentrator is to efficient transfer étendue or in simple terms the angle-area product, from object to target. In general, *étendue* is represented as four-dimensional quantity given by $n^2 dx dy dL dM$, where x and y are spatial coordinates and L and M are the x

and y direction cosines. This quantity is determined by the given source, and optical systems attempt to transfer this quantity efficiently [9-10].

Existing CPV systems span the range of concentration from 2 to greater than 500, depending on the application and type of PV cell. Low concentration systems, those with concentrations up to 10, are often used for fixed (non-moving) terrestrial applications as well as some space-based concentrators. This and similar systems use modified existing PV cells but reduce the PV materials needed with simple optics. Low concentration systems attempt to lower system cost by reducing photovoltaic area without the need for precision tracking mechanisms. Medium concentration systems range from 10 to 100 and need only one-axis tracking depending on the design. These systems attempt to balance significantly reduced cell areas with inexpensive tracking. High concentration systems (greater than 100) allow for the greatest photovoltaic-to-system cost savings, but require two-axis tracking. Since the cell size is so small compared with the collected area, very efficient cells can be used. High concentrations systems have the highest generated energy per collected area, but they require precise alignment and tracking.

Many medium and high concentration systems use *secondary optics*. *Secondary optics* are elements that provide increased concentration, expand acceptance angle, improve irradiance uniformity at the cell, and are located near the cell. The clear apertures of these elements are smaller than the input aperture of the concentrators. There are many forms of secondary optics, ranging from refractive elements and mixing rods to square or round non-imaging concentrators. Refractive elements are usually placed near the cell and roughly pupil-image [10]. Imaging the pupil creates uniform irradiance but causes the angles of incident light, instead of the actual location of the spot, to “walk” on the detector [11]. Since a cell’s efficiency is much less sensitive (if not totally insensitive) to angle walking, this type of secondary can perform very well.

Figure 1.1: Pupil imaging secondary concentrator

Mixing rods, which can be either solid or hollow, work differently. One end of the rod is placed at the focus of the primary concentrating element, and the other end is cemented or held near the PV cell. The mixing rod's length and cross-sectional shape determine the irradiance uniformity, and, since the main goal is simply to get away from the focus (since getting away from the focus makes the irradiance more uniform for certain cross-sectional shapes), these elements can be fairly short, depending on the uniformity required. Tapering or curving the rod adds additional concentration, since the output can now be smaller than the input face. This “squeezing” of the output face is the basis for a host of nonimaging concentrators, the most commonly known of which is the compound parabolic concentrator (CPC) [8].

Most CPV systems require some type of tracking mechanism—a means of re-pointing the system toward the sun as it moves throughout the day. Single axis tracking comes in two varieties with the single axis of rotation that is either aligned east-west (as with parabolic troughs) or north-south (also called azimuthal). The east-west configuration allows long uninterrupted parabolic reflective troughs, which are especially advantageous for solar- thermal collection, where liquid flows in a tube placed at the focus of the trough. The liquid is heated by the sun's energy then used directly as heat for industrial processes or used to power steam turbines for electricity generation. A north-south, or *azimuthal*, configuration allows for the maximum possible one-dimensional concentration, and many PV systems—from flat-plate to medium-concentration—use this type of one-axis tracking. Trackers decrease the required acceptance angle of concentrators, allowing for higher concentration ratios. Trackers also eliminate the “cosine falloff” that occurs when the sun is low in the sky. The effect is shown in Figure 1.2. Without tracking, the projected

area of the sun's energy, and therefore the collecting area, grows small as the sun approaches the horizon. Stationary systems sacrifice nearly half of the potential energy because of this cosine falloff.

Figure 1.2: Cosine falloff effect

The characteristics of the sun and sky, which depend on geographic location, weather conditions and the time of day and year, play a critical role in the choice of solar collection technology. The amount of cloud cover is the biggest factor to consider when choosing the type of solar collector, since a cloudy sky changes the source from direct to diffuse. Figure 1.3 and Figure 1.4 show the insolation data measured in Golden, CO, for a cloudy day, a sunny summer's day, and a sunny winter's day. The direct component is the irradiance coming from a ± 5 degree cone centered on the sun. The diffuse component is the irradiance coming from the rest of the sky, typically measured on a horizontal plane. The irradiance of diffuse radiation on a cloudy day varies from 100W/m^2 to 400W/m^2 , depending on the type of cloud cover.

Figure 1.3: Characteristic cloudy day insolation data, Golden, CO

Figure 1.4: Characteristic sunny-day insolation data, Golden, CO, December and June

The solid angle that a concentrator can use at any given time is the reciprocal of the concentration ratio. For instance, a concentration of 10 limits the cell to “seeing” only one-tenth of the sky. As a result, in cloudy regions, flat-plate or low-concentration systems make sense because incident energy is coming from all parts of the sky at once. To collect the maximum energy, the collector must be able to “see” large portions of the sky. In sunny regions, most of the incident energy comes directly from the small patch of sky near the sun, so a collector only needs to see this small patch at any given point. In such locations, high-concentration systems can outperform flat-plate and low-concentration systems.

The angular extent of the sun is approximately 0.5 degrees full angle, so a sunny-region solar concentrator must be able to “see” this amount of the sky or more. Practical concentration ratios generally do not exceed 1000, even though the upper limit of optical concentration (for a cell in air, 0.5 degree acceptance full angle) is upwards of 50,000, because very few optical or photovoltaic materials can withstand such high energy densities. Even the most robust PV cells optimized for maximum energy density lose performance above roughly 500 [12]. Figure 1.5 shows a plot of measured efficiency versus concentration for a 40.8 percent efficient triple-junction solar cell. Similarly, silicon cells lose efficiency at very high concentration, even when active cooling is used [13]. In addition, the acceptance angle must be oversized to account for manufacturing and alignment tolerances of the concentrator system, as well as allowing for errors in the tracking mechanisms.

Figure 1.5: Plot of efficiency versus concentration for a III-V PV cell

1.3 Solar Energy Markets

Solar energy is used for many applications in installations ranging from kilowatts (residential and portable) to multi-megawatt (utility). Table 1.1 shows the breakdown of market segments. Solar energy production is classified by size into one of five categories: portable, residential, commercial, industrial, and utility. Portable systems produce less than 1kW peak power and work to provide the highest power-per-area and the lowest power-per-weight. These systems are more expensive on a cost-per-energy basis, since cost is secondary to portability. Residential systems produce less than 10kW peak power and are generally installed on rooftops pointed southward. Commercial systems range from 10kW to 100kW and are installed on flat rooftops or on vacant land close to the point-of-use. Industrial systems range from 100kW to 1MW and also tend to be placed on vacant land close to the point-of-use. Finally, utility scale systems having peak capacities exceeding 1MW can be placed in close proximity to high-demand areas or located in sunny areas with power fed into the electricity grid and transmitted over large distances. The type of solar technology depends strongly on the scale of the installation. Solar thermal is limited to industrial and utility scale power generation, while photovoltaics can be used for all size scales.

Portable	< 1kW
Residential	1kW to 10kW
Commercial	10kW to 100kW
Industrial	100kW to 1MW
Utility	>1MW

Table 1.1: Solar collector market segments

Solar thermal energy is generally limited to either heat production at any scale or large-scale utility installation because of the required heat-to-electricity conversion infrastructure. Applications include utility electricity production, steam-heat for manufacturing, and residential or commercial hot water. Figure 1.6 shows a 10MW solar thermal electric power system. Each mirror (left) has an area of 100 square meters, and the system has 700 mirrors. The geometrical concentration is approximately 500. Each mirror directs solar energy onto a boiler at the top of the tower (upper right), where the energy is turned into steam then used to turn steam turbines. A steam reservoir allows the system to continue operating for up to two hours after the sun sets.

Figure 1.6: Abengoa Solar 10MW “power tower” outside Seville, Spain (photo by author)

Hot water can be produced at small and large scales using concentrators or selective surfaces [14]. Selective surfaces have vastly different emissivities in the visible and infrared (IR) parts of the spectrum. These surfaces readily absorb visible and near IR energy but have very low emissivities in the thermal IR. In this way, heat energy is trapped inside the material and can generate temperature differentials of tens or hundreds of degrees. By flowing water or heat transfer fluid through the substrate material, this heat energy can be collected.

On a cost per kilowatt-hour basis, photovoltaics tend to be more expensive than solar thermal, but have critical advantages. Photovoltaics are more versatile with respect to the scale of installations and don't require the amount of infrastructure that solar thermal does. Also, while solar thermal is a developed technology, technological advancements in photovoltaic materials and concentrator design continue to reduce the cost of photovoltaics. Residential photovoltaics installed on rooftops typically are flat-plate or low concentration PV, since for the most part, trackers are better suited for installation on flat land. Low concentration systems are discussed in section 1.4.1. Also, trackers have moving parts, which are subject to breaking and hence require regular maintenance. Commercial and industrial systems allow for the option of trackers, so these installations can be any concentration from 1 (flat plate) to 1000 or more (high concentration PV). Medium and high concentration systems are discussed in section 1.4.2 and 1.4.3. The advantage of PV at these scales is the simplified infrastructure and high energy-to-land ratio compared with solar thermal. Finally, utility scale PV system can use any of the PV technologies and to maximize energy collection, trackers are commonly used. Utility PV system can be installed in a variety of locations, not just perpetually sunny locations. The following discussion details the current concentrator technologies competing in the PV market.

1.4 Types of CPV systems

1.4.1 Low Concentration Systems (<10x)

A few companies are pursuing low concentration photovoltaic systems. Table 1.2 lists these companies, the type of optical configuration, and geometrical concentration[15-16]. These systems range in concentration from 1.5 to 4. Only Abengoa Solar places their concentrator on a tracker in order to eliminate the cosine falloff effect. This limits the Abengoa Solar design to commercial scale and larger installations. Most low concentration systems are designed for fixed installations and can be used on rooftops at the residential and small commercial scale. The motivation behind these concentrators is not efficiency, but rather cost reduction by reducing the area of semiconductor material watt produced [17]. All of the systems use silicon photovoltaic cells. Figure 1.7 shows an image of a reflective concentrator with a concentration ratio of two. Covalent Solar is currently working to commercialize fluorescent planar lightguides, but

currently does not have an operational prototype. Fluorescent planar lightguides use fluorescent dyes embedded in a planar guide layer to concentrate light. Light is absorbed by the dye and is reemitted into all angles. A portion of that light is trapped in the guide and transported to the edge. Fluorescent concentrators are discussed further in chapter 2.

Company	Optics Type	Concentration	Tracking	URL
Abengoa Solar	Reflective V-trough	1.5 - 2.2	Two-axis	www.abengoasolar.com
Covalent Energy	Fluorescent lightguide	5	Fixed	www.covalentsolar.com
Prism Solar Technologies	Holographic	2	Fixed	www.prismsolar.com
Solaria	Linear trough	2	Fixed	www.solaria.com
Stellaris	TIR V-trough	3	Fixed	www.stellaris-corp.com
WS Energia	Reflective V-trough	2	Fixed	www.ws-energia.com
Zytech Solar	Reflective V-trough	1.6	Fixed	www.zytech.es

Table 1.2: Summary of low concentration CPV companies

Figure 1.7: Image of a 2x reflective concentrator with silicon PV cells (photo by author)

Prism Solar's module is unique because it uses bifacial silicon cells, a diffractive film to divert incident light into the glass layer, and primitive light guiding [18]. Figure 1.8 shows a schematic of the Prism Solar concentrator. Part of the light is absorbed directly by the top surface of the PV cells, which are spaced apart laterally between two glass plates. Diffractive film is placed in the areas between the PV cells, and incident light in these areas encounters the diffractive film. The film diverts some of the light at angles that support total internal reflection and this light is guided along the glass layer until it meets a PV cell. Since the diffractive film can just as easily couple light out of the guiding layer, the distance traversed within the guide before meeting a PV cell must be small.

Figure 1.8: Prism Solar – Holographic Planar Concentrator

1.4.2 Medium Concentration Systems (10x to 100x)

Medium concentration systems require one or two axis tracking, and most medium concentration systems use silicon PV cells. The fields-of-view of these devices are large compared with high concentration systems. Table 1.3 shows a list of companies that have developed medium concentration systems [15-16]. Four of these systems use a reflective trough to focus solar energy to a line. These systems have small fields-of-view in the tracking direction and very wide fields-of-view in the non-tracking direction [19]. Reflective troughs are cheap to produce, and are a developed technology because of the solar thermal industry. Some medium concentration systems attempt to use both the visible and thermal components of the sun's energy by converting the visible spectrum into electricity, using PV materials and siphoning off the thermal energy with heat transfer fluid. These systems have had limited commercial success because of the complexity associated with active cooling [20].

Company	Optics Type	Concentration	Tracking	URL
Absolicon Solar Concentrator	Reflective trough	10	One-axis NS	www.absolicon.com
Cpower	Reflective Point-focus	25	Two-axis	www.cpower.it
Entech Solar	Extruded Cylinder Fresnel	20	Two-axis	www.entsolar.com
HelioDynamics	Reflective louvered trough	50	One-axis NS	www.hdsolar.com
Skyline Solar	Reflective trough	10	One-axis NS	www.skyline-solar.com
Whitfield Solar	Reflective trough	70	One-axis EW	www.whitfieldsolar.com

Table 1.3: Summary of medium concentration CPV companies

Medium concentration systems are also being developed for ultra-high efficiency systems using spectral splitting [21]. These systems work to maximize the power per unit area for applications that are space-limited or where portability is required. Figure 1.9 shows a schematic of the module developed at the University of Rochester for the DARPA Very High Efficiency Solar Cell program. These devices have demonstrated module efficiencies of 38.5 percent [22]. The design has a field-of-view of ± 5 degrees and a

concentration of 40. The optics were designed, modeled, and tested at the University of Rochester. Incident light is focused by a refractive element before being spectrally split using a dichroic mirror. The visible band is directed to a cell at the top of the diagram and the IR is transmitted to a cell at the right of the diagram. Each cell has two band gaps and is independently optimized for the split spectrum.

Figure 1.9: Schematic of ultra-high efficiency module, developed for DARPA VHESC

1.4.3 High Concentration Systems (>100x)

High concentration systems are the dominant technology within CPV. The cost reduction approach for high concentration systems is to use extremely efficient and therefore expensive, photovoltaic materials in order to maximize the value of the optical and tracking systems [23-26]. In order to make these PV materials competitive, their area must be very small compared to the collected area. Table 1.4 shows a list of companies that have developed high concentration PV systems [15-16].

Company	Optics Type	Concentration	Tracking	URL
AEST	Refractive point-focus	500	Two-axis	www.aest.it
Amonix	Refractive point-focus	500	Two-axis	www.amonix.com
Arima Eco Energy Tech	Refractive point-focus	476	Two-axis	www.arimaeco.com
Beghelli	Refractive point-focus	500	Two-axis	www.beghelli.it
Concentrix Solar	Refractive point-focus	385	Two-axis	www.concentrix-solar.de
Cool Earth Solar	Reflective point-focus	400	Two-axis	www.coolearthsolar.com
Emcore	Refractive point-focus	1050	Two-axis	www.emcore.com
Enea Portici Research Center	Refractive point-focus	300	Two-axis	www.enea.it
Energy Innovations	Refractive point-focus	1200	Two-axis	www.energyinnovations.com
Enfocus Engineering	Refractive point-focus	300	Two-axis	www.enfocus.us
Everphoton	Refractive point-focus	1000	Two-axis	www.everphoton.com
Green and Gold Energy	Refractive point-focus	1370	Two-axis	www.greenandgoldenergy.com.au
Greenfield Solar	Segmented reflective dish	1000	Two-axis	www.greenfieldsolar.com
Greenvolts	Reflective point-focus	1000	Two-axis	www.greenvolts.com
Guascor Foton	Refractive point-focus	400	Two-axis	www.guascorfoton.com
INER	Refractive point-focus	476	Two-axis	www.iner.gov.tw
Isofoton	Refractive point-focus	1100	Two-axis	www.isofoton.com
Menova Energy	Reflective louvers	1450	Two-axis	www.power-spar.com
Morgan Solar	Stepped lightguide	1100	Two-axis	www.morgansolar.com
Opel	Refractive point-focus	500	Two-axis	www.opelinc.com
Pyron Solar	Refractive point-focus	1000	Two-axis	www.pyronsolar.com
Shap	Reflective dish	500	Two-axis	www.shap.it
Sharp	Refractive point-focus	700	Two-axis	www.sharp.co.jp
Sol3g	Refractive point-focus	476	Two-axis	www.sol3g.com
Solar Systems	Reflective dish	500	Two-axis	www.solarsystem.com.au
Solfocus	Reflective point-focus	500	Two-axis	www.solfocus.com
Soliant Energy	Refractive point-focus	500	Two-axis	www.soliantenergy.com
Sunrgi	Refractive point-focus	1000	Two-axis	www.sunrgi.com
Zenith Solar	Reflective dish	1000	Two-axis	www.zenithsolar.com

Table 1.4: Summary of high concentration CPV companies

1.4.3.1 Fresnel-Type

By far the most common type of concentrator design is the Fresnel type refractive point-focus concentrator. Fresnel concentrators use a Fresnel lens as the primary focusing element, typically with numerical apertures around 0.5 [27]. Some extreme numerical aperture Fresnel lenses use total internal reflection at their outer facets to focus light, since refractive Fresnel lenses are limited to numerical apertures of less than 0.65 [28]. For refractive Fresnel lenses, light beyond this numerical aperture TIRs from the facet and is lost. If instead, the facet angle is adjusted to a steep angle, light TIRs from the facet and is then refracted through the draft face [29]. Figure 1.10 shows ray traces of a refractive Fresnel facet operating near its limit and Fresnel facet optimized for TIR.

Figure 1.10: Refractive Fresnel facet at the limit of refraction (left), and a TIR Fresnel facet (right)

Fresnel lenses are typically injection molded with plastics such as PMMA or polycarbonate, or are formed into silicone that is adhered to flat glass substrates. Both of these fabrication methods lend themselves to high volume and low cost. For solar applications, the lenses are used at infinite conjugates, and for the best transmission, the Fresnel surface is typically placed toward the image. This accomplishes two things. First, it protects the grooved Fresnel surface from the environment, an environment that can be dusty or moist- severely reducing optical performance or shorting the life of the optic. Second, the transmission efficiency for high numerical aperture Fresnel lenses is greatly improved when the Fresnel surface is toward the image. This is contrary to traditional optical design and aberration theory in which one attempts to split the optical power between surfaces. Figure 1.11 shows ray traces for facets near the edge of Fresnel lens with an NA of 0.5. The left trace shows the Fresnel facet toward the sun (object side), and the right ray trace shows the Fresnel facet toward the PV cell (image side). Notice in the left image, a large portion of light is refracted at the surface and then diverted by the draft of the lens. The draft is the vertical, or nearly vertical, surface that connects adjacent facets.

Figure 1.11: Fresnel facet on object side (left) and image side (right)

In order to remove a replicated lens from its mold, the draft faces cannot be totally vertical, since this would “lock” the part to the mold. To avoid this, a draft angle is introduced, and this angle is no less than 2 degrees and is more typically 5 to 10 degrees[30]. Another fabrication constraint is the sharpness of the intersections between Fresnel surfaces. Since neither machining nor molding can produce perfectly sharp edges, Fresnel lenses have some edged rounding at these intersections. This rounding is specified by a fillet radius, the radius of the edge rounding. Fillet radii range from 2 to 20 micrometers depending on the mold fabrication, replication technique, and size of the Fresnel features. Both draft angles and fillet radii reduce the optical efficiency of Fresnel lenses, so minimizing both is critical for high optical efficiency. Figure 1.12 shows diagrams of a draft angle and fillet radius. In some processes, the fillet radii of the peaks and valleys differ.

Figure 1.12: Draft angle (left) and fillet radius (right)

Fresnel lens point-focus concentrators also typically employ secondary concentrators to further concentrate light and to homogenize light at the cell plane. Without secondary optics, Fresnel lenses produce small focal spots that “walk” around on the cell, creating high peak irradiances and significant dark

areas. This impacts cell performance. Secondary concentrators are typically nonimaging devices that are either hollow reflectors, or more commonly solid glass using TIR. Plastics cannot be used, since the flux near the focus of a Fresnel is extremely high. Solid secondaries are optically cemented to the cell to reduce reflection losses and to take advantage of the increased étendue throughput of a high index material. Figure 1.13 is an image and schematic of a Fresnel concentrator array. The Fresnel lenses (top) focus light to a spot near the top surface of the secondary concentrators (bottom), which then further concentrates and homogenizes. Light exits at the bottom of the secondary concentrators onto triple-junction, high efficiency PV cells.

*Figure 1.13: Sol3G Fresnel concentrator module (left) and schematic of a lens plus secondary (right)
(photo by author)*

1.4.3.2 Reflective

Reflective concentrators use one or two mirrors to focus and concentrate solar energy. Reflectors have the advantage of avoiding chromatic aberration, so the primary concentration can be significantly higher than Fresnel systems. Reflective system must contend with shadowing losses, unless the mirror system is significantly off-axis. For rotationally symmetric systems, a PV receiver or secondary mirror shadows the primary mirror. Minimizing the size of this obscuration is critical to high efficiency. Reflective systems do tend to be flatter than refractive systems, since the optical path is folded back on itself [31]. As with Fresnel concentrators, most reflective systems require some type of secondary concentrator to homogenize light at the cell plane.

Boeing and Spectrolab have partnered to develop a single mirror, plus nonimaging refractive secondary concentrator design [32]. This optical path of one reflection plus refraction is denoted as XR [33-34]. The mirror figure and secondary concentrator shape were simultaneously optimized for maximum performance using the simultaneous multiple surfaces (SMS) method [35]. Figure 1.14 shows a schematic of the XR concentrator design. The system has a concentration ratio of 1,000 and an acceptance angle of ± 1.8 degrees. The aperture diameter is approximately 250mm. The primary disadvantages of this system is that the PV cells, heat sinks, and electrical interconnects stand in front of the mirrors; and the mirror surfaces and secondary concentrators are exposed to the elements. The exposure of the reflective and refractive surfaces means that mirror lifetime is shortened. After just a few months, optical surfaces exposed to environment must be cleaned for optimal performance. Since the mirror are not accessible for cleaning, except by power washing, dust and dirt buildup decreases the reflectance of these mirror over the life of the system.

Figure 1.14: Schematic of the XR concentrator, US Patent App. 20080223443

The commercial leader in two-mirror designs is Solfocus. The Solfocus design resembles a high numerical aperture Cassegrain-type telescope. The optical path involves two reflections and a TIR reflection, denoted as XXI [36]. Figure 1.15 shows a schematic of the XXI concentrator design. Light reflects from a nearly parabolic concave primary mirror, reflects from a convex hyperbolic mirror, and back through a hole in the primary mirror to a focus. A secondary concentrator is placed near the focus, and light is further concentrated and is homogenized [37-38]. The secondary mirrors are placed on the back of a flat cover glass, which encapsulates the two reflective surfaces. This overcomes one of the lifetime issues of the XR design.

Figure 1.15: Schematic of the XXI concentrator design, US Patent App. 20090159126

The state-of-the-art for reflective concentrator designs are the XX Kohler integrating concentrator developed by Winston, and the RXI concentrator developed by Miñano. Winston's double reflection Kohler integrator removes the need for a secondary concentrator by sub-aperture pupil imaging [39-40]. Each annulus of the primary and secondary mirror surfaces pupil images and fully fills the cell plane. This creates a uniform irradiance at the cell plane. The primary challenge of this design is fabrication, since the surface figure of the primary and secondary mirrors as well as the alignment of the two mirror surfaces must be tightly controlled. Figure 1.16 shows a schematic of the Kohler integrator, and the ray paths demonstrate the sub-aperture pupil imaging.

Figure 1.16: Schematic of the XX Kohler integrator concentrator design, US Patent App. 20090231739

Miñano proposes a solid concentrator consisting of a refraction, reflection, and TIR reflection to correct all of the optical aberrations [41-42]. This concentrator design performs well as both an imaging and nonimaging concentrator, but it does have one drawback. The receiver plane is immersed inside the volume of the concentrator. Figure 1.17 shows a schematic of the RXI concentrator design with immersed receiver.

Figure 1.17: Schematic of the RXI concentrator design, US Patent Ap. 6639733

Winston expands on this idea and constrains the target plane to be at the back surface of the concentrator [43-44]. As with the original RXI, this design works well as an imaging concentrator and approaches the étendue limit. As with the many of the previous designs, this design requires a secondary optic for homogenizing light at the target plane in order to prevent damage to a PV cell.

An important factor in cost effective concentrator designs is aspect ratio, the ratio of aperture width to the total thickness. Chaves et al propose techniques for using a plurality of sub-aperture concentrators fed into a larger secondary concentrator that has the benefits of CPC-type nonimaging concentrators and the flat aspect ratio of lightguides[45]. Chaves' concentrators use the same optimization algorithms as the design of the previously mentioned concentrators and theoretically have equally high performance [46]. These ultra-flat concentrators provide a glimpse into the potential benefits of thin aspect ratios, but the designs while theoretically possible, are not manufacturable due to their complexity. Chapter 2 discusses lightguides as concentrators and introduces the subject of this research, dimpled planar lightguide concentrators. This research works to incorporate nonimaging concentrator design with lightguides to provide highly efficient, ultra-flat, manufacturable solutions to solar concentrators.

2 Lightguide Concentrators

2.1 Background

2.1.1 Lightguides

Lightguide are structures that trap light in a high index medium by use of total internal reflection. For angles above the critical angle of a guiding medium and its bounding medium, light is reflected perfectly (less material absorption, and surface and material scattering). Lightguides have had a range of applications, most notably in two areas: fiber-optics communications and backlights. Despite widespread use in these fields, very few practical concentrators have been developed using light guiding. The potential advantage of lightguide concentrators is their thin aspect ratio, which serves to reduce material usage and weight, and allows for alternative fabrication and manufacturing techniques.

In fiber-optic communications, the *core*, the central region with highest index, is nominally rotationally symmetric. The *cladding*, the material surrounding the core, has a lower index of refraction. Light is trapped and guided within the core and because of the lossless nature of total internal reflection, light can be transmitted long distances with minimal reduction in signal. Rotationally symmetric light guides can be broken into two size scales- large-core light guides, where light can be described by the geometrical optics, and small-core light guides, or *waveguides*, where light is described by physical optics, and the transmitted energy is carried in both the core and cladding. Fiber-optic light guides generally have the same cross-section along their length, and work to maintain or transfer all of the angles of light injected to the output. In other words, they attempt to maintain but not transform the injected étendue, as defined in section 1.2. Fiber-optic light guides transfer an input with a small area and large angular extent to an output with small area and similar large angular extent.

Backlights use lightguides to distribute light from either a line or point source, across a large output area. For these applications, the lightguide surfaces are often planar, so light is trapped and guided between two parallel or mostly parallel surfaces. Unlike fiber-optic lightguides or concentrators, backlights work to meet prescribed output characteristics such as wide and uniform angular distributions (for wide viewing angles), and uniform spatial distributions. The additional constraints placed upon backlights makes

them inherently inefficient with respect to étendue. Often, scattering, polarization, and recirculation are used to achieve a desired result. Backlights generally work to transfer an input with small spatial extent and large angular extent to an output with a large spatial extent while meeting prescribed angular and uniformity specifications at the output.

2.1.2 Lightguide Concentrators

In the past, lightguides have been used as transport components within concentrator systems, but in recent years, a few groups have begun exploring the potential of lightguides as concentrators. Lightguide concentrators are distinguished from systems simply using lightguides for light transport. Lightguide concentrators require that the lightguide plays an integral part in concentrating or combining light. A number of techniques have been proposed for lightguide concentrators. The oldest is the luminescent lightguide concentrator, which uses a planar slab of plastic or glass embedded with fluorescent dye. Light is absorbed then reemitted by the dye isotropically, so that a portion of the emitted solid angle is guided by the planar guide

Morgan Solar, a Canadian company, proposes a swept-stepped lightguide composed of a focusing layer and an injection-guiding layer, seen in Figure 2.2. Light is focused using refractive elements onto angled injection features that turn the light into angles supported by a stepped guide. Light is then transported to a central receiver plane.

A group from UC San Diego proposes a micro-structured solar concentrator composed of a refractive focusing layer, a planar slab guiding layer, and micro-prism injection features. Finally, a group at the Complutense University of Madrid (UCM) has filed a patent application that employs a plurality of focusing elements placed above corresponding injection elements, which exist within a planar guiding layer. Light is injected in one direction and is guided to one edge of the planar guide. Their design most closely resembles the dimpled planar lightguide. These design forms are discussed in detail and demonstrate the wide variety of design forms enabled by lightguides.

2.1.3 Luminescent lightguide concentrators

Luminescent lightguide concentrators were proposed more than sixty years ago as a means to amplify the signal of fluorescent radiation counters [47-48]. With the development of photovoltaics, luminescent guiding and concentrating was revisited as a means to cheaply concentrate solar energy without the need for trackers [3, 49-50]. In theory, luminescent concentrators are not limited by the phase-space conservation of Liouville's theorem, since the light is absorbed and reemitted by dyes or quantum dots within the guide [9, 51]. In practice, however, luminescent concentrators have low optical efficiency because most dyes do not have sufficient separation of the absorption and emission bands. These concentrators have been shown to operate at efficiencies up to 4 percent, with concentration ratios approaching 10 [52].

Figure 2.1: Luminescent Concentrator – US2005/0166953A1

Figure 2.1 is a schematic of a planar luminescent concentrator. Incident energy excites fluorescent molecules contained within a planar lightguide. These molecules reemit this energy at a longer wavelength and are assumed to emit isotropically. Roughly 60 percent of the solid angle satisfies total internal reflection and is captured by the guide. If the absorption and emission bands are separated sufficiently, light is transmitted within the guide without re-absorption. This separation of absorption and emission bands is the primary challenge behind luminescent concentrators, and is the primary cause for their poor optical efficiency. Even a small overlap in these spectra is problematic, since the number of interaction between light and dye molecules is large.

2.1.4 Swept-stepped lightguides

Morgan Solar proposes another optical solution to lightguide concentrators[53]. In this design, a series of extruded and swept lenslets focus into a lightguide, where light is diverted by injection elements and captured by the guide. The guide is stepped so that at each injection face, the guide grows larger in height. The top and bottom surfaces of the guide are nominally parallel with respect to each other, so the guide itself does not provide any concentration. Instead, this technique allows for a far flatter concentrator than the refractive or reflective equivalent. Figure 2.2 shows both a schematic of the Morgan Solar lightguide concept and an isometric rendering of the swept lenslet layer.

Figure 2.2: Schematic from US Patent App. 12/113705, 20080271776 (left), and Isometric plot of a swept lenslet layer (right)

Morgan Solar claims that this design form can achieve concentrations from 700 to 1,400; however there are no published results on actual performance. Ray trace models show that high concentrations are possible using this geometry, but there are serious challenges to its practical use. Most importantly, the stepped lightguide design requires molding complicated geometries into solar resistant materials. The only practical materials for molding Morgan Solar's design are plastics, but solar resistant plastics degrade quickly under high concentrations, both from ultra-violet degradation and infrared heating. For instance, accelerated lifetime testing of materials is conducted by placing the material under 100x to 500x concentration. Under these concentrations, one month of accelerated testing typically corresponds to ten years of one-sun exposure. Solar resistant PMMA typically shows a 10% reduction in transmission through 5mm after 3 months of accelerated testing. For concentrators to be viable, the guiding layer must maintain high transmission for the life of the device, generally more than 3 months. Assuming the UV is blocked, IR

still poses a serious problem at high concentration in thick plastic parts. Since plastics have low thermal conductivity and low melting temperatures, even minor absorption at high concentrations can cause extreme temperatures within the guide. Glass would be the preferred guiding material, but no method has been shown for molding fine features directly in glass.

2.1.5 Planar micro-prism lightguide

Karp and Ford at the University of California, San Diego have proposed another type of solar concentrator based on an array of lenslets, a slab lightguide, and a corresponding array of prismatic features [54]. Figure 2.3 shows a schematic of this layout. This type of lightguide resembles some of the features of the dimpled planar lightguide, and the materials choices are similar to the materials for the dimpled lightguide. Notice that light is injected bi-directionally from small patches of accordion-like 30 degree microprisms. This requires that receiver cells be placed on both ends of the guide or that one end of the guide is mirrored to reflect light back into the guide.

Figure 2.3: Perspective view of the slab lightguide with microprisms

Because the prisms are small compared to the cross-section of the guide, the guiding efficiency is high despite the continued interaction of light with the injection features as light traverses the guide. However, the prisms do have a drawback. Since they are angled at 30 degrees, light is turned 60 degrees (not 90 degrees), so the central ray is injected at 30 degrees with respect to the plane of the guiding surfaces, resulting in a substantial hole in the light's angular distribution. This severely limits the theoretical upper limit on concentration.

Karp and Ford do propose a novel method for self-alignment of the lenslet and injection features. The microprism features are molded across the entire back surface of the planar lightguide. The lenslets are then placed on top of the guiding layer and the device is exposed to UV radiation. This cures small patches of the prism surface. The microprism layer is then etched, leaving the small patch of exposed prisms. Since the lenslets are used to define both the injection region and to inject solar energy, lenslet-to-injector misalignments are eliminated. Any lenslet pitch mismatch, tilt, or decentration also misaligns the injection feature, so each lenslet-injector pair, while individually misaligned, are together aligned to the nominal field-of-view.

2.1.6 UCM Lightguides

The group at the Complutense University of Madrid (UCM) has developed a concentrator consisting of an array of focusing elements placed above an array of injection element in a planar guiding layer [55]. Each focusing element focuses onto a corresponding injection element, and these elements turn and inject light into the planar guiding layer. Light is injected in one preferred direction and travels through the guide to one edge. A PV cell is placed at the edge to collect and convert solar energy into electricity. Figure 2.4 is a side-view of the injection scheme outlined by UCM. Light is diverted by notches or air-prisms that are fabricated into the planar guiding layer.

Figure 2.4: Side-view of the UCM injection elements and guiding layer. US Patent App. 12490432

This design of lightguide concentrator most closely resembles the dimpled planar lightguide concentrator, the focus of this research. However, UCM design lacks a bypass element, which limits the potential concentration of their design.

2.2 Dimpled Lightguide Concentrators

In this thesis, the dimpled lightguide concentrator is analyzed, fabricated, and tested. The dimpled concept, along with stepped lightguide concepts were developed at the University of Rochester [56-57]. The dimpled lightguide uses microstructured surfaces and a planar guiding layer to concentrate and transport light using a plurality of focusing elements and injectors[58]. These microstructured surfaces have the ability to preserve étendue using an extremely thin geometry [59]. The dimpled light guide is composed of four components: an array of lenslets, and array of injection elements, and array of bypass elements and the guiding layer. The *lenslets*, which can be refractive or reflective, concentrate the incident light to a small focal spot within the guide layer. The *injection elements* then direct the light from a direction nominally normal to the guiding layer to a direction nominally parallel to the guiding layer. Light must be turned to angles that satisfy TIR by the guiding layer. Once light has been captured by the guide and is traveling along the guide, it has some probability of interacting with the upstream side of subsequent injection elements. To minimize losses from these interactions, *bypass elements* are placed in front of the injection elements. These bypass elements divert light around the injection elements, increasing optical efficiency and concentration. Together, the injection and bypass elements form the *dimple*. Finally, the planar *guiding layer* traps the injected light and transports it to one edge of the device. The maximum angle of incidence of transported light is determined by the index of the guiding layer and the bounding medium.

2.2.1 Lenslets

Incident light is first concentrated by an array of lenslets, which can be refractive or reflective. The lenslets have a focal length and a numerical aperture based on the system design constraints. In a common example, the lenslets are on one side of the lightguide concentrator and the dimples are on the opposite surface of the concentrator. For this case, the focal length of the lenslets is approximately the total thickness of the lightguide concentrator, with the focal spot at or near the opposite surface of the concentrator. The exact focal length is chosen or adjusted to minimize the focal spot size at the injection elements, where the injection faces may be tilted with respect to the optical axes of the lenslets.

Figure 2.5: Schematic of rectangular running-bond refractive lenslets

The numerical aperture of the lenslets defines the range of angles initially injected into the guiding layer. Indirectly, it also defines the lenslet aperture size and shape, as well as the spacing of the dimples. In some cases, the apertures can have significantly different numerical apertures in X , the dimension transverse to light propagation within the guide and, Z the dimension parallel to light propagation within guide. These asymmetric apertures not only change the mixture of angle focused to the injection element and injected into the guide, but also changes the X and Z spacing of the dimples. Since the dimple spacing is a major driver in determining optical efficiency and maximum concentration, aperture geometry is an important parameter.

To maximize optical efficiency, the lenslets must fill up the total area of the input aperture of the lightguide concentrator. Only certain shapes satisfy close packing. The regular polygonal shapes of rectangles and hexagons can be close packed. Also, quadrilaterals and non-regular pentagons can be close packed, but most of these shapes have no real concentration benefit.

The **injected concentration ratio** is defined as the area of the lenslet aperture divided by the projected area of the injection face in the X - Y plane. Since the injection element resides in the guiding layer, light transported in the guide must avoid the injection element. Although light reflected from the injection face expands to fill the height and width of the guiding layer, this injected concentration defines the étendue efficiency of the lenslet and injection elements. Loss or dilution of the étendue during injection reduces the maximum possible étendue transfer potential of the lightguide concentrator.

2.2.2 Injection Elements

The injection elements redirect incident light from the Y direction- the direction normal to the guide layer, to the Z direction- the nominal guiding direction parallel to the guiding layer and normal to the output face of the guide. Injection elements can be refractive, reflective, diffractive, or use total internal reflection (TIR). Refractive injection elements deviate an incident beam of light by small amount due to the limited beam turning ability for a single refractive surface. To use refraction as the injection element, the incident light must already be close to an angle that the guide can transmit.

Figure 2.6: Schematic of an injection element

Figure 2.6 is a schematic of the reflective or TIR injection element by itself. Reflective and TIR injection elements act similarly to one another, deviating incident light by the law of reflection. Reflective injection elements turn the beam in any way that light can be reflected from a surface. TIR injection element deviate light in this way too, but the angles of incidence are constrained to satisfy total internal reflection. Specifically, for light to totally internally reflect, the angle of incidence must satisfy eq. (2.1),

$$\theta_{\text{injected}} < \theta_{\text{critical}} = \sin^{-1} \left(n_{\text{bounding}} / n_{\text{guiding}} \right) \quad (2.1)$$

where θ_{injected} is the angle of incidence of light with respect to the surface normal, θ_{critical} is the critical angle of the materials, n_{bounding} is the index of refraction of the bounding medium, and n_{guiding} is the index of refraction of the guide layer. Although TIR injectors are constrained compared to reflective injectors, they have one distinct advantage. Total internal reflection is lossless, as long as the surface is

highly specular. However, any scattered component does have the potential of being transmitted through the injection element or reflected into an angle not supported by the guide.

To illustrate the constraints for TIR injectors, consider a guiding layer with an index of refraction $n=1.5$ and a bounding medium with index $n=1.0$. The critical angle is 42 degrees with respect to the plane of the guiding surface. Therefore, for the injector to maintain total internal reflection for all angles of incidence, it must be tilted at greater than 42 degrees, with respect to the guiding surface. Also consider that the lenslets increase the angular distribution incident on the injectors. If the lenslets have a numerical aperture of 0.5 (f-number of 1), the angular distribution is roughly ± 30 degrees in air, or approximately ± 20 degrees in index $n=1.5$. So, to maintain TIR at the injection face for all angles, the injector must be placed at 62 degrees (42 degrees + 20 degrees) with respect to the guiding surfaces. For an injector placed at 62 degrees, the central ray is deviated by 34 degrees from parallel with respect to the plane of the guide. The central ray defines the center of the field-of-view and passes through the center of a lenslet's aperture. So for this example, the guide must support 34 degrees from the initial injection, plus 30 degrees for the numerical aperture half-angle, plus the extent of the field of view. This totals 62 degrees with respect to the planar guiding surfaces. The guide can only support rays with angles up to 48 degrees with respect to the guide. There is now both a significant loss of light from the guide and a hole in the central region of the angular distribution of light in the guide. This severely limits the maximum attainable concentration of this example. Figure 2.7 shows a schematic of the example f/1 lens, 62 degree injection element, and guiding layer. Figure 2.8 shows the angular distribution of light before and after injection into the guide. Notice the missing angular components in the central region of the angular distribution in the right plot. Also notice the increase in angular extent of the distribution.

Figure 2.7: Example of an $f/1$ lens focusing and injecting light into a guiding layer

Figure 2.8: Angular distribution of light after the lenslet but before injection (left), and angular distribution after injection within the guiding layer (right)

If the lenslets' numerical aperture is decreased to 0.2 (an f -number of 2.5), the angular distribution is ± 11.5 degrees in air, or ± 7.5 degrees in the guide. So to maintain TIR for all angles, the injector is placed at 49.5 degrees with respect to the guiding surface. Now, the injected central ray is just 9 degrees from parallel with respect to the plan of the guides, so the numerical aperture of the guiding layer can be smaller while still maintaining TIR guiding. Now also, the guide needs only to support a maximum of 16.5 degrees. This would indicate that small numerical apertures are better; however, another other effect, dimple density, acts in an opposite direction. This is discussed in detail in section 3.3.1. The optimal lenslet numerical aperture for totally internally reflecting dimples balances these two driving factors.

Reflective injectors do not have the same angular limitations as TIR injectors. If only the injection element is coated for reflection, the single reflection loss may be acceptable and one group has

demonstrated selectively coating injection elements to couple light into a guiding layer [54]. Their design was discussed in section 2.1.5.

If the entire dimple layer is coated with a metallic reflector, the optical losses from multiple interactions between guided light and the surface are significant, assuming a broadband source. For instance, silver has a broadband reflectivity of up to 95 percent. For a guiding layer with a 20-to-1 aspect ratio, one side coated with silver, and light with a 30 degree angle within the guide, light interacts with the reflective surface an average of 5 times. After just 5 interactions, the transmitted efficiency is just 77 percent. If the guide has an aspect ratio of 100-to-1, there will be an average of 25 reflections from the silvered surface, and the transmitted efficiency is just 28 percent. Aluminum has a broadband reflectivity of up to 90 percent, and while gold has exceptional reflectivity in the IR, it has poor performance across the blue and UV spectra. Alternatively, if the entire dimple layer is coated with a dielectric reflector, the optical efficiency could be excellent.

Diffraction injection elements pose an interesting alternative to “geometrical optics” injectors. Instead of using the physical tilt of the injection element to deviate light into a direction supported by the guiding layer, a diffractive injector uses physical optics to deviate a beam. Choosing the appropriate grating period and profile can inject light injected into the guide from “flat” patches on or in the guiding layer. Since the diffraction grating is only used to deviate the incident light, chromatic effects inherent with diffractive elements are unimportant so long as the diffracted orders of interest are guided for all wavelengths of interest. Since diffractive injection can be flat with relatively shallow features (roughly a few wavelengths of light), there are a number of potential fabrication methods that diffractive features can employ that are not allowed by reflective or TIR injectors. The detailed derivation of diffractive injectors is beyond the scope of this research.

2.2.3 Bypass Elements

Bypass elements allow light traveling in the guide to be diverted away from the injection elements, reducing optical losses resulting from interaction with the injection elements. Without the bypass elements, light traveling in the guide encounters the injection element and is ejected from the guide, since

the injection element can couple light out of the guide just as easily as it can inject light into the guide.

Figure 2.6 is a schematic of this loss mechanism. The injection element essentially sits in the shadow of the bypass element. For example, imagine the upstream side of the dimple as the bow of a ship. If the bow is square (as in the case of an injector without a bypass element), there will be tremendous drag as the boat moves through the water. This will limit the speed and efficiency of the boat because of the turbulent flow around the bow. Now image the bow is a long smooth curve. Although the cross-section at the stern may be the same, the top speed and efficiency will be much greater because water can smoothly flow around the bow. The same amount of water is displaced as the boat moves through the water, but with the smooth bow, water is redirected in a consistent way, reducing turbulence and increasing efficiency.

Similarly, the bypass element does not reduce the chance of light interacting with a dimple; it simply diverts light in a consistent and efficient way. Instead of light being ejected from the guide, its angular spectrum is changed. The étendue is changed instead of the optical efficiency; and since these interactions make room in the angular space of the guide, each additional injection element can then contribute to the concentration potential of the dimpled lightguide. Bypass elements can be refractive, diffractive, gradient index, or use total internal reflection. The type and shape of bypass element depends on the type of injection element, the anticipated fabrication methods, the desired concentration ratio, the desired acceptance angle, and the index difference between the guiding and low index layers.

This research focuses on TIR or reflective bypass elements. Since the goal of the bypass element is to “shadow” the injection element from upstream light, one end of the bypass element is constrained to have the same cross-section as the injection element. If the bypass element is undersized with respect to the injection element, light will interact with the injection element and be lost. If the bypass element is oversized with respect to the injection element, the shadow region will be unnecessarily large and more light is diverted than is needed. The length and shape of the bypass element determines its effect on light traveling in the guide. The cross-section of the bypass element may be rectangular with a decreasing width in its X dimension, rectangular with a decreasing width in its Y-dimension, rectangular with a decreasing width in both X and Y dimensions, triangular, elliptical, or otherwise smoothly shaped with decreasing size towards its tip. These variations are seen in Figure 2.9.

Figure 2.9: Dimple variations – pyramid (left), triangular (center), and elliptical (right)

The modeling presented in the next chapter focuses on a preferred embodiment- a bypass element that is nominally rectangular in cross-section near the injection element and decreases in the X-dimension toward the tip, coming to a sharp edge, seen in Figure 2.10. The Y-dimension of the bypass element does not change, creating a flat top surface. This geometry diverts light into greater X-angles within the guide without changing the Y-angles. As discussed in chapter 3, the numerical aperture of the guiding layer limits the transport angles in the Y-dimension of the guide. It is assumed that the X-dimension of the guide is nearly infinite, so the only loss mechanism for light having large X-angles is coupling out of the bypass element faces when the TIR condition is no longer satisfied.

Figure 2.10: Schematic of the knife-edge dimple with bypass element “tail”

For this preferred embodiment, the angle of the bypass faces is determined by the width of the injection face and the length of the bypass element. The apex angle of the bypass element is given by,

$$\theta_{BP} = 2 \tan^{-1} (W / 2L). \quad (2.2)$$

Light that interacts with the bypass element in Figure 2.10 only has a change in its X-angle, and each interaction adds to the angular spectrum. Since the width and height of the bypass element is

constrained by the injection face width and height (a result of the desired acceptance angle), bypass element length is the only variable for changing the apex angle and hence the angular effect on incident light.

This shape of dimple has been chosen prior to the choice of a fabrication method. The first generation prototypes are based on this knife-edge design, and operate less efficiently than expected. This is due to the incompatibility of the knife-edge design with the fabrication method. The second generation dimple shape differs significantly from the knife-edge design. Figure 2.11 is a schematic of the revised dimple shape. The shape has a nominally triangular cross-section and the bypass element (right) tapers as it extends away from the injection face (left). The sharp edges have been rounded over along the top edge and around its perimeter. Unlike the knife-edge design, reflections from the bypass element contribute to both the X- and Y- angular spectrum. This blended geometry accounts for the limitations of the fabrication processes outlined in chapter 4.

Figure 2.11: Schematic of the revised dimple geometry

For other bypass element shapes, more variables are introduced, since the geometries are less constrained. To minimize the angular deviation of a given interaction with the bypass element, the length should be as long as possible. A longer “tail” means light may interact with dimple more times before being coupled out of the guide. However, there is a compensatory factor. As the tail length increases, there is more chance for light to interact with the bypass element. Since multiple interactions with dimples does lead to coupling losses, the greater chance for interaction balances the decreased angular deviation.

Since dimples make up a small part of the cross-sectional area of the guide layer, only a small percentage of light interacts with any given dimple. This interaction probability depends on the relative size and spacing of the dimples the incidence angle of light on the dimples. Light with large lateral components experiences larger dimple cross-sections because the bypass prisms are long and thin.

2.2.4 Guiding Element

The guiding element is a planar sheet of plastic and/or glass that transports injected light from the injection elements to the output face at one of its edges. For high-flux solar applications, there are very few polymer materials that have sufficient lifetimes. So for solar use, the preferred guiding element will be composed of glass. Because of the difficulty of molding accurate features in glass, a thin index-matched polymer layer containing the microstructured features can be bonded to the glass layer. The guiding element is now composed of both the glass layer and thin polymer layer, and light travels with equal ease through both. Since the polymer dimple layer is thin, the optical path within the polymer is minimized; so reductions in transmission over the lifetime of the concentrator will have a smaller impact on total guide transmission.

The numerical aperture of the planar guiding element defines the maximum angle carried by the guide and is related to the index of the guide and the index of the bounding media. If the indices of refraction of the bounding media on either side of the guide are different, the limiting index of refraction is the one closest to the index of the guiding layer. For instance, if the guide has an index of refraction of $n=1.5$, the top of the guide is bounded by index $n=1.35$, and the bottom of the guide is bounded by index $n=1.0$, the top bounding medium ($n=1.35$) determines the numerical aperture. For this case, the numerical aperture of the guide is 0.45, which corresponds to a maximum angle with respect to the guiding surface of 27 degrees. From the previous example of the lenslets numerical apertures, this guiding structure supports lenslets with numerical apertures of 0.2, but not lenslets with numerical apertures of 0.5. The maximum numerical aperture supported by this example is 0.24. Even for lenslets with small numerical apertures, the NA of the guide limits the concentration within the guide. In order to avoid light leaking out of the low-index layer, dimple interactions must avoid adding Y-components to the guided light.

3 Modeling

3.1 Overview

Lightguide concentrators are a family of nonimaging optics that concentrate and/or transport light by use of a lightguide element. In this chapter, mathematical models are developed to provide the basis for understanding the performance constraints of lightguide concentrators. These models provide insight into the guide's response to simple factors, such as dimple density, numerical aperture, and dimple size, and dimple shape. The models also help to understand the theoretical performance limitations of lightguide concentrators. In this chapter, ray tracing is used to verify the accuracy of the mathematical models. Next, detailed physical geometries of lightguide concentrators are modeled using non-sequential ray tracing. Sensitivity analyses of a characteristic embodiment of the dimpled lightguide concentrator are presented. Finally, ray trace models are used to perform sensitivity analyses of potential fabrication errors.

The primary modeling and ray tracing tools for this research are LightTools® (Optical Research Associates), and SolidWorks® (Dassault Systèmes SolidWorks Corp). LightTools® is an element-based optical modeling program specifically optimized for non-sequential ray tracing. This tool is connected dynamically to SolidWorks®, a widely used mechanical solid modeling program. Combining these two tools allows the model to use the strengths of both programs. LightTools® provides a robust non-sequential ray trace engine, and SolidWorks® provide a means to create complicated blended geometries as well as real-world fabrication features [60]. It is assumed that the physical features of the lightguide are large enough to avoid physical optics and diffractive effects. This assumption is valid, since the features of the lenslets and dimples, as well as the size of the guide in all dimensions are large compared to the wavelength of light. When scattering or diffractive properties must be taken into account, those properties are applied as surface properties.

3.2 System Parameters and Boundary Conditions

3.2.1 Source Specification

Solar radiation consists of a direct circumsolar component, and a diffuse component [61].

Circumsolar radiation is light coming directly from the solar disk, approximately ± 0.25 degrees, plus light that is forward scattered within the atmosphere and exists within a narrow cone around the sun up to ± 5 degrees. Diffuse radiation is defined as all light that exists outside the ± 5 degree cone. A number of models exist for characterizing the angular distributions of the direct and diffuse components. The simplest model assumes that all of the solar radiation is evenly distributed within the ± 0.25 degree cone and no direct light exists outside this cone. Many models use a circumsolar ratio, which uses a simple equation to define the distribution of direct and near-direct components [62]. The circumsolar ratio depends on atmospheric conditions such as water vapor content and the air mass. Air mass is a measure of the amount of atmosphere between the observer and the sun. When the sun is directly overhead, the air mass is 1. When the sun is near the horizon, the air mass can be 4 or higher. Still more complex models exist, using measured data to completely define the angular and angular-spectral distribution of the solar radiation.

Diffuse sky models also range from simple to complex. The simplest diffuse model assumes a uniform “blue-sky,” in which the diffuse irradiance and spectrum is uniformly distributed over the entire hemisphere. More complex models account for atmospheric absorption from water vapor, carbon dioxide, sulfur dioxide, and a number of other trace gasses and particulates in the atmosphere. The most complete models also account for local ground effects such as vegetation and soil type [63]. Diffuse models are particularly important for modeling the performance of flat-plate PV solar collectors and concentrators with wide fields-of-view. High concentration systems have narrow fields-of-view and therefore rely primarily on the direct component.

Since dimpled planar lightguide concentrators have small fields-of-view, the mathematical and ray trace models assume that only the direct component of solar radiation is captured. Furthermore, since these concentrators have acceptance angles much larger than ± 0.25 degrees, the direct radiation model is

assumed to be the simplified uniform disk model. The source is assumed to be ± 0.25 degrees with uniform filling of that angular cone.

For solar applications, the spectrum of interest is typically defined by the ASTM 1.5G173 spectral standard [64]. This full solar spectrum extends from 280nm to 4,000nm. Figure 3.1 shows the ASTM 1.5G173 spectrum, truncated at 2,500nm. This excludes 0.8 percent of the solar energy, changing the irradiance from $1,000\text{W/m}^2$ to 992W/m^2 . When photovoltaics are used as the receiver, the spectrum is typically truncated below the lowest band gap. For instance, if silicon with a band gap of $1,100\text{nm}$ (1.1eV) is used, the solar spectrum is truncated at wavelengths greater than $1,100\text{nm}$, since silicon cannot convert photons with wavelengths longer than $1,100\text{nm}$ into electricity. Some high efficiency III-V triple junction solar cells use germanium for the bottom cell. Germanium has a band gap of 0.7eV , or $1,770\text{nm}$, so the source spectrum is truncated for wavelengths greater than $1,770\text{nm}$.

Figure 3.1: ASTM 1.5G173 standard solar spectrum, truncated at 2,500nm

3.3 Limits on Concentration

The theoretical maximum concentration is defined by the étendue of the source. In simple terms, étendue is the angle-area product of light, represented by the four-dimensional quantity $n^2 dx dy dL dM$, where n is the index of refraction, dx and dy are the spatial coordinates, and dL and dM are direction cosines. For solar concentrators, the source is assumed to be an area with uniform irradiance at an input plane with a

defined angular acceptance region. For the purpose of this research, acceptance region, acceptance angle, and field-of-view are used interchangeably to indicate the angular components collected by a concentrator. Typically, solar concentrators are defined by an axisymmetric acceptance angle, where acceptance angle is the half-angle of the angular extent of the source. A concentrator's goal is to efficiently transfer and transform the input area and acceptance angle to a target area. This target area can only accept light from at most a hemisphere (assuming a one-sided target), so the maximum angle is ± 90 degrees, or an output solid angle of 2π . This relationship can be written as,

$$n_{in}^2 A_{in} \sin(\theta_{in,x}) \sin(\theta_{in,y}) = n_{out}^2 A_{out} \sin(\theta_{out,x}) \sin(\theta_{out,y}), \quad (3.1)$$

where A_{in} is the input area, A_{out} is the target area, θ_{in} is the acceptance angle, θ_{out} is the maximum output angle, n_{in} is the input index of refraction, and n_{out} is the index of refraction bounding the target. Assuming the input index of refraction is air, $n_{in} = 1.0$, from the definition of geometrical concentration, and assuming rotational symmetry, the geometrical concentration is,

$$C_{geo} = \frac{A_{out}}{A_{in}} = \frac{n_{out}^2 \sin(\theta_{out})^2}{\sin(\theta_{in})^2}. \quad (3.2)$$

In the vertical dimension of the guide, the guiding layer can only support angles of incidence up to its critical angle, defined by eq. (3.3) with respect to parallel to the guide surface,

$$\theta_{critical} = \sin^{-1}(n_{low}/n_{guide}). \quad (3.3)$$

In the lateral (X) dimension of the guide, light is contained for larger angles. If there are no dimples to interrupt the guiding layer and the lightguide is infinitely wide, light could be transported at arbitrarily large angles. The maximum angle of incidence for light within the guide is,

$$\theta_{AOI} = \pi / 2 - \theta_{critical}. \quad (3.4)$$

Also, since the dimples are also in the guiding layer, TIR conditions apply to the bypass sides as well as the sidewalls of the guide. The maximum primary guiding concentration depends on the numerical aperture of the guide. The numerical aperture of the guide is given by eq. (3.5), and applying this numerical aperture to eq. (3.2) yields and eq. of the maximum guidable concentration, given by eq. (3.6).

$$NA = n_{\text{guide}} \sin U = \sqrt{n_{\text{guide}}^2 - n_{\text{bounding}}^2} \quad (3.5)$$

$$C_{\text{max,guide}} = \frac{n_{\text{guide}} \sin(\theta_x) NA_{\text{guide}}}{\sin^2(\theta_{\text{in}})} = \frac{n_{\text{guide}} \sqrt{n_{\text{guide}}^2 - n_{\text{bounding}}^2} \sin(\theta_x)}{\sin^2(\theta_{\text{in}})} \quad (3.6)$$

If the later angles are unconstrained in the guide, $\theta_x = \pi/2$, so $\sin(\theta_x) = 1$. Eq. (3.6) reduces to eq. (3.7) The maximum concentration attainable without output angular constraints given by eq.(3.8) and the ratio of the maximum guiding concentration to the maximum possible concentration, $R_{\text{guide}} / R_{\text{max}}$, is given by eq. (3.9).

$$C_{\text{max,guide}} = \frac{n_{\text{guide}} \sqrt{n_{\text{guide}}^2 - n_{\text{bounding}}^2}}{\sin^2(\theta_{\text{in}})} \quad (3.7)$$

$$C_{\text{max}} = \frac{n_{\text{guide}}^2}{\sin^2(\theta_{\text{in}})} \quad (3.8)$$

$$R_{\text{guide/max}} = \frac{\sqrt{n_{\text{guide}}^2 - n_{\text{bounding}}^2}}{n_{\text{guide}}} = \frac{\sqrt{2n_{\text{guide}}\Delta n - \Delta n^2}}{n_{\text{guide}}} \quad (3.9)$$

The difference in index of refraction between the guiding and bounding medium divided by the index of refraction of the guiding medium is defined as B, and is given by eq. (3.10). This is applied to eq. (3.11), and yields the simplified eq. (3.12).

$$B = \frac{\Delta n}{n_{\text{guide}}}, \Delta n < n_{\text{guide}} - 1 \quad (3.10)$$

$$R_{\text{guide/max}} = \frac{\sqrt{2n_{\text{guide}}(Bn_{\text{guide}}) - (Bn_{\text{guide}})^2}}{n_{\text{guide}}} \quad (3.11)$$

$$R_{\text{guide/max}} = \sqrt{2B - B^2} \quad (3.12)$$

Figure 3.2 is a plot of the ratio of guiding concentration versus B. For small Δn , the guiding concentration is low. If the guide index is large and the Δn is large, the maximum guiding concentration approaches the maximum possible concentration.

Figure 3.2: Plot of the ratio of guiding concentration versus B

3.3.1 Focusing Element Numerical Aperture

The numerical aperture of the focusing element defines the angular content initially injected into the guide and indirectly defines the dimple density within the guide. A large numerical aperture means the dimples are spaced further apart, which reduces the interaction of light with the dimples. However, a large numerical aperture also implies that the initial angular content within the guide is large. This section focuses on the study of the geometrical constraints of the injection element. In section 3.3.2, dimple density is discussed, and the balance between numerical aperture and dimple density is discussed.

The numerical aperture plays a role in setting the minimum angle of the injection face with respect to the planar guiding layer. The following discussion assumes that the numerical aperture is rotationally symmetric. In practice, the numerical aperture can be different for the X and Z dimensions, with the Z component of the numerical aperture providing the primary constraint on injection face angle and dimple height. For reflective dimples, the numerical aperture, injection face angle, injection element height, and system field-of-view are coupled together and shown in eq. (3.13). If the numerical aperture, field-of-view, and injection face angle are defined, the nominal height of the dimple can be directly calculated. The requisite height of the dimple is larger than its width, since the injection face is tilted with respect to the

“image” plane. Figure 3.3 shows an illustration of this coupling between the system and lenslet parameters and the dimple heights.

$$h = \frac{FOV}{\tan U - \cot \theta_{\text{injection}}} \quad (3.13)$$

$$NA = n \sin U \quad (3.14)$$

Figure 3.3: Schematic of the reflective injection face

There are additional constraints for dimples using total internal reflection. Specifically, the injection face must be angled such that all angles from the numerical aperture of the focusing elements satisfy the TIR condition. While the reflective injection face could be angled at any angle of interest, nominally 45 degrees, the TIR injection face has a minimum angle with respect to the planar guiding layer. Eq. (3.15) shows the relationship between numerical aperture and the minimum angle of injection face. The bounding medium at the injection face is assumed to be air, the critical angle of the guiding layer and hence the injection face depends only on the index of the guiding medium.

$$\theta_{\text{injection}} > \theta_{\text{critical}} + \theta_{NA} \quad (3.15)$$

Figure 3.5 is a plot of numerical aperture versus injection face angle as well as numerical aperture versus the angular extent of light inside the guide considering an injection face angle oriented at this minimum angle. The plot assumes the guiding medium index is $n=1.5$, and the bounding medium index is $n=1.0$. Ideally, the injection face is oriented at 45 degrees, and for small numerical apertures, the TIR condition is satisfied for all angles within the numerical aperture. The largest numerical aperture for which the injection face is angled at 45 degrees is called the *critical numerical aperture* in this dissertation. For a

guiding medium of $n=1.5$ and a bounding medium $n=1.0$, the critical numerical aperture is 0.08, or a half-angle of 5 degrees, or 3 degrees in the guiding medium.

Figure 3.4: Plot of injection face angle versus numerical aperture of the lenslet

Beyond this point, the numerical aperture within the guide grows two times faster than the input numerical aperture. Each additional degree of angle added to the half-angle size of the numerical aperture contributes two degrees to the angular extent within the guide. The solid line in Figure 3.5 shows the numerical aperture injected into the guide due to the constraints on the injection face angle. The dashed line shows the numerical aperture that could have been injected if the injection face was kept at 45 degrees. Beyond the critical numerical aperture, these two lines diverge.

Figure 3.5: Plot of NA versus the injected angular extent

As the numerical aperture injected into the guide diverges from the numerical aperture of the lenslet, the maximum attainable concentration decreases. Only the z-dimension numerical aperture of the lenslet drives the injection face angle. Up to the critical numerical aperture, the injection of light into the guide has no effect on the maximum attainable étendue. Beyond this numerical aperture, a hole in the angular spectrum forms and there is no method for recovering this étendue.

Figure 3.6: Plot of the percent of retained étendue versus lenslet Z numerical aperture

The constraint of TIR on injection elements to efficiently inject light of all angles would indicate that the numerical aperture should remain small. However, in section 3.3.2, dimple density is shown to work in the opposing direction, pushing the dimples further apart and hence increasing the numerical aperture of the focusing elements. The angular extent injected into the guide scales linearly with numerical aperture, while the injected area scales quadratically with numerical aperture, the nominal balance between dimple density and numerical aperture sets the angle of the injection face slightly steeper than 45 degrees.

3.3.2 Dimple Density

Dimple density is a measure of the closeness of the dimple features to one another in the XZ plane. For symmetric numerical apertures, the X and Z pitches of the dimple scale together, so that a linear change in the dimple spacing corresponds to a quadratic change in the dimple density. Figure 3.7 is an illustration of three dimple packing densities. Since the dimple exist in the guiding layer, and since the

primary loss mechanism for the dimpled lightguide is interactions with dimples; the dimple density is a driving factor in the guiding efficiency and resulting maximum attainable concentration.

Figure 3.7: Three dimple densities, seen from above

3.3.3 Lightguide Aspect Ratio

The lightguide aspect ratio is the length of the lightguide in the Z dimension divided by the height of the guiding layer. This aspect ratio is also called the primary geometrical concentration ratio. The frequency of dimple interaction also depends on the ratio of the dimple height to the guide height. The larger this ratio, the more opportunity there is for light to interact with a dimple. The ratio is minimized by either reducing the height of the dimple or increasing the thickness of the guide. The former solution reduces the field-of-view of the concentrator and increases the sensitivity of a design to misalignment errors. The latter decreases the primary concentration of the guide. Correspondingly, as the guiding layer gets thicker, the distance traveled down the guide increases to achieve the same concentration ratio.

3.4 Mathematical Models

3.4.1 Overview

Two mathematical models are developed for calculating the guiding efficiency of dimpled lightguides. In section 3.4.2, the moiré method shows how the dimples can be represented as two-dimensional rectangular screens. This method provides a means of calculating the spatial and angular interaction distributions for dimples without bypass elements. In section 3.4.3, the probability model presents a method for calculating the interaction probability as a function of angle and guiding efficiency

versus length. While this method neglects the point-by-point local spatial distribution within the guide, it accounts for the angular effects of bypass elements.

3.4.2 Moiré Model

Moiré methods help describe the patterns resulting from the overlay of two or more periodic structures, and are a natural way of expressing the dimple distributions [65]. The dimple layer is composed of a two-dimensional array of dimples with period spacing, and the dimples exist in a planar lightguide, which acts like a hall of mirrors [66]. Light is totally internally reflected from the top and bottom surfaces of the guide, creating, in effect, a series of reflected images of the dimple array spaced at intervals of the height of the guide. The height dimension of the guide, the dimension orthogonal to the plane of the guide is the Y dimension.

Figure 3.8: Lightguide acting like a hall of mirrors

Figure 3.8 shows how dimple features appear to light traversing the lightguide. Rows of dimples formed in the X dimension are those that run transversely to the nominal direction of light transport. Each row and its multiple reflected images form a single two-dimensional periodic structure, called screens. These screens are separated by the pitch spacing along the nominal direction of light transport, the Z direction. The purpose of the moiré model is to provide a means of calculating the optical efficiency and angular distributions. Figure 3.9 is a photoreal rendering from LightTools® of the injection faces from the viewpoint of the cell plane. The array of injection faces forms a single layer of white squares in the image, and the reflective images of the injection faces form layers above and below the initial layer. Notice how these layers overlap, creating rudimentary moiré patterns.

Figure 3.9: Photoreal rendering of the injection faces observed from the cell plane

A simple example helps explain the basis for the mathematical model. This example starts with two identical binary, periodic transmission gratings, each with a constant period, T , and an opening in the grating, τ . This binary grating is described by eq. (3.16) and is shown in Figure 3.10. If two or more gratings are placed in contact, the resulting transmission function is represented by the product of the individual transmission functions, shown in eq. (3.17) , and depends on the position and orientation of one grating with respect to the other. The product of the screens yields a map of whether interactions will occur or not.

$$r(x) = \sum_{n=-\infty}^{\infty} \text{rect}\left(\frac{x-nT}{\tau}\right) \quad (3.16)$$

$$r(x) = r_1(x) \cdot \dots \cdot r_m(x) \quad (3.17)$$

The Fourier transform of the total interaction function for the product of all grating is given by eq. (3.18). The Fourier spectrum of the product of gratings is the convolution of the individual spectra.

$$R(u, v) = R_1(u, v) \otimes \dots \otimes R_m(u, v) \quad (3.18)$$

Each grating can be decomposed into a Fourier series, shown in eq. (3.19). The Fourier coefficients, a_n and b_n , are given by eq. (3.20). Also, if $p(x)$ is symmetric, (i.e. the individual square waves are centered on zero), then $b_n = 0$ for all n .

$$p(x) = \sum_{n=-\infty}^{\infty} a_n \cos(2\pi nx / T) + \sum_{n=-\infty}^{\infty} b_n \sin(2\pi nx / T) \quad (3.19)$$

$$a_n = \frac{1}{T} \int_T p(x) \cos(2\pi nx / T) dx, \quad \text{and} \quad b_n = \frac{1}{T} \int_T p(x) \sin(2\pi nx / T) dx \quad (3.20)$$

For the case of the symmetric binary square wave, the coefficients are given by eq. (3.21).

$$\begin{aligned} a_0 &= \tau / T \\ a_n &= \frac{\tau}{T} \text{sinc}(n\tau / T) \\ b_n &= 0 \end{aligned} \quad (3.21)$$

If the gratings are slid past one another, the resulting periodic pattern and percent transmission depends on the amount of displacement, Δ . Eq. (3.22) shows the square wave function for the m^{th} displaced grating in both piecewise form and as a Fourier series. Alternatively, the gratings can be rotated with respect to one another by some angle, θ , and eq. (3.23) shows the two-dimensional Fourier series representation for the m^{th} rotated grating. Note that if the periods and opening widths of two gratings are equal and as those gratings are rotated with respect to one another, the effective period and opening width of one grating with respect to the other will be different.

$$r_m(x) = \sum_{n=-\infty}^{\infty} \text{rect}\left(\frac{x - nT - \Delta_m}{\tau}\right), \quad \text{or} \quad r_m(x) = \sum_{n=-\infty}^{\infty} a_n \cos[2\pi n(x + \Delta_m) / T] \quad (3.22)$$

$$r_m(x, y) = \sum_{n=-\infty}^{\infty} a_n^{(m)} \cos[2\pi n(x \cos \theta_m + y \sin \theta_m) / T_m] \quad (3.23)$$

As an illustrative example, let the total transmission of a single grating be 50 percent, so $\tau = T/2$.

Figure 3.10 shows the percent transmission as a function of displacement. Similarly, if the gratings are clocked with respect to one another, the transmission pattern and percentage change in a regular way.

Figure 3.10 also shows the percent transmission as a function of rotation from 0 to 90 degrees for this simple example.

Figure 3.10: Binary transmission grating (left), transmission as a function of displacement (center), transmission as a function of rotation (right)

Next, envision that the two grating structures are separated from one another by some distance, z , with the two gratings aligned laterally. Now the transmission pattern also depends on the viewing angle. At a viewing angle of 0 degrees, the two gratings exactly overlap, but as the viewing angle changes, the separation causes an apparent displacement. The apparent displacement, x , of one grating to another is shown in eq. (3.24),

$$x = z \tan(\theta). \quad (3.24)$$

Notice that the apparent displacement is a function of both the angle, θ , and the separation, z , of the two gratings. For small separations, the apparent displacement is small. As the separation increases, the apparent displacement becomes more pronounced. Figure 3.11 shows a schematic of the separated gratings (left), as well as percent transmission as a function of angle for a z distance of 2τ .

Figure 3.11: Schematic of two gratings separated by distance, z (left), and transmission as a function of viewing angle (right)

This technique of calculating percent transmission can be expanded from two gratings to an arbitrary number of gratings, each separated by a distance, z . Expanding the previous example, imagine five binary gratings, each separated by 2τ . Now, the transmitted angular distribution is more complicated. Figure 3.12 shows the five-grating case and the associated transmission as a function of angle.

Figure 3.12: Schematic of five gratings separated by distance, z (left), and transmission as a function of viewing angle (right)

Now, instead of binary line gratings, each row of dimples can be represented by a two-dimensional screen, $r_m(x,y)$. Each screen consists of an array of rectangles, and if light encounters one of these rectangles, light is assumed to be absorbed by that feature. This interaction function is the sum of individual screens, represented by Figure 3.11.

Each ray angle in the guide sees a slightly different dimple width and spacing. Let w , h and l be the width, length, and height of the dimple in the x , y , and z dimensions respectively. Also, let W , H , and L be the distance between dimples in the x -dimension, H be the height of the guide layer, and L be the distance between dimples in the z -dimension. Let the direction of light travel be represented by two angles: θ_x denotes the angular component in the XZ plane, and θ_y denotes the angular component in the YZ plane. Both angles are drawn with respect to the optical axis of the guide, Z . The dimple width, τ , and period, T , is expressed as a function of angle, shown in equations (3.25) and (3.26).

$$\tau(\theta_x) = w \cos \theta_x + l \sin \theta_x, \quad \text{and} \quad \tau(\theta_y) = h \cos \theta_y \quad (3.25)$$

$$T(\theta_x) = W \cos \theta_x + L \sin \theta_x, \quad \text{and} \quad T(\theta_y) = H \cos \theta_y \quad (3.26)$$

For the purpose of calculating the projected width and height of the dimple, the dimple is assumed to be a rectangular box. Although the resulting calculation does not account for any taper of the bypass element's tail, it does set a conservative upper bound on dimples' extents within the guide. By combining eq. (3.22) with equations (3.25) and (3.26), two dimensional rectangular grids are calculated for each

angle θ_x and θ_y , and shown in eq. (3.27). The dimples are spaced apart along the guide in integer multiples of L . From before, this causes an apparent offset of each rectangular screen, which depends on the viewing angle.

$$r(x, y, \theta_x, \theta_y) = \text{rect} \left[\frac{x - n(W \cos \theta_x + L \sin \theta_x) - \Delta_x}{w \cos \theta_x + l \sin \theta_x} \right] \text{rect} \left[\frac{y - mH \cos \theta_y - \Delta_y}{h \cos \theta_y} \right] \quad (3.27)$$

$$\Delta_x = L \tan \theta_x, \quad \text{and} \quad \Delta_y = L \tan \theta_y \quad (3.28)$$

Figure 3.13 shows the rectangular grid pattern for two angles: 0 and 60 degrees. Let $w=h=0.25$, let $W=H=1$, and let $L=l=1$. Notice the change in the width of the dimple due to the projection of the bypass element. As X angles grow larger, the projection of the dimples becomes larger. However, as the bypass element grows longer, the reflected angle from the bypass element is smaller. In section 3.4.3, bypass element length is balanced by these two competing factors, reflected angle and interaction probability.

Figure 3.13: A single 2D rectangular screen for $\theta_x=0$ degrees (left) and $\theta_x=60$ degrees (right)

Figure 3.14 shows the resulting distribution from the calculation of screens separated by distance L . As previously noted, the product method calculates whether or not a dimple interaction will occur. The number of screen interactions can be extended indefinitely for a guide of arbitrary length.

Figure 3.14: Dimple distribution after 5 screens, $\theta_x = \theta_y = 5$ degrees

3.4.3 Probability Model

The probability model calculates the likelihood of a particular angular component within the guide interacting with a dimple features. This assumes the guide is of sufficient width and length that, light uniformly fills the guide spatially. This assumption is tested against a ray trace model with the knife-edge bypass prisms. As in the moiré model, let w , h and l be the width, length, and height of the dimple in the x , y , and z dimensions respectively. Also, let W , H , and L be the distance between dimples in the x -dimension, H be the height of the guide layer, and L be the distance between dimples in the z -dimension. Let the direction of light travel be represented by two angles: θ_x denotes the angular component in the XZ plane, and θ_y denotes the angular component in the YZ plane. Both angles are drawn with respect to the optical axis of the guide, Z . The simple lightguide model is shown in Figure 3.15, where the bypass prisms have vertical walls, as shown in Figure 2.10.

Figure 3.15: Schematic of the simplified geometry

The likelihood of a particular angular component of light interacting with a dimple in a single unit cell is simply the ratio of τ/T , which depends on both θ_x and θ_y , and is expressed by eq. (3.29),

$$P(\theta_x, \theta_y) = \frac{h}{H} \frac{w \cos \theta_x + l \sin \theta_x}{W \cos \theta_x + L \sin \theta_x}. \quad (3.29)$$

As light interacts with the dimples, this interaction causes a deflection of the light by the angle angles of reflection from the bypass element. The generalized reflection function given by eq. (3.30), where F_x and F_y are the x and y reflected angles from bypass element. For the specific case of a bypass element with constant height in Y, and forming an isosceles triangle in the XZ plane, the angular reflection function is to eq. (3.31),

$$\theta_{x,m+1} = \theta_{x,m} + F_x, \quad \text{and} \quad \theta_{y,m+1} = \theta_{y,m} + F_y, \quad (3.30)$$

$$\theta_{x,m+1} = \theta_{x,m} + 2\theta_{BP}, \quad \text{and} \quad \theta_{y,m+1} = \theta_{y,m} \quad (3.31)$$

$$\text{If } \sqrt{\theta_{x,m+1}^2 + \theta_{y,m+1}^2} > \theta_{critical}, \quad \text{then } E_{m+1}(\theta_{x,m+1}, \theta_{y,m+1}) = 0. \quad (3.32)$$

By applying these equations recursively, it is possible to calculate how that energy is transferred from one row of dimples to another. At the first row, a part of that energy interacts with the bypass element, given by eq. (3.29), and to this portion of the energy, the reflected angle is calculated using eq. (3.30). Now the original energy is split into two components. At the next row, each component has a certain probability of interaction, and for each component, the associated angular component is added again. Now there are three total components. This process is repeated until the last row of dimples is reached. Since the guide cannot contain arbitrarily large angles, light with angles greater than either the numerical aperture of the guide or that do not satisfy TIR at the dimple interaction are lost from the guide,. Therefore,

$$E_k^{(m)} = E_{k-1}^{(m-1)} P_{k-1} + E_k^{(m-1)} (1 - P_k), \quad (3.33)$$

$$\sum_k E_k^{(m)} = A_k, \quad (3.34)$$

$$\text{and } A_k \leq A_0. \quad (3.35)$$

This recursive process is repeated for each angle up to the numerical aperture of the modeled lenslet. Eq. (3.33) shows the recursive calculation of the energy contained in each initial angle and the

energy reflected by the bypass elements into the m th angle. Eq (3.34) states that the sum of energy into all reflected angle equals the amplitude A_k . This amplitude is equal to the input amplitude until pass/fail conditions of eq. (3.32) are applied to the relationship, given by eq. (3.35), and this amplitude is always less than the input amplitude after these conditions are applied.

3.5 Comparison of Probability & Ray Trace Models

In order to verify the accuracy of the probability model, the results of the probability model is compared to a LightTools® ray trace model. The probability model is effective for the parameterization of various phenomena within the guide, calculating bounds on concentration, acceptance angle, optical efficiency, and étendue efficiency. Since the probability model is limited in its ability to model complicated geometries, the model chosen for comparison is simplified. It is composed of a planar guiding layer, with parallel top and bottom surfaces, infinite extent in its lateral dimensions, the guide thickness is 1.0mm, and dimple features cut directly into the guide. The bounding medium on both top and bottom of the guide are, $n=1.0$. The guiding medium is constant index, $n=1.5$, with no absorption. The source is monochromatic; it has an angular extent that replicates an ideal lenslet with a given rotationally symmetric numerical aperture of 0.25, with an infinitesimal field-of-view. Figure 3.15 shows a schematic of the simplified geometry. The dimple features consist of a planar injection face oriented at 45 degrees with respect to the plane of the guide, and a bypass element. The bypass elements have planar vertical walls, constant height, and taper to a knife-edges at their bypass tips.

Efficiency as a function of transport distance within the guide is calculated. Light that interacts with dimples is totally internally reflected from the bypass faces if the angle of incidence supports TIR, and is completely lost from the guide if the angle of incidence does not satisfy TIR. Figure 3.17 shows a plot of efficiency versus guiding distance from both the probability models and the ray trace model.

Figure 3.16: Comparison plot of efficiency versus guiding distance, red is the ray trace model and blue is the mathematical model, dimple length is 0.5mm

Figure 3.17: Comparison plot of efficiency versus guiding distance, red is the ray trace model and blue is the mathematical model, dimple length is 0.25mm

The two models are consistent but do not match exactly. This is due to the simplifying assumptions used in the probability model. First, the projected size of the dimple in the probability model is based on a rectangle of width w , and length l , and height h ; and the projected size of the dimple in the ray trace model is based on the actual bypass tail geometry. Second, the probability model assumes that the

guiding layer is uniformly filled with light. In practice, light is injected at small patches within the guide. This means that light must travel some distance down the guide before filling the full extent of the guide. Moreover, since light is diverging from these small patches, the spatial-angular distribution within the guide is not uniform. For instance, light that is injected directly down the guide will encounter dimples more than the probability model predicts, and light that is injected at certain angles may not encounter dimples at all.

These mathematical models provide a basic framework for calculating the guiding efficiency and angular distributions of dimpled lightguides. However, for complicated guide and dimple geometries, the mathematical models become computationally intensive and the simplifying assumptions begin to break down. In order to assess the performance of complicated systems and dimple geometries, it is concluded that ray trace modeling provides a more robust basis for calculations and optimization.

3.6 Ray Trace Model

The general ray trace model consists of sources, optical path, and receivers. Figure 3.18 shows a drawing of the general ray trace model including the property definitions. The source defines the illumination conditions presented to the lightguide, specifically spectrum, divergence, source size, and source position. The receiver records incident rays at the target plane. The receiver provides a number of metrics including total incident power, irradiance distributions, intensity (angular) distributions, and spectral information. If needed the raw ray data can be collected for later use, or can be coupled with a user-defined merit function for optimization. The optical path is defined by elements, each of which has surface, material, and interface properties.

Figure 3.18: Schematic of the general ray trace model

The general model for dimpled lightguides consists of four main components: 1) the lenslet array, 2) the low-index TIR layer, 3) the bulk guiding medium, 4) and the dimple array. These make up the dimpled lightguide structure. Figure 3.19 shows a drawing of a lightguide with refractive lenslets and injection elements. The source is aimed to be normally incident to the top of the lenslet layer with a prescribed divergence. In this drawing, the source is above the refractive lenslets pointed downward. The receiver is placed at the output of the guiding layer, which puts the receiver at the right edge of this picture. Finally, the bypass elements are not shown, but are placed to the left of each injection element. Additionally, material indices of refraction and spectral transmission are defined to realistically model transmission through long distances of lightguide.

Figure 3.19: Schematic of the general dimpled lightguide model

Both the lenslet array and dimple array are modeled using three-dimensional textured surface properties, a method of arraying complicated geometries in LightTools®. Each surface texture is constructed by arraying a single unit cell. Figure 3.20 shows a schematic of a single lenslet unit cell and the resulting lenslet array formed by the 3D surface texture. This unit cell contains the geometric features and optical surface properties, and by changing just the unit cell, the entire array is changed. This is critical because optimization of system performance depends on the ability to minimize design parameters and variables. With surface textures, the model is reduced to one lenslet with a radius of curvature and conic constant, a lenslet layer thickness, a guide layer thickness, one dimple consisting of an injection element and bypass element, and the array spacing of the lenslets and dimples. By minimizing the design parameters, it is possible to model, optimize, and perform sensitivity analysis on a design with thousands of arrayed elements.

The lenslets are either refractive or reflective. Figure 3.19 shows a model of a lightguide using refractive elements. Figure 3.21 is a schematic of the reflective lightguide model. Reflective lenslets avoid chromatic aberration and have small surface sags compared with equal NA refractive lenslets; but reflective lenslets must be placed behind the dimple feature, which shadows the mirror surface and reduces injection efficiency. Also, reflective lenslets require tighter control of the surface figure. Reflective lenslets avoid the shadow losses inherent with reflective lenslets, but require steeper surfaces and deeper surface sags for high numerical apertures. The choice between reflective and refractive lenslets depends on the intended fabrication method and dimple design. For reflective lenslets, if the dimple is small compared to the input

aperture, the shadow loss may be justified. The prototypes presented in chapter 4 use refractive lenslets, and future prototypes are planned to test reflective lenslets.

Figure 3.20: Lenslet unit cell (left), and lenslet array formed by the 3D surface textures (right)

Figure 3.21: Schematic of the reflective layout

In order to analyze the effect of the dimples' effect on the angular distribution on light transporting in the guide, the ray trace model is used to produce detailed angular spectrum maps. These angular spectra are collected near the injection element and at increasing distances from the injection element. Figure 3.22 is an example angular spectrum plot. The central circular region represents the extent of the injected numerical aperture. Each circular region to the left and right of the central region represents light reflected one, two, or three, times from a bypass element. Notice that angular components that are traversing parallel to the guiding layer are nonexistent. Also notice the fine structure contained within each circular region. This structure has the potential to instruct the design of optimal bypass element geometries.

Figure 3.22: Angular spectrum at 100mm distance from the injection elements for a circular lenslet aperture, injection angle of 45 degrees, 1mm dimple spacing, and knife-edge dimples

3.7 Sensitivity Analysis

In order to determine manufacturability, a sensitivity analysis was performed on a general model of the dimpled lightguide design. A summary of the model parameters is given in Table 3.1, and a summary of the sensitivity parameters is listed in Table 3.2. This model assumes a nominal knife-edge dimple design. This dimple design was chosen prior to identifying a fabrication technology, so the sensitivity analyses are in general terms. After the fabrication of the generation 1 prototype, based on this knife-edge dimple design, the dimple was revised and re-optimized to synergize with the fabrication processes. Many of the sensitivities do apply to any dimpled lightguide design, but certain sensitivities such as bypass tip radius and bypass wall draft angle are specific to the knife-edge design.

Component	Parameter	Comment	Value	
Focusing element	Type		Refractive	Reflective
	Radius (mm)		1.88	10.50
	Conic Constant		-0.46	-1.00
	Thickness (mm)		0.74	0.30
	Clear Aperture (rectangular, mm)	X	3.00	3.00
Dimple		Z	1.00	1.00
	Injection element (mm)	X / Y / Z	0.14 / 0.14 / 0.13	0.17 / 0.17 / 0.16
	Bypass element (mm)	X / Y / Z	0.14 / 0.14 / 1.65	0.17 / 0.17 / 1.65
Light Guide	Thickness (mm)		5	5
	Elements placement (mm)	X	3	3
		Z (shifted orthogonal)	1	1
	TIR layer position	From dimple layer	2.5	2.5

Table 3.1: Nominal values for 2-sided refractive and reflective lightguide model with knife-edge, vertical walled bypass prism.

Sensitivity analyses are performed by individually sweeping each parameter across a range of values and calculating the partial derivative as percent change collection efficiency per unit of measure. Positioning error is the bulk misalignment of the lenslet layer with respect to the dimple layer. Registration error is the individual and accumulated placement error of individual dimples with respect to their corresponding lenslets. Injection element dimensions means the over- or under- sizing of the injection face from nominal, and similar, bypass element dimensions are the non-nominal dimensions of the bypass element. The length, width, and height are shown in Figure 3.23

Figure 3.23: Schematic of dimple dimensional labels

Curvature sensitivities were performed by applying a Bezier curve to that surface and displacing the center of the element by a specified amount. Draft angle refers to the non-verticality of the bypass walls, a necessary tapering in order to remove the replicated dimple array from its mold, shown in Figure 3.24.

Figure 3.24: Schematic of bypass wall draft angle

Bypass sidewall chamfering is a bevel applied to the top edge of the bypass surfaces. Bypass tip radius is the fillet radius of the knife-edge bypass tip, shown in Figure 3.25.

Figure 3.25: Schematic of bypass tip radius

Dimple bypass chamfer refers to the chamfer associated with intersection of the top edge of the bypass walls with the bypass roof, shown in

Figure 3.26: Schematic of bypass tail chamfer

The focusing element sensitivities include radius, tilt, and chamfer size. Radius refers to the radius of curvature of the surface measured in millimeter, with sensitivities measured in micrometer changes in radius of curvature. Tilt refers to the angle the vertex of the surface is tilted with respect to nominal. Chamfer size refers to the width of the perimeter around each focusing element where neighboring elements intersect. Notice that the radius and tilt sensitivities of the refractive and reflective focusing elements are substantially different, due to the difference in Δn for the two cases. For refractive lenslets, the Δn is roughly 0.5 whereas the Δn for the reflective lenslets is 3.0. In the absence of a manufacturing process, this suggests that refractive lenslet are superior to reflective lenslets. This sensitivity information is used to determine that the prototypes, discussed in chapter 4, should have refractive lenslets. What is lost in

this analysis is that the surface sag of refractive lenslet is approximately four times greater than reflective lenslet of the same optical power. This means that some manufacturing processes can be applied to reflective systems but not refractive systems.

The lightguide sensitivities include temperature effects, TIR layer thickness variations, and guiding layer thickness variations. Temperature effects include varying the temperature of the entire guiding layer together as well as the individual components. Since the coefficients of thermal expansion (CTE) are very different between the focusing and guiding layers, assumed to be PMMA and N-BAK1 glass respectively, these two conditions yield the same results. PMMA has a CTE roughly 50 times that of glass. The CTE of PMMA is approximately $100 \mu\text{m/m}/^\circ\text{C}$, compared with glass which typically has a CTE of 2 to $5 \mu\text{m/m}/^\circ\text{C}$. Thickness variations in the TIR layer and guiding layer are modeled as micrometers per mm, and unless the guiding substrates are substantially non-parallel, this is not a driving sensitivity.

	Parameter	Comments	Partial Derivative	Unit
Dimple	Registration error	Z	0.59	% per micron
		X	0.62	
	Positioning error	Z	0.50	% per micron
		X	0.35	
	Injection element dimensions	linear	0.24	% per micron
		angular	0.08	% per arc minute
	Bypass element dimensions	Z	0.002	% per micron
		Y	0.06	
	Curvature on bypass sides		0.09	% per micron of sag in the surface center
	on bypass top		0.08	
	on injection diagonal		1.21	
	Draft angle		1.10	% per degree
Focusing element (refractive)	Chamfer on dimple sides		0.15	% per micron
	Radius on bypass end		0.54	% per 1 micron of radius value
	Radius		0.30	% per micron
	Tilt	Z	0.10	% per arc minute
		X	0.03	
Focusing element (reflective)	Chamfer size	On short side	0.02	% per micron
		On long side	0.08	
	Radius		1.80	% per micron
	Tilt	Z	1.34	% per arc minute
		X	0.42	
Light guide	Temperature effect (TCE and dN/dT)		0.04	% per degree C
	TIR layer flatness		0.005	% per micron
	Random thickness variation across light guide		0.03	% per micron

Table 3.2: Sensitivities analysis of the general 2-sided vertical refractive and reflective lightguide models, primary dimensions of the dimples, lenslets, and guiding layer

The most sensitive parameters are the registration error of the dimples with respect to the lenslets and the bypass tip radius. Registration error manifests itself in a two main ways: element-to-element misalignments and accumulated errors. The element-to-element error results for random or systemic error in the fabrication of the master tooling. For instance, if the lenslet mold is machined, the absolute positioning accuracy of the mill determines the absolute position and accuracy of the individual elements within the mold. Random errors in the machining process transfer directly to random error in the elements and there is no compensatory mechanism for this error. Accumulated errors are those that add up over a number of elements. For instance, if each element is 1 micrometer too large or small, the hundredth element is displaced by 100 micrometers with respect to nominal. This type of error can occur during machining, due to part shrinkage during and after molding, or due to temperature fluctuations during or

after machining or molding. In chapter 4, this type of accumulated error is a major contributor to performance degradation in the generation 1 prototypes.

One additional error that was thought to be a driving sensitivity is clocking between the lenslet and dimple layers. It turns out not to be an important error because of an unexpected alignment test method. Specifically, the array of lenslets acts as a lenticular surface to create a magnified image of the dimple. The magnification of the lenticular dimple image is related to the clocking of the lenslet and dimple layers. When the two layers are perfectly aligned, the size of the dimple becomes very large, filling the full input aperture of the lightguide. As the two layers are misaligned, the size of the dimple image shrinks.

4 Fabrication & Testing

4.1 Introduction

The ultimate goal of this research is to build and test a working prototype of the lightguide concentrator with an eye towards large-scale manufacturing of solar concentrator modules and creation of another tool for increasing green energy production. The culmination is the fabrication of two generations of lightguide concentrators. The goal of the first generation prototypes is to test the ray trace models and demonstrate the manufacturability of the lightguide design; and the goal of the second generation prototypes is to prove the design's ability to achieve high optical efficiency. In both cases, the lenslet layer is made by diamond turning and injection molding, the guiding layer is composed of glass, and the dimple layer is made by laser-writing lithography and cured polymer on glass.

4.2 Fabrication Methods

Analysis of the lightguide prototypes can be divided into two categories: component testing and assembly testing. As part of the component fabrication timeline, the lenslets and dimples were tested individually. The lenslets were analyzed using microscopy and by white-light interferometry. The dimple master tool was analyzed using microscopy, white-light interferometry, and scanning electron microscopy (SEM). The results of these tests were fed back into the ray trace model to predict and verify the as-built performance of the lightguide system.

4.2.1 Materials

The choice of optical materials is critical to solar concentrator performance. In addition to high optical transmission, materials must have long lifetimes under long-term exposure to solar flux, large changes in temperature, and large changes in humidity and other environmental factors. In addition, dissimilar materials must be compatible over large temperature ranges and irradiance levels. This is especially important for lightguide concentrators where different materials are cemented together. Even small differences in coefficients of thermal expansion (CTE) can cause the material stack to warp or even delaminate. These considerations would seem to push the material choice to thermally and optically stable

materials; however in order to fabricate lightguide concentrators, compromises must be made. Glass is far more optically and thermally stable than plastic, but molding microstructures in glass in large scale is beyond the state-of-the-art. Plastics can be molded into the required shapes, but the solar flux carried by the guide layer exceeds the capability of most plastics. Instead, the lightguide was fabricated from a glass-and-plastic stack, to avoid significant bending and warping due to changes in temperature. The specific plastic materials and thicknesses were constrained to minimize the internal stress resulting from large temperature fluctuations.

The guiding layer is composed of highly transmissive glass (N-BAK1 or Borofloat). The lenslet layer is made of injection molded plastic (polycarbonate or PMMA). The dimple layer is made of a UV curable polymer matching the index of refraction of the glass guiding layer. And the low-index layer is a UV or thermally curable plastic or silicone. The lenslet and dimple layers are relatively thin, so as they attempt to expand and contract, their movement is constrained by the glass guiding layer. Instead of expanding laterally, which would result in a misalignment as a function of lateral position, they are constrained to expand vertically. The resulting change in surface figure has minimal impact on system performance. Also, if the glass guide layer sufficiently thick and well supported, warping is minimized. Figure 4.1 shows a schematic of the general prototype model, including lenslet layer, TIR low index layer, guiding layer, and dimple layer.

Figure 4.1: Schematic of the general prototype model

Figure 4.2: Photograph of the generation 1 prototype. The lenslet array is 50mm by 60mm.

4.2.2 Lenslets

The lenslet layer consists roughly 3,000 closely packed, hexagonal aperture lenses, each with a diameter of 1mm along their major dimension. The radius of curvature of all lenses is 1.0mm, and the lenslet aperture dimension is nominally 1.0mm along the hexagons major axis. The material of the lenslet layer is polycarbonate ($n=1.57$) for the generation 1 prototypes, and is PMMA ($n = 1.49$) for the generation 2 prototypes. The thickness of the lenslet layer is adjusted between prototype generations to adjust for the focal shift resulting from the difference in index of refraction of the materials. Lenslet thickness for generation 1 is 1.7mm, and the thickness for generation 2 is 1.9mm. The primary reason for changing of lenslet materials between generations 1 and 2 is material lifetime. Accelerated lifetime testing of the polycarbonate revealed significant yellowing when exposed to UV radiation[67]. PMMA is comparatively UV resistant. Polycarbonate has a reduction to 90% its original transmission after less than 10 years, whereas PMMA has a reduction to 90% its original transmission at 30 years. Figure 4.3 shows a close-up of the hexagonally packed lenslet array. The fillet radius between adjacent lenses is less than $5\mu\text{m}$.

Figure 4.3: Close-up photograph of the hexagonal lenslet array

The lenslet master tool is precision machined via single-point diamond turning into nickel. That master tool is then used in two separate injection molding runs, one with polycarbonate and one with PMMA. Two constraints drive the lenslet array design to its final form. First, the intersection between lenslets must form a continuous surface. This limits the aperture shape of the lenslets to rectangles or hexagons for close packed geometries. Theoretically, offset rectangles provided the highest system efficiency, but the inherent discontinuities made that design form impossible for the chosen fabrication method. Geometries that are not close-packed may also be considered, but the inherent area losses due to packing fraction generally make these geometries inefficient. Second, the tool clearances for the particular diamond turning apparatus used allows for a maximum of 30 degrees of slope from flat. This limits the numerical aperture of the lenslets, effectively which causes the dimples to be packed more closely together than the nominal design dictates.

4.2.3 Dimples

The dimple layer master tool is fabricated by laser-writing lithography. A laser beam is focused and scanned across photoresist and the intensity of the beam is varied to produce an irradiance map of the feature to be patterned. The resist is then developed and etched into a silicon wafer which becomes the master for the microstructured surface. Next, a silicone elastomer master mold is formed from this pattern by thermal curing. This silicone mold is used to replicate the dimple pattern into a polymer-on-glass layer. The silicone mold is covered with UV curable polymer with an index of refraction closely matching the glass guiding layer. The total layer thickness is 0.15 mm with the dimple features having a height of

0.125mm. Optically, this thin plastic dimple layer becomes part of the guiding layer, since light will be transported in both the glass and plastic dimple layers. The dimple features are written so that each injection face lies directly beneath its corresponding lenslet. The integral bypass element (tail) is also written at the same time. Although the plastic dimple layer may have more optical absorption than the glass, it is thin compared to the glass guiding layer, so the optical path in this layer a fraction of its total optical path from injection face to target. The percentage of light traveling in the dimple layer is simply the ratio of the dimple layer thickness to the glass guide layer thickness, roughly 10 percent in generations 1 and 2.

Figure 4.4: Model of the plastic dimple layer on glass (left) and 10x microscope image of fabricated dimple layer (right)

The dimple layer has lateral dimensions of 50 mm by 60 mm, and it has a thickness of 0.15 mm. The placement of each dimple corresponds to the placement of lenslets, and the spacing is hexagonal, with the long space being 1.0 mm (Z-dimension) and the short space being 0.866 mm (X-dimension). Figure 4.4 shows both a model of the plastic dimple layer and an image of the first fabricated dimple layer.

4.2.4 Guide Layer

The guide layer is composed of glass. In order to maximize optical efficiency, both for injection and transport, a high index glass with very high transmission lowest dispersion was chosen: Schott N-BAK1. The index of refraction is $n=1.57$, with an Abbé number of $v=57.5$. Its internal transmission is greater than 98 percent from 380nm to 1100nm through 25 mm of material. Additionally, N-BAK1 is resistant to environmental and chemical attack, and has a hardness equivalent to NBK7 making it easily

polished. The guide layer is 1.0 mm thick and has lateral dimensions 50mm by 60mm. Five of six sides are polished with minimal bevel. The sixth surface is 50mm by 1mm is the surface farthest from the target plane. By polishing the left and right edge surfaces, light is totally internally reflected, minimizing loss at the edge boundaries of the lightguide.

4.3 Testing Methods

4.3.1 Instrumentation

4.3.1.1 *White Light Interferometer*

A white light interferometer allows for non-contact profilometry of optical parts. It allows for characterization of surface roughness, micro-feature lateral dimensions, and accurate measurement of feature height. The instrument used for this research is a Zygo NewView 600s, fitted with a 20x objective. Its measurement field is 350 μ m by 260 μ m, with a pixel resolution of 0.55 μ m. The instrument has a vertical resolution of <0.1nm. With its 20x objective, the interferometer can measure surfaces with slopes up to 22 degree, which accommodates the vast majority of lenslet and dimple layer measurements.

4.3.1.2 *Boroscope*

The boroscope allows for close inspection of the dimples in-situ as well as verifying good contact between the lenslet array, low-index TIR layer, and glass guide layer. The boroscope has a distinct advantage over a traditional macro lens for viewing lightguide features. Its extended depth-of-focus and wide field-of-view allow dimples deep in the lightguide to be viewed through the output face. Unexpectedly, the boroscope can also be used to view the angular distribution of guided light at the output. The total internal reflection of the guide creates a “hall of mirrors,” discussed in chapter 3. Figure 4.5 shows a boroscope image of the generation 1 prototype from the same perspective. The large bright spots are the injection facets directly viewed. The smaller spots are the reflected image of the injection faces after two TIR bounces.

Figure 4.5: Photograph looking back into the proof-of-concept lightguide from the output plane

4.3.1.3 Solar Simulator

All lightguide system measurements were made using a custom built solar simulator. The simulator consists of an arc lamp source, homogenizing optics, collimating optics, and interchangeable spectral and neutral density filters. Since the simulator is intended to illuminate concentrator systems, its goal is to match the divergence of the sun, approximately ± 0.25 degrees. To meet this goal, it is necessary to compromise on the irradiance of the simulator. The irradiance of the simulator is approximately 200 W/m^2 , whereas the standard solar irradiance is $1,000 \text{ W/m}^2$. Most commercially available simulators attempt to match irradiance without regard to divergence. This is problematic when measuring concentrator optics, since the acceptance angles of many high-concentration systems are small.

4.3.1.4 Photovoltaic Solar Cells

All system efficiency measurements are made using characterized photovoltaic cells that have been diced to the output dimension of the lightguide concentrator. Since short circuit current, I_{sc} , of a single junction solar cell scales linearly with incident optical power, assuming sufficient illumination to neglect dark current; efficiency measurements are made by comparing the bare cell current density to the lightguide-attached current density.

The photovoltaic cells used for generation 1 are single junction GaAs. These cells were fabricated at the National Renewable Energy Laboratory (NREL) using molecular beam epitaxial using the same processes as commercial concentrator solar cells. Between generations 1 and 2, it was determined silicon

photovoltaic cells were more practical for prototype lightguides. All generation 2 prototype lightguide systems use either reclaimed photovoltaic cells from generation 1 prototypes or silicon cells. Short circuit current is measured using a LabView® connected Keithley 2420 source meter with Kelvin probes. This allows for short circuit current measurements to be incorporated into an automated measurement setup. Figure 4.6 is a characteristic light I-V curve for a silicon photovoltaic cell. A light I-V curve is a measure of the current flow versus voltage while the photovoltaic cell is being illuminated. Short circuit current, I_{SC} , is the current flow as the voltage approaches zero. It is the current flow that would occur if the positive and negative terminals of the PV cell were short circuited. I_{SC} scales linearly with incident irradiance. Open circuit voltage, V_{OC} , is the voltage applied to just balance the voltage generated by the PV cell, and at this point, current does not flow. V_{OC} depends on the bandgap of the semiconductor, the quality of the PV cell, the incident irradiance, and the temperature.

Figure 4.6: Characteristic light-I-V curve for a photovoltaic cell

4.3.2 Component Tests

4.3.2.1 Dimples

The dimples serve two functions. First, the injection element of the dimple redirects light from the lenslets into the guide layer, and second, the bypass element redirects light around the injection element to reduce losses. In these prototype designs, both injection and bypass functions rely on total internal

reflection (TIR) for maximum efficiency. Therefore, in addition to the geometrical constraints on the dimple shape, including size, angle, and position; the surfaces of the dimples must be smooth enough to allow for TIR. In order to verify the geometry and surface smoothness, a number of component level tests are run, and those tests are outlined below. Figure 4.7 shows the injection and bypass elements that compose the dimple features.

Figure 4.7: Dimple, including injection and bypass elements

Before fabricating full dimple arrays, the manufacturer, Rochester Photonics Corporation, creates a series of test parts to tune the laser writing lithography and etching processes. Silicone replicas of these tools are made. These replicas are sputter coated with gold and placed in a scanning electron microscope (SEM). The SEM allows for viewing of the dimple geometry and surface features, but it does not provide z-height data. The depth of focus for the SEM is large, enabling quick analysis of geometrical issues. Figure 4.8 shows SEM perspective images of the generation 1 and 2 test samples. The generation 1 as-built bypass prisms differ from the designed geometry significantly. The generation 1 design has vertical walls, which was not compatible with the fabrication method. The generation 2 as-built prisms match the nominal design, because the laser-write fabrication method was factored into the dimple design process.

Figure 4.8: SEM image of generation 1 test sample (left) and generation 2 test sample (right)

4.3.2.2 Lenslets

The lenslet layer serves to focus light onto the dimple layer, and each the focal spot of each lenslet must be aligned with its corresponding injection face. In order to ensure accuracy of the focal lengths of the lenslet and their positions, two techniques were used. First, a measuring microscope was used to verify the lenslet-to-lenslet spacing of the lenslet array. The lenslet layer thickness was simply measured with calipers. Second, white light interferometry was used to both verify surface quality and radius of curvature.

The measuring microscope consists of a 60x microscope objective with CCD camera and a motorized linear stage with 0.1 μ m repeatability. Since the position of each lenslet in the master tool had been verified by the manufacturer, the primary dimensional concern is overall shrinkage of the plastic part due to cooling after injection molding. This shrinkage results in accumulated error, the additive effect of a slightly incorrect pitch. In order to measure the accumulated error, the distance between lenslets on opposite edges is measured along the 60mm dimension. This measurement is then divided by the number of lenslets along this dimension. Since lenslets have been molded using both polycarbonate and PMMA, measurements are taken on representative samples from lenslets of both materials, and those results are discussed below.

The surface quality and radius of curvature of the lenslet array is verified using a white light interferometer. Since the consistency of the lenslets in the array has been verified by the manufacturer, only a few lenslets in the central region of the array and a few lenslets near one corner of the array are tested.

For each lenslet, a measurement of the three dimensional profile of the lenslet surface is taken. Then the best-fit sphere is applied to that surface. The radius of curvature of the lenslets is $1.05\text{mm} \pm 0.01\text{mm}$.

4.3.3 System Tests

4.3.3.1 Acceptance Angle

Both generations 1 and 2 prototypes are designed to have acceptance angles of roughly ± 1 degree. The exact shape of the acceptance region depends on the shape of the useable area of the injection face. By carefully mapping out the acceptance region of the lightguide concentrator, it is possible to determine which part of the injection face is working efficiently and which parts are not.

Acceptance angles are measured using a system consisting of two motorized rotation stages. The stages are placed orthogonal to one another and the aperture of the system under test is placed at the center of rotation of both stages. The stages are automated using LabView®, along with a Keithley 2420 source meter for short circuit current measurements. This automated system allows for high resolution angular measurements, critical in diagnosing potential system errors. Figure 4.9 shows a model of the automated system and lightguide assemblies. The system is designed to accommodate a wide range of optical systems with input apertures as large as 200mm in diameter.

Figure 4.9: Isometric view of automated system (left) and lightguide prototype assembly(right)

Two-dimensional acceptance angle data is collected on a grid. The primary axis of rotation extends vertically from the large rotation stage and passes through the center of the 50mm dimension of the lightguide. The secondary axis of rotation extends horizontally outward from the center of the small

rotation stage through roughly the center of the 60mm dimension of the lightguide. The recorded angles from the measurement apparatus are the angular readings from the individual rotation stages. Since the secondary stage rotates within the reference frame of the first, these angles are the conventional Euler angles. These angles match the output angular coordinates of the ray trace models.

4.3.3.2 *Full-aperture*

Solar concentrator efficiencies are typically reported as the percentage of direct-normal radiation entering the front aperture of the device that reaches the output plane. Although both generations 1 and 2 suffer from spacing mismatch (detailed discussion in section 4.4.4.1), the full aperture efficiency still remains an important measure of system performance. It allows for the direct comparison of the lightguide system performance to other types of concentrators.

4.3.3.3 *Sub-aperture*

In order to separate spacing mismatch losses from other potential loss mechanisms, a slit aperture is placed between the solar simulator source and prototype lightguide. This small aperture illuminates only a small portion of the lightguide at a time. With the prototype on motorized translation stages, it is possible to illuminate a given section of the guide and take field-of-view measurements. Over any given small portion of the guide, the acceptance angle is constant. When comparing far separated portions of the guide, the field-of-view moves. The shape of the field-of-view remains mostly unchanged, but the direction in which that field-of-view is oriented does change.

Figure 4.10: Sub-aperture lightguide measurement

This technique also enables the separation of the injection and guiding losses. When the aperture is very close to the output aperture, it can be assumed that all of the observed losses occur in a short optical path that includes only the lenslet, injection face, and very few bypass elements. Since the replication of the lenslets and dimples are uniform, it can also be assumed that the magnitude of this injection loss is the same for all sections of the guide. Therefore, any decrease in efficiency observed when the aperture is moved far away from the cell plane is due to guiding losses.

4.4 Generation 1 Prototypes

4.4.1 Generation 1 Model

The generation 1 prototype model is designed to closely replicate the fabricated geometries and material characteristics. The model consists of a close-packed plastic lenslet array with hexagonal apertures, a plastic dimple layer, a glass guiding layer, and a low-index TIR layer. The source spectrum is the standard ASTM 1.5G solar spectrum, truncated for wavelengths shorter than 360nm and longer than 1170nm. The source acceptance angle is ± 1.0 degrees, and the total emitted power is 1.0 Watts. The model's receiver is placed at the output face of the guiding layer.

The overall dimensions of the device are 60mm in the guiding dimension, 50mm in the dimension perpendicular to light propagation, and 3.85mm in the direction of initial light propagation. It consists of a hexagonal array of lenslets-dimple pairs, separated by the guiding layer. The material models included index of refraction as a function of wavelength and spectral transmittance. Each lenslet has a hexagonal aperture of 1.0mm in the long dimension with a radius of curvature of 1.05mm and a conic constant of -0.4. This results in 0.3mm of surface sag, with the lenslet array having a total thickness of 1.7mm. The lenslet material is polycarbonate, with an index of $n=1.57$. This lenslet layer is separated from the guiding layer by a low-index adhesive. Since the absorption properties of the low-index layer are unknown, and since the layer has a nominal thickness of just 25 μm , this layer is assumed to have no absorption.

Figure 4.11: Side-view of the nominal ray-trace model

The optical performance of the four types of generation 1 prototypes is modeled. The respective index of these materials is $n=1.45$, $n=1.41$, and $n=1.0$. In all cases, the material is assumed to have a constant index of refraction, since data on the spectral properties of these materials is proprietary to Rochester Photonics Corporation.

The next component in the optical path was the guiding layer. Two types of devices have been fabricated, using two types of glass: N-BAK1 and Borofloat. N-BAK1 is manufactured by Schott glass. It has an index of $n=1.57$ and an Abbé number of $v=60$, and has been chosen because it has a high index of refraction and spectral transmission across the solar spectrum. N-BAK1 has an average internal transmittance of better than $99.6\% \text{cm}^{-1}$ from 380nm to 1700nm. Borofloat is also manufactured by Schott glass. It has an index of $n=1.47$ and an Abbé number of $v=70$, and it has been chosen as a low-cost potential material for manufacturability. Since it is difficult to mold precise structures into glass, a polymer layer is bonded and molded to the bottom surface of the guiding layer. This polymer has the dimple molded into the bottom surface. The dimples comprise the final component in the injected optical path. The polymer dimple layer has an index of refraction of $n=1.57$ when used with the N-BAK1 guiding layer and an index of $n=1.47$ when used with the Borofloat. Since the polymer dimple layer is part of the guiding structure with

the glass, the indices of refraction of the two materials must be closely matched. The dimple layer is modeled to be $150\mu\text{m}$ thick with the dimple having a maximum depth of $125\mu\text{m}$.

Figure 4.12: Wide view of the prototype model (left) and top view (right)

The angular spectrum is calculated from the ray trace model in order to understand the effect of the generation 1 first generation dimple geometry on the angular spectrum within the guide. Light is injected through one lenslet onto one injection face, and the angular spectrum is recorded for increased distances from the injection face. The figure below shows the angular spectrum for four distances from the injection face: 1mm, 18mm, 36mm, and 52mm.

Figure 4.13: Angular spectrum at increasing distances from the injection element. From top to bottom, 1mm, 18mm, 36mm, and 52mm

4.4.2 Fabrication

Ten generation 1 prototype assemblies were fabricated. Table 4.1 provides a summary of the generation 1 prototype modules. Nine of ten prototypes have a polycarbonate lenslet array, a N-BAK1 glass guiding layer, and a dimple layer made using the same master tool, made from $n=1.57$ index UV curable polymer. Seven of these nine, generation 1.0, have an $n=1.45$ low index TIR adhesive that attaches the lenslet array to the top surface of the N-BAK1 guiding layer. The eighth prototype, generation 1.1, has an $n=1.41$ low index silicone layer in place of the $n=1.45$ index material. The ninth prototype, generation 1.2, has a $25\mu\text{m}$ air-gap as the low index TIR layer and is held in place at four corners by standoffs. The reason for lowering the index of eighth and ninth prototypes was in response to the non-nominal steepness of the injection facet, which results in a larger than anticipated angular distribution within the guide. Lowering the index of refraction of the low-index TIR layer expands the numerical aperture of the lightguide, allowing more high-angle light to traverse down the guide. Injection facet steepness is discussed in detail in section 4.4.4.1.2.

The tenth prototype, generation 1.6, has the same polycarbonate lenslet array, but the glass guide layer is replaced with Borofloat glass. Borofloat is an ideal choice for a manufacturable system because it is produced in high volume and comparatively low cost compared with optical glasses. Borofloat has an index of $n=1.47$. The polymer used for the dimple layer was changed to match Borofloat and has an index of roughly $n=1.47$. The low-index TIR layer is created by a $25\mu\text{m}$ air-gap.

Generation 1 Dimpled Light Guide Versions					
Version (modules)	Unit Dimensions L,W,H (mm)	Layer	Thickness (mm)	Index	Material
Gen 1.0 (1-7)	60,50,3	Lens array	1.7	1.57	PC
		Low Index TIR	0.025	1.45	RPC polymer
		Guide layer	1.0	1.57	N-BAK1
		Dimples	0.125	~1.57	RPC material
Gen 1.1 (LI)	60,50,3	Lens array	1.7	1.57	PC
		Low Index TIR	0.025	1.41	Silicone Nusil
		Guide layer	1.0	1.57	N-BAK1
		Dimples	0.125	~1.57	RPC polymer
Gen 1.2 (A1)	60,50,3	Lens array	1.7	1.57	PC
		Low Index (LI) TIR		1.0	air
		Guide layer	1.0	1.57	N-BAK1
		Dimples	0.125	~1.57	RPC polymer
Gen 1.6 (A2)	60,50,3	Lens array	1.7	1.57	PC
		Low Index (LI) TIR		1.0	air
		Guide layer	1.0	1.47	Borofloat Glass
		Dimples	0.125	~1.47	RPC polymer

Table 4.1: Summary table of generation 1 prototypes

The performance of the as-built generation 1 dimpled light guide is significantly lower than the nominal model predicts. This is not unexpected, due to the complexity of the fabrication processes and novelty of the design. From extensive metrology data, an optical model of the non-nominal, as-built lightguide and dimple geometries is constructed in LightTools® to verify the measured results and determine the effect of the individual errors. The major sources of efficiency degradation are 1) the spacing mismatch between the lenslet and dimple layers, 2) an error in the angle of the injection face, 3) the width of the dimple, 4) the fillet rounding of the bypass tip, 5) and the surface roughness of the bypass walls. Table 4.2 shows the losses parsed out error-by-error. Figure 4.15 shows a plot of the slit scan experiment. It shows the optical efficiency versus the distance from the injected light to the cell. The total losses of the measured and modeled systems correlate well, as do the slit-scan results. This provides confidence in the optical model. The reported efficiency losses due to the individual fabrication errors in Table 4.2 are from the optical model.

4.4.3 Performance

4.4.3.1 Full Aperture Efficiency

The measured full aperture efficiency for the generation 1.0 prototype is $17 \pm 5\%$ and is reported in Table 4.2. The extremely low efficiency is due to the combination of a smaller-than-designed injection face and a lenslet-to-dimple spacing mismatch. The details of this loss are described in detail later in this chapter.

	Optical Loss	Optical Efficiency	Calculation
Nominal Efficiency:		92 %	
Injection Losses			
Injection Face, 12° Too Steep	35%		
TOTAL	35%		
Injected Efficiency***		57%	$= 92\% - 35\%$
Guiding Losses			
25μm Bypass Tip Radius	22%		
Bypass Wall Surface Roughness	14%		
Dimple Too Wide (150μm)	7%		
5° draft angle	3%		
TOTAL	46%		
Modeled Efficiency (Losses summed independently) **		31 %	$= 57\% - (57\% * 46\%)$
Modeled Efficiency (Losses modeled in a single model) **		34 %	
Measured Efficiency ***		33 ±5 %	
Loss from Spacing Mismatch	52 %		$= 17\% / 33\%$
Measured Efficiency, no corrections		17 ±5 %	
** By including all loss mechanisms in a single model, actual efficiency is 3% greater than the sum of the individual losses. This is an expected effect due to weak coupling between loss mechanisms. *** Efficiency was maximized by adjusting the field-of-view using a small aperture scanned over the guide, then integrated. This compensates for the different spacing between lenslet and dimple layers.			

Table 4.2: Summary of loss mechanisms for the generation 1.0 prototype

4.4.3.2 Slit Scan Efficiency:

The generation 1.0 prototype's optical efficiency, corrected for lenslet-dimple spacing mismatch is $33 \pm 5\%$. The method for this calculation is simple. Using a small aperture, a two-dimensional field-of-view is measured at a number of distances from the output plane. The peak efficiency at each distance is extracted from the field-of-view data and that efficiency versus distance-from-output data is integrated. Figure 4.15 shows efficiency versus distance plots for the nominal model, the as-built model, two prototype

lightguide measurements corrected for spacing mismatch, and prototype lightguide measurement without the spacing mismatch correction.

From Figure 4.15, the injection efficiency is $90 \pm 5\%$. The optical path for the efficiently transferred light is simply lenslet, injection face, and output face. Light efficiently totally internally reflects off of the injection face before being collected by the photovoltaic detector. Within 5mm, the efficiency drops to $55 \pm 5\%$. This precipitous drop is caused by the steep injection face. While light reflects from the injection face, its angle within the guide is large, so the majority of light does not satisfy TIR at the interface between the guide and low-index layer that separates the guide from the lenslets. From 10mm onward, optical losses are due to the non-nominal shape and surface roughness of the bypass elements. This loss is observed as the slope of the optical efficiency beyond 10mm.

The slit scan method allows for careful analysis of injection and guiding losses, but also provides a detailed measure of system performance, which can be compared against modeled results. For instance, the dip in efficiency between 2 and 3mm and the subsequent rise between 6 and 8mm is an effect of the non-nominal injection face shape. The face has a flat region that is too steep, then a roll-off region between the injection face and top surface of the dimple, shown in Figure 4.14

Figure 4.14: Schematic of the as-built generation 1 injection face with roll-off

A simple model of the dimple, adjusted for this injection face steepness, does not explain the local maxima or the relatively high efficiency from 10mm onward. The simple model predicts almost no

transmission of light beyond 8mm. However, the more complete dimple model, constructed from component measurements, does recreate these features, and allows for a greater understanding of the mechanisms involved with both injection and guiding.

Figure 4.15: Generation 1.0 slit scan optical efficiency, measured and modeled

4.4.3.3 Field-of-View

The field-of-view for the generation 1 prototypes depends greatly on the location at which light is injected into the guide. Since the lenslets and dimples have slightly different pitch spacing, the centroid of the field-of-view changes position, depending on the location of the injected light. For the lightguide to function properly, all of the lenslet-dimple pairs must be aligned so their fields-of-view overlap. This is discussed in detail in section 4.4.4.1.1.

The shape of the field-of-view changes as a function of location as well. This is due to the incomplete use of injection face. When light is injected near the output plane, a portion of light that is not supported by the guiding layer's numerical aperture is collected by the receiver. This allows a large portion

of the flat region of the injection face to contribute to the output signal. However, when light is injected far away from the output plane, light does escape from the guiding layer and is lost. “Far away” constitutes any position more than 3mm from the output face of the guide. In this region, only light injected from a small roll-off region between the steep injection face and flat top of the dimple is used. All field-of-view plots are normalized to the maximum injected signal from the “near” field-of-view. Each pair of near and far fields-of-view is measured on the same scale.

4.4.3.3.1 Generation 1.1, LG-05 field-of-view

For light injected close to the output plane, the field-of-view is approximately ± 1 degree by ± 0.25 degrees, far smaller than the nominal field-of-view. This significantly smaller field-of-view is caused primarily by fabrication errors of the injection face. This face is far steeper than the nominal design, so light is not contained by the guiding layer. Figure 4.16 shows a comparison of the near and far fields-of-view for the generation 1 prototype. The color scale is normalized to the peak value of the near field-of-view, and from the figures, it is clear that the transmitted energy for the far field-of-view is small. The dashed circles represent the nominal designed field-of-view. In addition to the undersized field-of-view and loss of energy, also not the angular shift of the fields-of-view between the near and far measurements. This is caused by the pitch mismatch between lenslet and dimple layers. This phenomenon is discussed in section 4.4.4.1.1.

Figure 4.16: G1.0-LG-05, field-of-view for light injected 1mm from output face, normalized (top), and field-of-view for light injected at 59mm away from the output plane, normalized to 1mm case (bottom)

Figure 4.17: G1.6-LG-02-air, field-of-view for light injected 1mm from output face, normalized (top), and field-of-view for light injected at 50mm away from the output plane, normalized to the 1mm case (bottom)

4.4.4 Fabrication Issues – Tests and Modeling

4.4.4.1 Injection Losses

Injection losses are defined as the losses that occur during the initial concentration and turning by the lenslet-dimple pairs. The nominal model predicts that injection efficiencies greater than 94% within the design acceptance angle are possible, with the primary loss mechanism being Fresnel reflections. In

practice, the generation 1 prototypes demonstrate lower injection efficiency. The primary loss mechanisms are spacing mismatch between the lenslets and dimples, steepness of the injection face causing light to be ejected from the guiding layer, and loss of TIR due to roughness of the injection face.

4.4.4.1.1 Spacing Mismatch

The dimpled lightguide design requires that all of the lenslet-dimple pairs are aligned with respect to one another, so that the field-of-view of each points in the same direction. The prototype device suffers from a total spacing mismatch across the 60mm dimension of $30\mu\text{m}$, or roughly $1.5\mu\text{m}$ per lenslet. This results from shrinkage of the polycarbonate injection molded lenslet layer. By comparison, the process for molding the polymer-on-glass dimple layer suffers little to no shrinkage. This mismatch resulted in a 52% reduction in efficiency when measuring the full aperture. This large reduction in efficiency was exacerbated by a smaller-than-designed injection face area. Spacing mismatch was addressed between generations 1 and 2 by adjusting the pitch of the laser-written dimple master tool. If instead the lenslet array had been adjusted, the lenslet mold would have been re-machined. The designed tolerance to spacing mismatch is $\pm 25\mu\text{m}$ with an acceptance angle of ± 1.2 degree. If the injection face had been nominal, the spacing mismatch would have had a far smaller effect on full aperture efficiency.

4.4.4.1.2 Injection face angle

The nominal injection face angle for generation 1 is 51 degrees while the fabricated injection face angle is $63 \pm 1^\circ$. This 12 degree difference from the nominal model results in 24 degrees of additional angular extent within the guide. Since the numerical aperture of the guide is approximately 0.38, the maximum angle of incidence supported within the guide is 22.5 degrees. This means that almost all of the light injected into the guide is quickly ejected from the guide. The optical model predicts that the efficiency should drop by 85% or more for an injection face angle of 63 degrees; however, the injection face angle error resulted in only a 35% reduction in efficiency.

On closer examination of the cross-section of the injection face, it is clear that the higher efficiency is due to the rounding of the injection face into the top face. Although the injection face angle is

incorrect, there is a transition region between the flat region of the injector and the flat top of the dimple. This small roll-off region passes through the angle at which light injects and propagates down the guide. Unfortunately, by using only this small transition region, the Z- direction field-of-view is very small, no more than 0.5 degrees total. Figure 4.18 shows a cross-section SEM image of the generation 1 dimple. The solution to fixing the injection face angle is straightforward: make a series of calibration laser-writes and etches to tune the process and achieve the desired angle. These calibration steps also allow for refinement of the bypass element geometry and wall roughness.

Figure 4.18: Cross-section SEM image of the generation 1 dimple injection face. Note the curved surface at the top of the dimple.

4.4.4.1.3 Injection face roughness

Since the injection face reflects light into the guide via total internal reflection, its roughness can be a substantial loss mechanism for the system. The injection face roughness is measured using white light interferometry, and there is substantial roughness in the flat area of the face. Interestingly, the transition region between the injection face and flat top of the dimple is smooth. If the injection had been fabricated at its nominal angle, the roughness would have caused a substantial decrease in injection efficiency. However, since the only injected and guided light comes from the transition region, the roughness does not play a role in efficiency issues in generation 1. This loss mechanism did not present itself until the generation 2.0a prototypes, and it is detailed in the discussion of the generation 2 prototypes.

Figure 4.19: Surface roughness measurement of the Generation 1 injection face

4.4.4.2 Guiding Losses

4.4.4.2.1 Bypass Tip Radius

The nominal bypass tip radius is $10\mu\text{m}$; however, the as-built generation 1 prototype has a tip radius of $25 \pm 5\mu\text{m}$. This blunt bypass end causes a significant portion of light to scatter out of the guide at each dimple interaction, and results in a 22% reduction in full aperture efficiency. This issue was caused by the incompatibility of the dimple design and the fabrication process in silicon. Mainly, laser write lithography cannot produce both smooth walled and sharp features. This issue is addressed in the generation 2 prototypes by redesigning the dimples to eliminate all sharp features. Figure 4.20 shows an SEM image of the dimple's bypass tip.

Figure 4.20: Scanning electron microscope images of the Generation 1 bypass tip (left) and modeled 10 micrometer bypass tip (right)

Figure 4.21: SEM image of the draft angle of the bypass tip

4.4.4.2.2 Bypass Wall Roughness

Another fabrication issue with the generation 1 prototype is the surface roughness on the bypass walls of the dimples. The nominal slopes of the dimple called for just a 5 degree draft angle on these bypass walls. The as-built bypass elements have a draft angle of greater than 10 degrees, shown in Figure 4.21. As previously mentioned, the laser written lithography process can produce either smoothly varying features or sharp features, depending on the chosen photoresist and process parameter. However, the process cannot provide both smooth and sharp features simultaneously in silicon. This issue has been corrected in

generation 2. Since the primary concern is the ability of the injection facet to provide efficiency TIR coupling into the guide, the bypass wall surface quality suffered. Also, because of the steepness of these features, it is difficult to separate the replicated parts from the master tool. Figure 4.22 shows the resulting wall roughness, measured with both the SEM and white light interferometer. The period of these rough features is approximately $10\mu\text{m}$ with peak-to-valley amplitude of between $0.5\mu\text{m}$ and $1\mu\text{m}$.

Figure 4.22: SEM image (left) and Zygo NewView image (right) of generation 1 bypass wall roughness

4.4.4.2.3 Dimple width and draft angle

The designed width of the generation 1 dimple is $100\mu\text{m}$, but the fabricated width is $130\mu\text{m}$. The lithography and etching process caused the dimple to be wider than specified at its base, and to have a greater draft angle. The draft angle is approximately 10 degrees, compared to the nominal design of 5 degrees. This extra width creates a larger bypass wedge angle and leads to an additional full aperture efficiency loss of approximately 10 percent. Figure 4.23 is a top view of the generation 1 dimple. The top surface of the dimple is the correct width at its widest point, $100\mu\text{m}$; however, with the addition of a 10 degree draft, the base of the dimple is $130\mu\text{m}$.

Figure 4.23: SEM image – top view of the generation 1 dimple

4.4.4.3 As-built dimple model

By combining SEM side-view images of the injection facet and bypass tip with top-view images of the full dimple profile, it is possible to create a trace map to define an accurate as-built dimple in SolidWorks®. Figure 4.24 shows this overlay of the SEM images in SolidWorks® (left), and the resulting as-built dimple (right). All of the major geometric features have been reconstructed, including the injection face steepness, injection face roll-off, bypass wall draft angle, bypass tip fillet rounding, and curvature of the top of the dimple near the bypass tip.

Figure 4.24: Overlay of SEM images and modeled as-built dimple (left), and as-built dimple

Additionally, the bypass wall roughness is added to the model as geometric features on the sidewalls of the bypass elements. Figure 4.25 shows these modeled features. The roughness is modeled using triangular gouges with a $10\mu\text{m}$ period. The angle of the triangles is adjusted so the amplitude is $0.5\mu\text{m}$. This as-built dimple model is then connected to the LightTools® model.

Figure 4.25: As-built dimple model, including bypass wall roughness

4.5 Generation 2 Prototypes

4.5.1 Overview & Design Changes

Generation 1 uncovered a number of design, material and process challenges, so the goal of generation 2 is to address and correct as many of these issues as possible. Since the generation 1 prototype demonstrated far lower optical efficiency than modeled and expected, the primary goal of generation 2 is to achieve high optical efficiency. A secondary goal is the demonstration of the lightguide concept using inexpensive material alternatives such as PMMA and Borofloat glass. In order to achieve these goals, two changes were made to the prototype design.

First, the dimple shape is altered. In generation 1, the nominal dimple had steep sidewalls, angular features, and a knife-edged bypass tip. In theoretical models, this design shape is highly efficient, but in practice, the limitations of micro-fabrication and replication prove the design to be impractical. Therefore, the primary task of the dimple redesign was to mesh geometries of the dimple with the intended fabrication processes. Second, the lenslet material is changed from polycarbonate to PMMA. Subsequently, the thickness of the lenslet layer was changed to account for the focal shift of approximately $250\mu\text{m}$ due to the difference in refractive index. The choice to change lenslet material from polycarbonate to PMMA is based on the comparison of UV accelerated lifetime data between materials. Polycarbonate yellows after just a few years of UV irradiation. This yellowing represents the absorption of the blue part of the spectrum. In contrast, certain grades of PMMA demonstrate little or no degradation in transmission after decades of UV exposure.

Another important change between generations 1 and 2 is the focus on process verification. Prior to writing any dimple master tools, a two of test writes are run. The first test write has coarsely separated dimple's angles and depths, and the second test write fine tunes the dimple's angles and depths. Extensive metrology is performed on these samples including scanning electron microscopy, white light interferometry, and light and dark field optical microscopy.

Generation 2 Dimpled Light Guide Versions					
Version (modules)	Unit Dimensions L,W,H (mm)	Layer	Thickness (mm)	Index	Material
Gen 2.0a (6)	60,50,3	Lens array	1.7	1.57	PC
		Low Index TIR	0.025	1.45	RPC polymer
		Guide layer	1.0	1.57	N-BAK1
		Dimples	0.125	~1.57	RPC material
Gen 2.0b (3)	60,50,3	Lens array	1.7	1.57	PC
		Low Index TIR	0.025	1.41	Silicone Nusil
		Guide layer	1.0	1.57	N-BAK1
		Dimples	0.125	~1.57	RPC polymer
Gen 2.0c (1)	60,50,3	Lens array	1.7	1.57	PC
		Low Index (LI) TIR		1.0	air
		Guide layer	1.0	1.57	N-BAK1
		Dimples	0.125	~1.57	RPC polymer

Table 4.3: Summary table of generation 2 prototypes

Results for the generation 2 prototypes are presented later in this chapter. Note that the generation 2 prototypes are labeled as 2.0a, 2.5a, and 2.0b. The label 2.0 denotes lightguides with an N-BAK1 substrate, and the label 2.5 denotes lightguides with a Borofloat substrate. The suffix of a, b, or c denotes the master tool from which the dimple layer of the lightguide is made. Both tools a and b are dimple masters etched into a silicon substrate. Tool c is a dimple master etched into fused silica. The master tools are used to create a silicone sub-master from which the dimple layer is soft molded via UV curing.

The angular spectrum is calculated from the ray trace model in order to understand the effect of the generation 2 dimple geometry on the angular spectrum within the guide. Light is injected through one lenslet onto one injection face, and the angular spectrum is recorded for increased distances from the injection face. The figure below shows the angular spectrum for four distances from the injection face: 1mm, 18mm, 36mm, and 52mm.

Figure 4.26: Angular spectrum at increasing distances from the injection element. From top to bottom, 1mm, 18mm, 36mm, and 52mm

4.5.1.1 Dimple design

The generation 2 dimple design is shown in Figure 4.27. The dimple dimensions are $90\mu\text{m}$ tall, $125\mu\text{m}$ wide, and $1,000\mu\text{m}$ long. The injection face is oriented at 49 degrees with respect to plane of the guide layer. This allows the injection face to satisfy TIR for the full numerical aperture of the lenslet. Ideally, the injection face would be oriented at 45 degrees in order to inject light into the guiding layer at the lowest possible angle. The bypass faces of the dimple are oriented at roughly 40 degrees with respect to the plane of the guide layer at opposing angles. The cross-section created by these bypass faces is roughly triangular and decreases in height and width as it extends from the injection face to its tip. The intersection of the two of the bypass surfaces has a $50\mu\text{m}$ fillet radius, the perimeter of the dimple is blended into the surrounding flat regions with a $40\mu\text{m}$ fillet radius, and the intersection of the injection face and bypass surfaces has a $20\mu\text{m}$ fillet radius. The resulting dimple shape has not sharp features, and the bypass element' tip is blended, fabrication errors that result in feature rounding are mitigated.

Figure 4.27: Isometric view of the generation 2 dimple shape

SEM results of the initial generation 2 test write shows a clear improvement in surface quality and show far greater fidelity in the replication of the dimple geometry. In generation 1, most of the surface roughness occurs on the bypass faces, likely caused by the steepness of the walls. Since the surface slope of the generation 2 dimples does not exceed 49 degrees, this source of surface roughness has been eliminated. Also in generation 1, the bypass tip nominally tapers to a knife edge, which causes those features to be highly sensitive to fabrication errors. Since the generation 2 bypass elements taper gradually toward the bypass tip and blend into the surrounding flat region, the geometry's sensitivity to fabrication errors is

greatly reduced. With confirmation that two of the primary causes of efficiency loss have been addressed, the subsequent test writes focus on tuning the depth of the dimple features and angle on the injection facet.

Figure 4.28: SEM isometric views of generation 2 dimple test write

Two dimple layer master tools have been fabricated for the generation 2 prototypes. Before each master tool is made, test patterns are written to tune the depth of the dimples. Each test pattern contains 10 sets of dimple features. Sample 1 has the lowest exposure, sample 10 has the highest exposure, and the intermediate samples are linearly spaced between 1 and 10. After etching, a silicone replica is made from the test pattern, sputter coated with gold, and placed in the SEM.

Figure 4.29: Gen 2 angular test sample, injection face angles measured with SEM, samples 1, 2, 4 (top row, left to right), 6, 9, and 10 (bottom row, left to right)

4.5.1.2 Pitch matching methods

The pitch of the PMMA lenslet array is different than that of the generation 1 polycarbonate lenslet array because of different coefficients of thermal expansion. Plastic injection molded parts shrink when removed from the mold tool as they cool from roughly 200°C to room temperature. If the injection molding process is carefully controlled, the part-to-part shrinkage is repeatable and uniform, and indeed the part-to-part uniformity of the lenslet arrays is good. As previously mentioned, the polycarbonate lenslet arrays are approximately 30µm too long across 90 lenslet apertures. The PMMA lenslet arrays are approximated 60µm too long. So, in order to insure proper alignment between dimple and lenslet layers, the pitch of the generation master tool must be adjusted.

Despite the adjustment of the dimple master tool pitch, prototypes continued to suffer from lenslet-dimple pitch mismatch. This was unexpected since the master tool is composed of silicon, a thermally stable material, and the dimple layer is constrained laterally by the glass guiding layer once cured. After a careful review of the process steps, it was determined that the silicone soft mold was expanding and contracting from temperature fluctuations. To correct this, the silicone mold is placed in a temperature controlled chamber adjusted to the temperature at which the silicone replica was cast. Also, by adjusting the oven temperature to temperatures other than its original casting temperature, it is possible to tune the pitch of a non-ideally spaced master tool as well. In the most recent generation 2 prototype lightguides, lenslet-dimple spacing mismatch has been solved. The specified design tolerance for space mismatch errors is $\pm 25\mu\text{m}$, and the generation 2 prototypes have a space mismatch error of $\pm 16\mu\text{m}$, well within the design specification.

4.5.2 Performance – Tests and Modeling

4.5.2.1 Generation 2.0a – N-BAK1

The full aperture efficiency of the generation 2.0a prototype is roughly $52 \pm 5\%$, a vast improvement from the 17 percent efficiency of generation 1, but far short of the expected >70 percent goal. The sub-aperture fields-of-view are shown in Figure 4.30. The triangular shape of the field-of-view is the result of the shape of the injection face. Notice also in Figure 4.30 that there is still a slight angular shift

between the near and far sub-aperture injection points. Although lenslet-dimple spacing mismatch has been addressed between generations 1 and 2, some mismatch still exists. The shift does not however have a detrimental impact on system efficiency, because the extent of the field-of-view is large enough to accommodate the error.

Figure 4.30: Sub-aperture field-of-view for generation 2.0a, 0mm (top) and 50mm (bottom), the color scale of both is normalized to the peak injection signal of the top plot

The slit scan measurement reveals the type of the efficiency loss, a critical part of determining the fabrication errors causing the loss. The measurement of injection efficiency is assumed to be independent

of injection position, and guiding efficiency assumes that this injection efficiency is constant at all positions in the guide. Two factors are apparent in Figure 4.31. First, the injected efficiency is only $71 \pm 5\%$ compared with a nominal modeled efficiency of 95 percent, a difference of 24 percent. This indicates that the injection facets are not efficiently coupling light into the guiding layer. Second, the slope of the efficiency versus distance is too steep, indicating that light is not being guided efficiently down the guide layer.

Figure 4.31: Slit scan measurements and model for generation 2.0a

As seen from the slit scan measurements, the largest loss mechanism for the generation 2.0a prototypes is loss at the injection face. This prompted a review of the white-light interferometry measurements of the injection face. The measurements in Figure 4.32 clearly show significant surface roughness on the injection facet. The result of this roughness is a loss of TIR at the surface, since there is now both a specular reflected component and a scattered component of the reflected light. Surface roughness is modeled in LightTools® by applying a Gaussian scattering property to the injection face. The Gaussian scatter angle is adjusted to match slit scan injection data. The modeled Gaussian scatter angle to achieve a 10 percent injection loss is 2 degrees, full-width half-max.

The guiding loss of 30 percent is a combination of two main loss mechanisms: scattering from pitting in the flat regions of the guide and material absorption from the UV curved dimple layer material.

Figure 4.32: Surface roughness on the generation 2.0a injection face, P-V is $4.5\mu\text{m}$

Figure 4.33: Pitting of the flat regions of the dimple layer, P-V roughness is $1.8\mu\text{m}$

4.5.2.2 Generation 2.0b

Generation 2.0b uses a new master tool that addresses the surface roughness issue present in the generation 2.0a and 2.5a prototypes. The cause of the surface roughness in the previous master tool was a material issue related to the etched substrate. That substrate was made from silicon, which is subject to pitting when developed using reactive ion etching. The generation 2.0b substrate is also made from silicon, but the etching process is reoptimized to minimize pitting.

Figure 4.34: Full aperture field-of-view for the generation

Prototype guides fabricated using this new master tool demonstrate a significantly higher optical efficiency. The injection efficiency is $82 \pm 5\%$, approaching the nominal model. The total guide efficiency is $65 \pm 5\%$, which is 13 percent more efficient than generation 2.0a, and 17 percent less efficient than the nominal generation 2 designed model. The residual loss mechanisms are material absorption, index mismatch between the polymer dimple and glass guiding layers, and minor surface ripple and roughness of the polymer dimple layer. Material absorption and index of refraction mismatches have been modeled, but due to the proprietary nature of the UV curing polymer, test samples of the material could not be obtained. The full aperture field-of-view matches the nominal model as well. The field-of-view for the full aperture generation 2.0b prototype is shown in Figure 4.34.

Figure 4.35: Sub-aperture field-of-view for generation 2.0b, 0mm (top) and 50mm (bottom), both plots are normalized to the maximum signal from the 0mm field-of-view

Figure 4.35 show plots of the sub-aperture fields-of-view close to the cell and 50mm away from the cell. Both fields-of-view are normalized to the maximum signal of the near-to-cell field-of-view. Notice that the field-of-view shift due to pitch mismatch has been eliminated. Also note that the guided efficiency is 70 percent of the injected efficiency. Also notice that the shape of the fields-of-view parallel the geometry of the injection face. This indicates that the full injection face is effectively injecting light into the guiding layer.

Figure 4.36: Optical efficiency versus distance from output for generation 2.0b

Figure 4.36 shows the slit scan test for the generation 2.0b prototype. The injected efficiency is $82 \pm 5\%$, which indicates that the effects of scattering and surface roughness at the injection face are reduced. The slope of the slit scan measurement is also shallower, indicating that scattering within the guiding layer has been reduced also. Scattering remains an issue, despite process improvement because of the use of silicon as the etched substrate. Generation 2.0c uses a fused silica substrate to further reduce or eliminate scattering at the injection face, at the bypass elements, and on the planar guiding layer.

Figure 4.37 is a comparison of the slit scans between the generation 1 and 2 prototypes. The plot shows the “ideal” modeled system, the nominal goal, the generation 2.0b prototype, and the generation 1 prototype. Between generation 1 and 2, the primary improvements are correction of the lenslet-dimple pitch mismatch, correction of the injection face angle, and smoothing of the dimple surface roughness. The generation 2.0b prototype is still 12 percent below the predicted nominal injection efficiency and 15 percent below the predicted full aperture efficiency because of remaining surface roughness issues, material absorption, and slight over sizing of the dimple features.

Figure 4.37: Comparison plot of generations 1 and 2 slit scan efficiency

Although the generation 1 and 2 prototypes did not achieve the goal full aperture efficiency of $80 \pm 5\%$, significant progress has been made in both modeling and fabrication techniques. The non-nominal ray trace models agree well with the measured data, and provide confidence for modeling and predicting actual performance of lightguide concentrators. The comparison plot of the generations 1 and 2 prototypes demonstrates the significant advances in fabrication techniques during the course of the project. Generation 1 had a full aperture efficiency of 17 percent, and generation 2.0b increased this efficiency to 65 percent.

Initial measurements on the next iteration of the generation 2 prototypes, generation 2.0c, indicate an injection efficiency of close to $85 \pm 5\%$ and a full aperture efficiency of greater than 70 percent. The primary change between the generation 2.0b and 2.0c prototypes is the substrate material of the dimple master tool. Generation 2.0b and earlier prototypes use a silicon substrate, which is subject to pitting. Generation 2.0c uses a fused silica substrate, which is less susceptible to pitting. Figure 4.38 shows surface profile measurements of both the injection face and the planar region surrounding the dimples. The surface roughness of the generation 2.0c prototype is an order of magnitude less than the previous generations.

Figure 4.38: Generation 2.0c surface roughness measurements of the injection face, $P-V$ is $4.5\mu\text{m}$ (left), and the flat regions, $P-V$ is $0.1\mu\text{m}$

Figure 4.39 is a plot of the measured slit scan data for the generation 2.0c prototype. Due to an issue during the laser-write mastering process, only two strips of dimple align to lenslets. These strips are nominally 15mm wide, and are shown in the figure. A linear fit has been added to represent the anticipated slit-efficiency data in the remaining regions. The peak efficiency is now $85 \pm 5\%$, and the slope of the slit-efficiency is consistent with the generations 2.0a and 2.0b prototypes..

Figure 4.39: Slit scan for the generation 2.0c prototype

Figure 4.40 is a comparison plot of the generation 2.0b and 2.0c slit scan efficiency. The generation 2.0c prototype shows some improvement.

Figure 4.40: Comparison plot of generation 2.0b and 2.0c slit scan efficiency

Over the course of this research, 20 prototype lightguides were fabricated and tested. Initial prototypes had measured efficiencies of 17 percent, and a number of design and fabrication issues were identified. These issues included dimple-lenslet pitch mismatch, incorrect injection face angle, injection face roughness, bypass face roughness, feature rounding and fillet radius. Through detailed component testing, analysis, and modeling, the contribution of each of these issues was identified and quantified. Through design adjustments and fabrication process refinements, all of these issues were addressed, and the efficiency was increased from 17 percent in generation 1, to more than 70 percent in generation 2.0c. With future refinements, it is expected that the dimpled lightguide can achieve efficiencies greater than 80 percent.

In order to achieve high optical efficiency and high concentrations, future work includes refinement of the current fabrication methods, exploration of alternate fabrication methods, and detailed modeling and analysis of alternate dimpled lightguide geometries. Using the fused silica master substrate significantly reduces surface pitting and scattering losses. The test write procedure employed between generations 1 and 2 must be repeated for the new substrate material to ensure proper feature depth. White

light interferometry and scanning electron microscopy have proven to be valuable tools in characterizing both the lenslet and dimple features.

Since the intended source for these lightguide concentrators is the sun, a solar simulator is used for the measurement of all of the optical efficiency measurements. Future work includes use of the dimpled geometry for other applications, so measurement of the lightguide prototypes using different spectra is suggested. Also, since there are unknown absorption characteristics of certain polymer materials in the lightguide, narrow-band efficiencies would give valuable insight into material performance. Future work is discussed in detail in chapter 5.

5 Conclusions & Suggestions for Future Work

5.1 Summary of Work

Chapter 1 introduced solar energy, the solar resource, and the basic constraints of concentrator design. Chapter 1 also provided an overview of concentrated photovoltaic manufacturers, as well as a description of the state-of-the-art in concentrator design. Solar concentrator designs range from low to high concentration. All of these systems have aspect ratios, the ratio of aperture diameter to system thickness, of less than three. Lightguides, specifically dimpled lightguides, have demonstrated aspect ratios of greater than fifty, and the remainder of the research focused on lightguides.

Chapter 2 provided a background and description of the invention at the heart of this research: the dimpled lightguide concentrator. The primary advance of this concentrator was the addition of a bypass element. The bypass element efficiently and predictably diverted light around the injection element, which adds to the angular spectrum but significantly decreases losses from light ejection. Chapter 2 also introduced the concept of lightguides and lightguide concentrators. Existing lightguide concentrator concepts were introduced, including the fluorescent lightguide, the swept-stepped lightguide, and the planar slab lightguide concentrator. These lightguides provide unique solutions, but have challenges that the dimpled lightguide concentrator addressed.

Chapter 3 introduced two mathematical models, the moiré and probability models; compared these models against ray tracing; then focused on ray tracing as the preferred method for analysis and optimization of the dimpled lightguide concentrator. Chapter 3 examined three driving mechanisms in the design of dimpled lightguides: focusing element numerical aperture, dimple density, and lightguide aspect ratio. Also, chapter 3 reviewed sensitivity analyses of characteristic dimpled lightguide systems as preparation for the fabrication and testing of prototype devices. The most sensitive parameter was the lenslet-to-dimple registration, reported in section 3.7. The driving nature of the registration error sensitivity was reinforced in chapter 4 by the challenges of lenslet-to-dimple matching during the fabrication of the generations 1 and 2 prototypes.

Chapter 4 provided a detailed analysis of the fabrication methods, testing methods, component testing results, and prototype system results. Two generations of prototypes were fabricated and tested, including detailed component tests. Component test data was folded back into the ray trace models to create as-built models, and those ray trace models agreed well with the experimental results. The first generation of prototypes had a full aperture optical efficiency of 17 percent. The second generation of prototype employed new dimple geometry and achieved a verified full aperture optical efficiency of 65 percent. Initial results of the latest prototypes indicate an optical efficiency of more than 70 percent. These efficiency gains are primarily due to fabrication process refinements.

5.2 Future Work

5.2.1 Process refinement

The laser-writing lithographic process, which enabled the microstructured dimple surface, was used to create the generation 1 prototypes, and was refined over the course of the generation 2 prototype efforts. The generation 1, 2.0a, and 2.0b prototypes exposed an issue with the process. The silicon substrates used for etching of the master tool were subject to pitting, which led to scattering at the injection face, from the bypass element, and from the flat regions between dimples. The generation 2.0c master tool corrected the scattering by substituting the silicon substrate with a fused silica substrate. Initial measurements on prototypes replicated from this master tool show major reductions in surface scattering. Therefore, the straightforward path to improved efficiency is to continue refining the laser-write lithography process for fabricating dimple structures.

Alternatively, micro-machining processes provide another path for dimple fabrication. Micro-machining represents the state-of-the-art in precision CNC machining techniques, and is used to fabricate master tools for a range of high-tech applications. The process constraints for machining are very different from lithographic techniques. Whereas lithographic techniques are best suited to continuous curved surface profiles, CNC machining can easily achieve sharp and angular features. For instance, the generation 1 dimple shape was not well suited to lithography, but would be well suited to machining processes. The

generation 2 dimple shape was optimized for lithography, but would be extremely difficult to fabricate with traditional machining techniques.

5.2.2 New lenslet geometries

The lenslets used throughout the fabrication and testing of this research were produced from the same master mold. In order to ensure high transmission through the lenslets and low surface scattering, the lenslet mold was fabricated by diamond turning. The manufacturer recommended design constraints on the lenslet mold, specifically that surface slopes could not exceed 30 degrees and the sag of the lenslets could not exceed 300 micrometers. This limited the numerical aperture of the lenslets to roughly 0.3. In order to maximize the concentration potential, the numerical aperture, especially in the X-dimension of the lightguide must be much larger.

To achieve the high concentration goal, the lenslets should have larger numerical apertures in the X-dimension, so the first lenslet improvement should be the exploration of alternate lenslet aperture geometries, such as rectangles or stretched hexagons. Since many fabrication processes limit the total sag of the optical surface, these higher numerical aperture lenslets may use Fresnel-type structures. As discussed in chapter one, Fresnel lenses provide a means of segmenting an optical surface into radial zones to provide high numerical aperture with minimum thickness. Some micro-Fresnel structures are suited for lithographic processes. If the lenslets and dimples are both fabricated by lithography, many of the pitch mismatch issues outlined in chapter four could be eliminated. Furthermore, both structures could be replicated as thin polymer layers on the same glass guiding layer.

5.2.3 New dimple geometries

The dimple geometry is critical to the efficiency and potential maximum concentration of the dimpled lightguide. Variations of the generations 1 and 2 dimples were presented in chapter three, but many other dimple shapes exist. Figure 5.1 shows one dimple concept, termed the dimple train. This design is a modification of the generation 1 knife-edge design. The knife-edge bypass element is decentered in the X-dimension, or “wagged,” and is extended so that it blends into the preceding dimple feature. This design

eliminates the knife-edge, and hence the bypass tip fillet radius. It also minimizes the wedge angle of the bypass element.

Figure 5.1: Dimple train concept

5.2.4 Non-uniform lenslet numerical apertures and spacing

Light injected near the cell plane experiences a very different optical path compared to light injected at the most distant point of the lightguide. Light injected near the cell plane experiences almost no interactions with dimples. Light injected far from the cell plane experiences tens of interactions with dimples before reaching the cell plane. If every lenslet injects light with the same numerical aperture, the angular spectrum of light from points near and far from the cell plane differ. In order to achieve the highest possible concentration, each point of the input aperture should map into the same angular spectrum at the cell plane.

Since the light injected close to the cell plane does not interact with dimples, its angular spectrum is simply the angular spectrum produced by the lenslet alone. The guide does not add to its angular spectrum. Conversely, light injected far from the cell plane experiences many interactions with dimple, so its angular spectrum is significantly modified by the guide and dimples. If the dimple shape is designed appropriately, the dimples could essentially increase the numerical aperture of the injected light as it traveled through the guide. Therefore, lenslets close to the cell plane should have high numerical apertures, and lenslets far from the cell plane should have small numerical apertures, since the guiding layer will add

to the numerical aperture. To maximize concentration and efficiency, the lenslets should have numerical apertures that decrease as a function of distance from the cell plane. This leads to a non-uniform spacing of the lenslet-dimple pairs. Lenslets and dimples near the cell plane are spaced far apart, and are packed closer together as a function of distances from the cell plane.

5.2.5 Analytical Solutions

Although specific designs for manufacturing are optimized by ray tracing, there exists a great deal of value in analytical solutions to the dimpled lightguide concentrator and similar systems. Some of the boundary conditions on efficiency and concentration are explored in this research, but there are many interesting questions waiting to be answered, questions that have been answered for other nonimaging systems. Can dimpled lightguides theoretically achieve maximum étendue transfer? How much étendue can be transferred using a uniformly arrayed dimpled lightguide? How much étendue can be transferred using non-uniformly arrayed lenslets and dimples? How do numerical aperture and acceptance angle effect concentration in lightguide concentrators? What is the ideal theoretical shape of the dimple? These questions and many more should be explored.

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A1 Appendix 1: Mathematical Models

A1.1 Moiré Model

A1.1.1 1D Translation Model Code

```

n = 500;
nth = 200;
z0 = 1;          % spacing between dimples along guiding direction
tau1 = .5;       % opening - width of dimple in X
T1 = 1; %linspace(0.8,1,20);          % period - pitch between dimples
in X
tau2 = .5;       % opening - width of dimple in Y
T2 = 1;          % period - pitch between dimples in Y
dx = linspace(-T1,T1,41);
[x,y,nth] = ndgrid(linspace(-T1*3,T1*3,n),linspace(0,T2*4,3),-nth:nth);
for ii = 1:size(dx,2)
    a1 = (tau1./T1).*sinc(nth.*tau1./T1);
end
rtot = sum(rxy,3);
for jj = 1:size(dx,2)
    temp1 = rxy(:,:,1).*rxy(:,:,jj);
    temp2 = ones(size(x,1),size(x,2));
    cont1(jj) = sum(temp1(:))./sum(temp2(:));
end
figure(1),
plot(dx, cont1)
title('Transmission vs. Displacement'),'FontSize', 14);
xlabel(['Displacement, \Delta (periods)'],'FontSize', 14);
ylabel(['Percent Transmission'],'FontSize', 14);
figure(2),
imagesc(x(:,1,1,1), y(1,:,1,1),rxy(:,:,1)'), colormap('gray'), axis off
figure(3),
imagesc(x(:,1,1,1), y(1,:,1,1), rtot(:,:,1)'), colorbar,
colormap('gray')

```

A1.2 1D Rotation Model Code

```

n = 1000;
thetaX = linspace(0, pi/3, 181);
z0 = 1;          % spacing between dimples along guiding direction
T1 = 1;          % period - pitch between dimples in X
l = .5;
w = .5;
h = .2;
numgratings = 0:1;
taux = w.*cos(thetaX);%+ l.*sin(thetaX);
T1 = T1.*cos(thetaX);
dx = z0*tan(thetaX);
[x,y] = meshgrid(linspace(0,10,n),linspace(0,10,3));
for ii = 1:size(thetaX,2)
    for jj = 1:length(numgratings)
        rx{ii}(:, :, jj) =
rect1((x+numgratings(jj).*dx(ii)),taux(ii),T1(ii));

```

```

        end
    end
    for ii = 1:size(thetaX,2)
        rxy(:, :, ii) = prod(rx{ii}, 3);
    end
    clear rout
    thold = .5;
    rxy(rxy <= thold) = 0;
    rxy(rxy > thold) = 1;
    for ii = 1:size(dx, 2)
        temp1 = rxy(:, :, ii);
        cont1(ii) = mean(temp1(:));
    end
    figure(1), plot(thetaX.*180./pi, cont1)
    plot(thetaX.*180./pi, cont1)
    title('Transmission vs. View Angle')%, 'FontSize', 14);
    xlabel(['View Angle, \alpha (degrees)']%, 'FontSize', 14);
    ylabel(['Percent Transmission']%, 'FontSize', 14);
    figure(2), imagesc(x(:, 1, 1), y(1, :, 1), rxy(:, :, 1), [0 1]), colorbar,
    colormap('gray')
    figure(3), imagesc(x(:, 1, 1), y(1, :, 1), rxy(:, :, 30), [0 1]), colorbar,
    colormap('gray')

```

A1.2.1 2D Model Code

```

n = 500;
thetaX = 5*pi/180;%linspace(0, 0.01, 2);
thetaY = 0;%linspace(0, 0.01, 2);

z0 = 1;           % spacing between dimples along guiding direction
T1 = 1;           % period - pitch between dimples in X
T2 = 1;           % period - pitch between dimples in Y
l = 0;
w = .5;
h = .5;
numgratings = 0:4;
taux = w.*cos(thetaX); %+ l.*sin(thetaX);
tauy = h.*cos(thetaY); % + taul.*sin(thetaY);
T1 = T1.*cos(thetaX);
T2 = T2.*cos(thetaY);
dx = z0*tan(thetaX);
dy = z0*tan(thetaY);
[x,y] = meshgrid(linspace(-2.25,2.25,n),linspace(-2.25,2.25,n));
for jj = 1:length(numgratings)
    for ii = 1:size(thetaX,2)
        for kk = 1:size(thetaY,2)
            rxy{ii,kk}(:, :, jj) = 1
            rect1((x+numgratings(jj).*dx(ii)),taux(ii),T1(ii)) .* ...
            rect1((y+numgratings(jj).*dy(kk)),tauy(kk),T2(kk));
        end
    end
end
end

for ii = 1:size(thetaX,2)
    for kk = 1:size(thetaY,2)
        rprod{ii,kk} = prod(rxy{ii,kk}, 3);
    end
end

```

```

        rsum{ii,kk} = sum(rxy{ii,kk},3);
        temp = rprod{ii,kk};
        cont1(ii,kk) = mean(temp(:));
    end
end
figure(1), plot(thetaX.*180./pi, cont1)
plot(thetaX.*180./pi, cont1(:,1), thetaX.*180./pi, cont1(1,:))
title('Transmission vs. View Angle')%, 'FontSize', 14);
xlabel(['View Angle, \alpha (degrees)'])%, 'FontSize', 14);
ylabel(['Percent Transmission'])%, 'FontSize', 14);

figure(2), imagesc(thetaX.*180/pi, thetaY.*180/pi, cont1), colorbar,
axis xy %colormap('gray')
figure(3), imagesc(x(1,:), y(:,1), rprod{1,1}, [0 1]), colormap('gray'),
axis off, axis square
figure(4), imagesc(x(1,:), y(:,1), rsum{1,1}), colormap('gray'), axis
off, axis square

```

A1.3 Probability Model

A1.3.1 Probability as a function of angle

The probability of light interacting with a dimple feature is the ratio of the projected dimensions unit cell of the dimple and of the unit cell of the guide.

$$P(\theta_x, \theta_y) = \frac{\tau}{T} = \frac{\tau(\theta_x) \tau(\theta_y)}{T(\theta_x) T(\theta_y)} \quad (\text{A1. 1})$$

The projected width and height of the dimple feature is given below. This assumes that the extent of the dimple is modeled as a rectangle.

$$\tau(\theta_x) = w \cos \theta_x + l \sin \theta_x, \quad \text{and} \quad \tau(\theta_y) = h \cos \theta_y \quad (\text{A1. 2})$$

The projected width and height of the unit cell of the guide is given below.

$$T(\theta_x) = W \cos \theta_x + L \sin \theta_x, \quad \text{and} \quad T(\theta_y) = H \cos \theta_y \quad (\text{A1. 3})$$

Combining the equations above yields:

$$P(\theta_x, \theta_y) = \frac{w \cos \theta_x + l \sin \theta_x}{W \cos \theta_x + L \sin \theta_x} * \frac{h \cos \theta_y}{H \cos \theta_y} \quad (\text{A1. 4})$$

which simplifies to,

$$P(\theta_x, \theta_y) = \frac{h}{H} \frac{w \cos \theta_x + l \sin \theta_x}{W \cos \theta_x + L \sin \theta_x} \quad (\text{A1. 5})$$

A1.3.2 Recursive Relationship

The injected numerical aperture is divided into the constituent angular components, and each component is separately calculated. At the m^{th} row of dimples, E_0^m is the energy in each initial angle, and E_k^m is the energy for all angles after interactions with dimples.

$$\begin{aligned} E_0^{(0)} &\equiv A_0 \\ E_0^{(1)} &= E_0^{(0)}(1 - P_0) \\ E_0^{(2)} &= E_0^{(1)}(1 - P_0) \\ E_0^{(m)} &= E_0^{(m-1)}(1 - P_0) = A_0(1 - P_0)^m \end{aligned} \quad (\text{A1. 6})$$

Below is the energy that exists in the first reflected order for the m^{th} row of dimples. All of the energy that resides in the first order has been reflected out of the zeroth order. Energy can be coupled out of the first order into the second order at each row of dimples.

$$\begin{aligned} E_1^{(0)} &= 0 \\ E_1^{(1)} &= E_0^{(0)}P_0 + E_1^{(0)}(1 - P_1) \\ E_1^{(2)} &= E_0^{(1)}P_0 + E_1^{(1)}(1 - P_1) \\ E_1^{(3)} &= E_0^{(2)}P_0 + E_1^{(2)}(1 - P_1) \\ E_1^{(m)} &= E_0^{(m-1)}P_0 + E_1^{(m-1)}(1 - P_1) \end{aligned} \quad (\text{A1. 7})$$

Below is the energy that exists in the second reflected order for the m^{th} row of dimples. All of the energy that resides in the second order has been reflected out of the first order. Energy can be coupled out of the second order into the third order at each row of dimples.

$$\begin{aligned} E_2^{(0)} &= E_2^{(1)} = 0 \\ E_2^{(2)} &= E_1^{(1)}P_1 + E_2^{(1)}(1 - P_2) \\ E_2^{(3)} &= E_1^{(2)}P_1 + E_2^{(2)}(1 - P_2) \\ E_2^m &= E_1^{(m-1)}P_1 + E_2^{(m-1)}(1 - P_2) \end{aligned} \quad (\text{A1. 8})$$

From above, the recursive relationship for the energy that exists in each reflected order for the m^{th} row of dimples is shown below. Light is coupled into an order by the $k-1$ order and is coupled out of the order into the $k+1$ order.

$$E_k^m = E_{k-1}^{(m-1)}P_{k-1} + E_k^{(m-1)}(1 - P_k) \quad (\text{A1. 9})$$

The sum of all energy at a given row of dimples must equal the input:

$$\sum_k E_k^{(m)} = A_0 \quad (\text{A1. 10})$$

Below is a proof to confirm that, in the absence of boundary conditions, energy is conserved.

$$\begin{aligned}
\sum_k E_k^{(m)} &= E_0^{(m)} + E_1^{(m)} + E_2^{(m)} + \dots + E_k^{(m)} = ? A_0 \\
&= E_0^{(m-1)}(1 - P_0) \dots \\
&\quad + E_0^{(m-1)}P_0 + E_1^{(m-1)}(1 - P_1) \dots \\
&\quad + E_1^{(m-1)}P_1 + E_2^{(m-1)}(1 - P_2) \dots \\
&\quad + \dots + E_{k-1}^{(m-1)}P_{k-1} + E_k^{(m-1)}(1 - P_k) \\
&= E_0^{(m-1)} + E_1^{(m-1)} + E_2^{(m-1)} + \dots + E_k^{(m-1)} \\
&= E_0^{(m-2)} + E_1^{(m-2)} + E_2^{(m-2)} + \dots + E_k^{(m-2)} \\
&= E_0^{(0)} + E_1^{(0)} + E_2^{(0)} + \dots + E_k^{(0)} \\
E_1^{(0)} &= E_2^{(0)} = \dots = E_k^{(0)} = 0 \\
\sum_k E_k^{(m)} &= E_0^{(0)} = A_0
\end{aligned} \quad (\text{A1. 11})$$

The sum of all of the individual energies reduces to the input energy, so energy is conserved, assuming no losses from bounds on the angles of incidence at the dimple features.

A1.3.3 Probability Code

```

load('lt_data_plxplpp25.mat');
index = 1.5;
AngleIn = 15;
thetaCrit = pi/2-asin(1/index);
[thetaX,thetaY] = meshgrid(linspace(0, AngleIn*pi/180, 50));
max_angle = AngleIn.*pi/180;
temp = sqrt(thetaX.^2 + thetaY.^2);
mask(temp<=max_angle)=1;
mask(temp>max_angle)=0;
mask = reshape(mask,size(temp));
mask_size = mask(mask==1);
mask_size = length(mask_size);
lo = 1; % spacing between dimples along guiding direction
L = 1; % period - pitch between dimples in X
W = 1; % period - pitch between dimples in Y
H = 1;
l = .5;
w = .1;
h = .1;
numgratings = 0:100;
bypass = atan(w./(2.*l));
AngE = numgratings.*bypass;
P(1)=0;
for ii = 1:size(thetaX,2)
    for jj = 1:size(thetaY,2)
        E = zeros(length(numgratings));

```

```

E(:,1)=1;
for mm = 1:length(numgratings)
    for kk = 1:mm
        tX = thetaX(ii,jj)+2*AngE(kk);
        tY = thetaY(ii,jj);
        if tX>pi/2
            tX=pi/2;
        end
        P(kk) =
(h./H).*(w.*cos(tX)+l.*sin(tX))./(W.*cos(tX)+L.*sin(tX));
        if kk==1
            E(mm,1) = E(mm,1).*(1-P(1)).^(mm-1);
        else
            E(mm,kk) = E(mm-1,kk-1).*P(kk-1) + E(mm-1,kk).*(1-P(kk));
        end
        Ang_after = acos(cos(tX).*cos(tY));
        temp = thetaCrit; %sqrt(thetaCrit.^2+tY.^2);
        if Ang_after>temp
            E(mm,kk)=0;
        end
    end
end
Out(ii,jj,:,:) = E;
OutP(ii,jj,:,:) = P;
Out2(ii,jj,:) = sum(E,2);
end
end
for kk=1:size(Out,4)
    temp1 = squeeze(sum(Out,4));
    temp1 = temp1(:,: ,kk).*mask;
    effic(kk)=sum(temp1(:))./mask_size;
end
OutM = squeeze(Out(:,: ,end,:));
for ii=1:size(Out,1)
end
figure(1), plot(numgratings,effic, aaa(:,1),aaa(:,2),'r-')
title('Transmission vs. Distance Traveled','FontSize', 14);
xlabel(['Distance in Guide (mm)'],'FontSize', 14);
ylabel(['Percent Transmission'],'FontSize', 14);

```