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Applications of Non-Imaging Micro-Optic Systems

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Electrical Engineering (Photonics)

by

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2012
The dissertation of Katherine Anne Baker is approved and it is acceptable in quality and form for publication on microfilm and electronically:

___________________________________________________________

Chair

University of California, San Diego

2012
DEDICATION

This dissertation is dedicated to my husband, Dennis Muldoon, and my family, Gene, Jill, and Sarah Baker, for their many years of encouragement and support.
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<tr>
<td>$\lambda$</td>
<td>Wavelength of Light (unit)</td>
</tr>
<tr>
<td>AR</td>
<td>Anti-reflective</td>
</tr>
<tr>
<td>CPV</td>
<td>Concentrated Photovoltaics</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Power</td>
</tr>
<tr>
<td>DEP</td>
<td>Dielectrophoresis</td>
</tr>
<tr>
<td>$F$</td>
<td>Focal Length</td>
</tr>
<tr>
<td>$F/#$</td>
<td>F-number</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium Tin Oxide</td>
</tr>
<tr>
<td>LSC</td>
<td>Luminescent Solar Concentrator</td>
</tr>
<tr>
<td>Nm</td>
<td>Nanometer (unit)</td>
</tr>
<tr>
<td>PMSC</td>
<td>Planar Micro-optic Solar Concentrator</td>
</tr>
<tr>
<td>TIR</td>
<td>Total Internal Reflection</td>
</tr>
<tr>
<td>$\mu m$</td>
<td>microns (unit)</td>
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<tr>
<td>UV</td>
<td>ultra-violet</td>
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PUBLICATIONS


Applications of Non-Imaging Micro-Optic Systems

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Professor Joseph E. Ford, Chair

While imaging optics necessarily transmit a clear image of an object, non-imaging optics manipulate light in many different ways. Two important applications are illumination and concentration. In this thesis, I cover an application in each of these areas involving small-scale optics.

Extremely low birth weight infants typically require intubation, but existing laryngoscopes for viewing the airway are not suited to this population. Small commercial cameras can fit within the required geometry, but need high illumination with low heating. Repurposing
the mechanical structure of the laryngoscope as a waveguide for an LED source meets both these requirements.

Concentrator photovoltaic systems accept sunlight over a large aperture and focus it to a proportionally small photovoltaic cell. This kind of configuration allows the cost of expensive but highly efficient multijunction cells to be amortized over a large area module, resulting in cost-effective, high efficiency systems. A prior design from our lab uses a lenslet array and mirrored micro-prisms to concentrate sunlight within a glass waveguide [1]. This enables high efficiency concentration with a compact form factor compatible with mass fabrication and eliminating problems associated with discrete PV cells.

I first adapt the basic planar concentrator design for specific applications. One-dimensional polar tracking is an attractive design space, and either passive optical tracking or mechanical micro-tracking [2] can be used to adapt the concentrator for this framework. The concentrator can also be used in solar thermal rather than photovoltaic applications with the addition of an output coupler.

I also address a completely different approach to concentrator tracking. This non-imaging system is nonlinear, implementing a reactive cladding layer to enable the system to self-track the sun. I present design studies to quantify the requirements of such a material, then present a candidate materials system to meet these requirements: high index particle concentration through optically-induced dielectrophoresis. Experimental results demonstrate the plausibility of the approach.

Finally, I investigate the use of a conformal cladding to simplify fabrication and potentially improve performance. Experimental results using silica aerogel successfully demonstrate a low-index, conformal coating, but a metallic coating on top has low reflectivity.
Chapter I:

Introduction

I.A Non-imaging Optics

Optical systems can broadly be divided into two categories: imaging and non-imaging. Many common optical systems are imaging: cameras, microscopes, telescope, etc. These systems transmit a clear image of an object to a screen, sensor, or an observer. However, many optical applications do not require an image. Instead, light is manipulated for a completely different purpose. Two common examples of non-imaging optical systems are illumination and concentration [3][4].

Illumination systems take light from a source and distribute it over an intended target area. Illumination systems provide ambient lighting indoors, specific lighting conditions for photography or experiments, or light up displays on electronics. A particularly interesting application of illumination systems is for medical devices. As there is obviously no ambient light inside the human body, medical imaging systems inserted into a body require compact illumination systems in order to take adequate images.

Another common non-imaging optical system is a concentrator. By far, the most common application of a concentrator is for solar energy. This could be for concentrator photovoltaics
(CPV), where sunlight is focused from a large aperture onto a small photovoltaic cell in order to create more cost-effective solar modules. Alternatively, sunlight can be focused by a concentrator system for concentrated solar power (CSP), also known as solar thermal [5]. Rather than converting light to electrical energy through the photovoltaic effect, these systems use the heat from sunlight as a power source to drive an engine or heat water for various applications. Prior work from our lab on planar micro-optic solar concentrators shows a novel approach for both these concentrator applications.

I.B Illumination for a Medical Device

![Figure I-1: (a) Premature infants have extremely small airways and typically require intubation. (b) Conventional laryngoscopes can use different shaped blades. (c) New laryngoscope technology includes video](image)

Among the thousands of extremely low birth-weight (less than two pounds, Figure I-1(a)) babies born each year, the vast majority (85-90%) will require intubation, a procedure where a plastic tube is inserted into the larynx to facilitate breathing [6][7]. The device used to visualize the airway during this procedure is known as a laryngoscope, and existing technology as shown in Figure I-1(b) is poorly-suited for this population. Even tools designed for full-term babies are too large for premature infants, and many are more consistent with adult anatomy than the
exaggerated anatomy of infants. Many commercial laryngoscopes have added imagers to the tip, whether in the form of a camera or a coherent fiber bundle, in order to improve visualization of the airway (Figure I-1 (c)). While this type of technology could substantially aid in intubation of extremely low birth weight infants, it is not commercially available in a suitable size.

In this project, my goal was to design and build a prototype video laryngoscope suitable for extremely low birth weight infants [8]. This prototype had to have a tip within a very limited cross-section (3 by 6.5 mm), with sufficient imaging optics and illumination to obtain a clear image of the infant’s airway. However, the device must not heat up enough to pose a risk of thermal damage to the infant’s throat and the overall geometry of the laryngoscope must be compatible with infant anatomy. This defined the illumination goals of this project.

I.C Concentration for Solar Power

Jason Karp’s work on planar micro-optic solar concentration presents an attractive approach to CPV [1]. Incoming sunlight is focused by an array of lenslets onto mirrored micro-prisms, as shown in Figure I-2. The light deflected from these mirrors enters guided modes of a slab waveguide. Photovoltaic cells index-matched to the edges of the waveguide collect the concentrated energy. The geometric concentration of the system is equal to the width of the waveguide over twice the slab thickness (assuming collection at both edges). Using this basic design, optimized components were simulated to have 82% optical efficiency at 300x geometric concentration. Secondary concentration techniques, such as sloping sidewalls and parabolic collectors at the PV cells, increase that simulated efficiency to 85% at 900x geometric concentration [9][10].
Figure I-2: A planar micro-optic solar concentrator uses a lenslet array to focus incoming sunlight to micro-optic injection features. The deflected light couples into a slab waveguide and propagates to photovoltaic cells at the edges of the waveguide [1].

Karp was able to fabricate a working prototype of this design using off-the-shelf optical components. The key process was to create the mirrored micro-prisms, which are illustrated in Figure I-3. Further details on this fabrication process are in Chapter V and Appendix C. Given the limitations of what was commercially available, the prototypes could not reach the simulated performance of optimized components. However, with measured efficiency of 52.3% using an Oriel solar simulator as shown in Figure I-4, the net flux concentration of the prototype device was around 20x [10].

Figure I-3: Mirrored micro-prisms
Figure I-4: Prototype solar concentrator being tested.

Figure I-5: A planar micro-optic solar concentrator shown (a) aligned, (b) misaligned, (c) with large-scale mechanical tracking, and (d) with mechanical micro-tracking [11].
The dominant source of loss for this system while moving to higher geometric concentrations is decoupling. If light already coupled into the waveguide strikes another micro-prism, it will deflect at angle below the critical angle and will decouple from the system entirely. This presents a strong motivation to keep the total area of the injection facets as small as possible. However, this has a tradeoff in terms of the angular acceptance of the overall system. If the concentrator is misaligned to the sun by a small amount (less than one degree), sunlight will miss the reflective features entirely and pass directly through the waveguide, as shown in Figure I-5 (b). In order to maintain high efficiency, angular acceptance must be sacrificed.

Low angular acceptance is actually an inherent problem in solar concentration due to the concept of étendue. This principle states that for the same medium, the product of numerical aperture and physical aperture size must remain constant throughout a system. Since a concentrator by definition has a smaller output aperture than input aperture, it must therefore have a smaller angular acceptance than angular output. For high concentrator systems where the difference in physical size is very large, then the angular acceptance must be quite small, even with a large angular output. The maximum 3-D concentration is given by [4]:

\[ C_{\text{max}} = \left( \frac{1}{\sin \theta} \right)^2 \]

Given that concentrator systems have low angular acceptance, they typically utilize large-scale high-precision 2-axis mechanical tracking, as in Figure I-5 (c). Another approach examined by our lab is lateral mechanical micro-tracking, illustrated in Figure I-5 (d). In this configuration, one slab of glass is moved relative to the other in order to bring the system back into alignment for off-axis illumination. Justin Hallas built and tested a micro-tracking system compatible with the existing prototype to test this concept. With three eccentric cams to reposition the waveguide as shown in Figure I-6 and a peak-finding algorithm, this setup accurately tracked both a laboratory solar simulator and the sun in an outdoor test [2].
Figure I-6: Three eccentric cams align the micro-prisms to the lenslets for a given directional input.

I examine both micro-tracking and passive optical tracking for use in polar tracked system. This tracking arrangement is when a panel is tilted at the latitude of the geographic location and the panel is rotated along one axis, keeping azimuthal alignment as the sun moves from east to west. The angular input from the sun then varies in one axis only by +/- 23.5 °, as shown in Figure I-7. This configuration provides an attractive middle ground between a completely static panel and precise 2-D tracking [12].
I also examine a completely different approach to concentrator tracking using a nonlinear material. This reactive cladding allows self-tracking of the concentrator, enabling it to accept a wide angular range at high concentrations without moving parts and without violating étendue [11].

I.D Thesis Outline

This thesis will examine non-imaging illumination with an application in medical devices and non-imaging concentration with an application in solar concentration. The organization of this thesis is as follows:

- Chapter II covers the design, simulation, fabrication, and testing of a video laryngoscope suitable for extremely low birth weight infants. It starts with the selection and
characterization of a commercial camera. Next, I discuss the inclusion of a remote LED light source and light pipe design. This section includes both optical and thermal simulations. Finally, I cover the actual fabrication and testing of the completed prototype.

- Chapter III covers several topics regarding adapting the basic solar concentrator design for different applications. First, the geometry is optimized for use in a polar-tracked mechanical system. Next, I examine output coupler designs to adapt the concentrator for solar thermal systems. I then look at integrated systems combining both of these.

- Chapter IV introduces the concept of reactive self-tracking as an alternative approach to tracking of a solar concentrator. Optical simulations define the requirements for such a material. A candidate materials system is proposed, and an example of the materials system is tested and characterized.

- Chapter V examines an alternate fabrication procedure. While the method of producing mirrored micro-prisms developed by Karp resulted in significant defects in the metal coating, a conformal cladding approach has the potential to enable more efficient mirrors while simplifying the fabrication process. Experimental results confirm the conformal approach, though the mirror reflectivity is low.

- Finally, in Chapter VI, I summarize the conclusions of the projects discussed in this thesis. I expand on the utility of non-imaging optical designs.

- In the three appendices, I show the Matlab code, the Zemax prescriptions, and the fabrication process that were used in these experiments.
Chapter II :

Neonatal Video
Laryngoscope

II.A  Camera Selection and Characterization

The first step in creating a prototype was to identify an imaging system. While a coherent fiber bundle was a possible solution, it would have been more difficult to integrate into varying prototypes as the design was changed. Instead, we identified a commercial camera small enough for use in this application, the Medigus IntroSpicio CCD camera, pictured in Figure II-1. This camera measures only 1.8mm in size, making it suitable for the small cross-section required. The lens of the camera has an f/# of 5.99 and an effective focal length of 0.712 mm. As this camera was intended for use in medical applications, it was also compatible with sterilization procedures, a necessity for an actual medical device. The image from the camera displays as an oval 300 pixels high and 350 pixels across.
While the medical researchers collaborating on this project qualitatively identified the camera as having sufficient resolution for the purpose, I also experimentally verified the specifications of the camera, and looked for aberrations in the images. By using the camera to take images of a US Air Force Resolution Target at varying distances as shown in Figure II-2, I could visually identify the minimum resolvable line pair, as shown in Figure II-3. Furthermore, by actually measuring the contrast of light and dark lines with the image processing software Image J, I was able to manually calculate the spatial frequency response of the imaging system, also shown in Figure II-3. For both of these measurements, vertical lines had better resolution than horizontal lines, most likely indicating that the pixel distribution was different in each dimension. Both measurements were also slightly below specifications, but still qualitatively sufficient for the purposes of this project. The working distance for the application is about 5 cm or less.
Experimenting with background lighting conditions with the camera defined the necessary illumination. At a 4 cm distance between the camera and the scene, the required
Illumination was around 600 lux. This corresponds to 130 lux at the sensor, using the equation

\[ E_{\text{image}} = \frac{\pi}{4} E_{\text{object}} \left( \frac{1}{(1 + m)F} \right)^2 \]  

[15].

### III.B Remote Illumination and Waveguide Design

As the inside of a throat has absolutely no ambient light whatsoever, appropriate illumination was crucial for the success of this project. While an LED mounted directly to the tip of the blade would provide sufficient illumination, it would also be likely to excessively heat up the device, posing a risk of thermal damage. I modeled this kind of configuration in Solidworks using a 1.6 W Luxeon III white LED with thermal resistance of 17 °C/W and a heat transfer coefficient to air of 15 W/(m²*K) [16]. The blade is made of solid aluminum. While an actual intubation takes less than sixty seconds, it is frequently necessary to need multiple attempts before successful intubation, particularly in patients with poor airway visibility, such as extremely low birth weight infants. In this case, the laryngoscope may be left on for some time. The device should be able to be left on for at least five minutes without reaching potentially damaging temperatures. In this model, as shown in Figure II-4, the tip of the laryngoscope reaches 27 ° above ambient temperature. Given that temperatures above 43.5 ° C can cause thermal damage [17], this design is unacceptable.
Another approach is to have a remote lightsource with a waveguide serving as the blade in of the laryngoscope. In this geometry, the LED is increased to 3.9 W in order to account for the light lost at the interfaces as well as along the curve of the laryngoscope. Thermal modeling of this geometry shows that the tip remains at ambient temperature, though the base of the LED reaches 65° above ambient. However, as the LED in the handle can have sufficient heat sink capability, only the tip temperature is of concern. The remote LED meets the thermal conditions for the device. An off-the-shelf Fraen lens is used to couple the light from the LED into the waveguide.

Using an acrylic waveguide as the blade of the laryngoscope maximizes the available area for the light to propagate. Because of the large angle of the waveguide, even with a very gentle curve, a fair amount of light decouples from the system. Furthermore, the tip of the blade must be sanded into a diffuse surface in order to illuminate the full field of view properly, which leads to some loss of efficiency. Zemax simulations of the LED, coupling lens, and waveguide design indicate an efficiency of 30%. The ray-trace can be seen in Figure II-5, along with the simulated light distribution at the tip of the laryngoscope and at distances of 2.5 cm and 5 cm.
from the tip. Both the thermal and optical simulations indicate that the remote LED source and waveguide blade are acceptable for the requirements of the device.

![Zemax optical simulation of laryngoscope blade light guide.](image)

Figure II-5: Zemax optical simulation of laryngoscope blade light guide. Illumination pattern are shown at tip and at 2.5 and 5 cm [8].

### III.C Blade Fabrication and Testing

The waveguide design needed to be fabricated in the lab, and combined with readily available products to create a testable prototype. The fabrication procedure was determined experimentally. I started with 0.25” thick sheets of Optix-brand acrylic by Plaskolite. These sheets were cut into 0.5” strips, in order to maintain the correct aspect ratio for the final product. I sanded the edges of the plastic strips with several increasing grits of sandpaper with water, then used a hydrogen-oxygen torch to flame-polish the edges to optical quality. The blanks were then baked in a 180° oven for eighteen minutes, heating the acrylic well past the glass phase transition point. Samples were carefully watched during this step to ensure no outgassing. The pliable heated acrylic was stretched into a tapered shape, with the thinnest cross-section meeting our geometric limits. I immediately stretched the tapered plastic over a cardboard mold with the correct curvature for the final blade. The cardboard was covered with felt in order to avoid mark-
off when the cooled plastic was removed from the mold. I then cut the excess plastic off of each end to the desired blade, milled a groove for the camera, and sanded the tip into a rounded, diffuse surface [8].

The completed blade is seen in Figure II-6. I modified an LED flashlight to serve as both the light source and the handle by removing the front window and reflector optics and making a rounded piece of Delrin plastic with a slit to hold the blade in place with the LED. Plastic tubing also protected the cord of the camera, which was held in the milled grooved by a small amount of UV-curable epoxy and textured tape, as seen in the inset of Figure II-6. This tape would also serve to keep the patient’s tongue in place. Bands of heat-shrink tubing helped keep the entire prototype together. The completed prototype is on the left in Figure II-6.

![Completed video laryngoscope prototype (left), LED illuminated laryngoscope blade (right), and close-up up laryngoscope tip with camera mounted (inset)](image)

This prototype was tested in a few ways. First, the distribution of illumination from the remote light source and waveguide was measured by placing a sheet of graph paper 1 cm from the tip while the device was on and taking an image of the scene. Using Image J software, I found the distribution of intensity along the graph paper. This distribution showed close adherence to the simulated distribution, as shown in Figure II-7.
The most important part of evaluating this prototype was qualitatively by the medical researchers. They used an anatomically-correct infant manikin of the type used to teach medical students to perform this procedure and attempted to intubate using the complete prototype, with LED source and camera both enabled. This test directed refinements of the design. In particular, the overall angle of the blade got larger, reaching 120°, in order to correctly accommodate exaggerated infant anatomy. This test can be seen in Figure II-8.

II.D Conclusions

The simulated intubation with an infant manikin identified the final design of the device. The Medigus IntroSpicco CCD camera had sufficient resolution for the medical researchers to be able to properly visualize the airway. A remote LED source in the handle of a commercial flashlight, coupled into the lab-fabricated acrylic waveguide with a Fraen lens, provided sufficient illumination for the scene to produce a clear image. Furthermore, the part of the device that would come in contact with a patient did not heat up while the device was in use. The actual measured
results of the illumination distribution and thermal increase were in good alignment with simulated results. Finally, the medical researchers were happy with the prototype as an example of a laryngoscope that could successfully be used in a medical setting to intubate extremely low birth weight infants.

The prototype device is currently with the Glidescope corporation in Vancouver, Canada, and they are evaluating it for commercial potential.

Figure II-8: Researcher Wade Rich intubating a manikin infant using laryngoscope prototype [8]

Chapter III:

Solar Concentrator

Optical Design

While the prototype designed by Karp was intended for 2-dimensional mechanical tracking [1], 1-dimensional polar tracking offers a promising design space. A thorough design study identifies the optimal configurations of the planar micro-optic concentrator for this framework. This technology is also adapted for CSP applications.

III.A Design Study

The prototype as designed requires 2-dimensional tracking, as is characteristic of solar concentrators [1]. However, the design can be adapted for 1-dimensional polar tracking [12]. This reduces the complexity of the mechanics. There are several variables that can be examined to adapt this system to this kind of tracking. First of all, I looked at the geometry of the lenslets: whether they were a linear array of cylindrical lenses or a hexagonal array of spherical lenses. The second variable was the beam path: whether the lenses were refractive as in the existing
design or reflective, where mirrored lenses are on the underside of the device. Last, I looked at the tracking: whether to use passive optical tracking with a long strip of injection facets or mechanical micro-tracking [2]. As there is no use to mechanical-micro-tracking with cylindrical lenslets, these three variables result in six variants to consider. These are enumerated in Table III-1. Variants 1, 3, and 5 are illustrated in Figure III-1 for a clearer depiction of the geometry.

Table III-1: Concentrator variants examined for use in 1-d polar tracked systems [12]

<table>
<thead>
<tr>
<th>Variant</th>
<th>Geometry</th>
<th>Lenslet</th>
<th>Micro-tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cylindrical</td>
<td>Refractive</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Hexagonal</td>
<td>Refractive</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Cylindrical</td>
<td>Reflective</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Hexagonal</td>
<td>Reflective</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Hexagonal</td>
<td>Refractive</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>Hexagonal</td>
<td>Reflective</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure III-1: Illustrations of (a) reflective cylindrical lenslets with passive tracking (Variant 3), (b) refractive cylindrical lenslets with passive tracking (Variant 1), and (c) hexagonal refractive lenslets with mechanical micro-tracking (Variant 5) [12].

A first pass design study compares all six variants for a general sense of how they measure up and to indicate which variants should be studied further. All concentrators are 250 mm long and use a 2.5 mm thick waveguide, resulting in 50X concentration. All glasses are BK7,
and all lenslet pitches are 2 mm. All glass surfaces are coated with an anti-reflective (AR) coating limiting reflection losses to 1% and all mirrored surface are enhanced aluminum with ~94% reflectance broad spectrum. The Zemax models used multiple configurations with each modeling the sun’s input on the 21st of each month in terms of angle to the concentrator and the relative intensity. With the lens curvature and thickness and the injection feature size as variables, the system was optimized to collect the most energy over all twelve configurations, representing the most energy collected annually. The results of the first pass design are shown in Figure III-2.

![Bar chart](image)

Figure III-2: Annual accepted energy for all six variants based on first-pass design [12]

Analysis of these results shows some general trends. Among the concentrators using passive tracking, the cylindrical lenses perform better than the hexagonal ones. Because of the hexagonal arrangement of the lenses, even at the same pitch, the strips of injection facets are more closely packed, leading to increased area covered by prisms and increased decoupling loss. Also, among the passively tracked systems, the reflective designs have better efficiency than the refractive ones. Although the reflective designs introduce several sources of loss: a second mirror reflection, a second pass through the air gap, and shadowing by the micro-prism, the focal spot is much smaller over a wide range of angles, leading to much less area covered by prisms and much less decoupling loss. However, micro-tracked systems have the best performance. Moving to
circles of injection features rather than strips reduces the facet area even further, leading to the best performance. The refractive design performs better here, as the additional loss sources from the reflective design are no longer cancelled out by the reduction in facet area. The downside of micro-tracking is the increased complexity of the system.

The designs selected for further consideration are the cylindrical refractive lenslets, the cylindrical reflective lenslets, and the refractive micro-tracked lenslets (Variants 1, 3, and 5). The Zemax prescription information for Variant 3, the cylindrical reflective design, is presented in Appendix B.A.

III.B Adaptation for Solar Thermal

All of the previous calculations have assumed edge-coupled PV cells as the target for the focused sunlight. However, there is another option. Concentrator systems are also used in solar thermal or concentrated solar power (CSP) applications. Sunlight is focused for use as heat rather than to be converted through the photovoltaic effect [5]. However, thermal receivers of the type used in these systems cannot be edge-mounted to the waveguide as they must be thermally isolated. Instead, the light in the waveguide must be decoupled from the glass and focused onto a thermally conductive micro-channel. Two examples of this type are shown in Figure III-3. The first uses a bk7 prism with a surface such that light emits normally to decouple the light. Two parabolic mirrors direct the light onto a rectangular micro-channel. The efficiency of this system is limited by the reflection loss at the prism (AR coating limits to 1%) and two mirror reflections (~6% each), reaching a total efficiency of 88%. Another approach eliminates one of the mirrors for higher efficiency. Instead, a much larger prism is angled such that the first surface is within the critical angle for the incoming light. The total internal reflection (TIR) is virtually lossless. Optical power is added to the surface where the light decouples. A parabolic mirror then focuses
the light onto the same rectangular micro-channel. With one fewer mirror, the efficiency is almost 93%. However this system does require much more glass, increasing the materials cost of the system.

One downside of these arrangements is the capacity to handle radiative losses by the thermal receiver. Much of this emitted heat would be lost from the system. Another approach is to focus the light into cup-shaped channels. This geometry would recapture most of the radiative losses. A design with an output prism and one parabolic mirror focuses light into the channel. The system of this type pictured in Figure III-6 has an efficiency of 91.6% entering the channel. Although this is lower than the TIR coupler featured previously, the radiation from the thermal channels will be recaptured within the receiver, lowering the overall losses. While this system has high efficiency, it is possible to increase the flux concentration by reducing the aperture size, even though that reduces the optical efficiency. The flux concentration is the geometric

Figure III-3: Output couplers to adapt the solar concentrator for CSP using (a) two parabolic mirrors and (b) a large prism with a TIR surface and one parabolic mirror [12].
concentration multiplied by the efficiency. In the case of this system, it would be the efficiency times the length of the concentrator divided by the aperture. Figure III-5 shows how changing the aperture affects this figure. However, reduced efficiency also means a reduction in the total energy. For now, I proceed with the design shown in Figure III-4.

Figure III-4: Using a cupped thermal receiver enables the recapture of radiation.
Figure III-5: Varying the size and location of the aperture will lower efficiency, but increase flux concentration.

### III.C Integrated Systems

The overall CSP system can be examined by combing the output couplers with the best designs from Section III-A. This is easily accomplished in Zemax Non-Sequential. Each of the three concentrator variants selected for further analysis are combined with each of the output couplers. Two examples are shown in Figure III-6. Figure III-6 (b) in particular shows the downside of the reflective design for CSP applications. Since the light must be decoupled directly from the waveguide, the output coupler must be placed on top of the concentrator. This shadows the concentrator significantly. Attaching the coupler from below would require cutting away part of the lenslet array at an awkward angle, increasing the complexity of fabrication though maintaining higher efficiency. Thus, as seen in the accepted energy values in Figure III-7, when adapted for CSP, the passive reflective geometry can have lower efficiency than the passive refractive geometry, even though the opposite is true for edge-mounted PV cell coupling.
Figure III-6: Integrated systems combining (a) the micro-tracked concentrator with the TIR output coupler and (b) the reflective passive concentrator with the two-mirror output coupler [12].

Figure III-7: Annual accepted energy for the various concentrator designs with each of the output couplers [12].

Chapter IV:

Reactive Tracking for Solar Concentration

In this section, the concept of reactive tracking for a planar micro-optic solar concentrator is introduced. Optical simulations define the requirements for such a system. A candidate materials system is introduced and tested.

IV.A Reactive Concept

As mentioned previously, the angular acceptance of solar concentrators is limited by étendue. However, one type of concentrator is not: the luminescent solar concentrator (LSC). This technology uses a material doped with fluorescent dye molecules. The dye absorbs the incoming sunlight, then reemits at a higher wavelength in all directions. Some of this light will be supported by total internal reflection in the waveguide [18][19][20]. Although the total efficiency is low, due to light emitted in non-coupling modes, energy lost in the wavelength shift, and emitted light reabsorbed, this system can accept sunlight from any angle, seemingly in violation of étendue.
Étendue holds true only for linear, passive systems. The nonlinear fluorescent dye allows the LSC to both concentrate light to a smaller physical aperture and have large angular acceptance.

An active, non-linear element can be added to the planar micro-optic concentrator. Ideally, we need a material that will respond to the sunlight in the system to maintain alignment. While we considered responses such as phase transition from liquid to gas and a diffusivity increase in response to a thermal differential, we settled on a change in index of refraction. As shown in Figure IV-1, a material with a low index of refraction acts as a cladding between the waveguide and a continuous sheet of reflective micro-prisms. This material must increase in response to the sunlight focused by the lenslet array by increasing in index of refraction. This enables the sunlight to properly couple into the waveguide, but as the rest of the material remains low index, the coupled light will still TIR at the interface between the waveguide and the cladding. This response must happen quickly and must be easily reversed in order to track the sun over the course of the day [11]. This effect is illustrated in Figure IV-1.

![Figure IV-1](image-url)

Figure IV-1: Reactive cladding increases index of refraction in response to focused sunlight (a). This response must track with the sun through the day (b) [11].
IV.B Optical Simulations

In order to properly quantify the required magnitude of response in change of index of refraction, it was necessary to model the entire reactive design in Zemax. The reactive cladding is modeled as a sheet of constant index with cylinders of high index material placed at the focus of each lenslet. Multiple configurations each with the sun at a different angle allow the system to be modified for each input.

![Figure IV-2: Injection facets can only couple light over a limited range of angles [11].](image)

In addition to defining the reactive cladding requirements, at this stage, we also must identify an optical system that will work over a wide range of angles. Ideally, the system would work within a static panel, requiring +/- 45° acceptance in each dimension. The coupling features themselves provide some limitation. While light tilted along the length of the prism still easily
couples into the waveguide, light tilted along the direction of corrugation will reach an angle that cannot couple, as shown in Figure IV-2.

Figure IV-3: (a) Singlet lens with inset showing high index coupling region and (b) doublet lenses with lower aberration and inset showing smaller high index region.

The lenslets must focus light over a wide angular range down to a small spot. The first lenslet design is similar to the one used in the original planar micro-optic design: an acrylic singlet with an F2 glass waveguide, as shown in Figure IV-4. After optimizing in Zemax Sequential over +/- 30°, the singlet is added to the Non-Sequential simulation. The Sequential prescription information is in Appendix B.B.
Figure IV-4: Zemax Sequential model of singlet lens, with spot sizes and encircled energy as a function of radius form centroid shown

Another option is to use an array of doublets: a stack of acrylic and polycarbonate lenses with the same waveguide as the singlet, as shown in Figure IV-5. This design lowers chromatic aberration and coma, minimizing the size of the high index region needed and thus minimizing decoupling loss. Zemax Sequential prescription information is in Appendix B.C. Both lenslet designs integrated into non-sequential systems are shown in Figure IV-3. All glass surfaces are assumed to be coated with an anti-reflective coating limiting reflective losses to 0.5%. All mirror coatings are assumed to be ideal silver with a reflectance of 98%. In reality, cost is the dominant driver for this kind of technology and less-expensive but less-effective coatings would likely be used.
The on-axis performance of the system varies with geometric concentration. The doublet has much better optical efficiency at higher concentrations, as shown in Figure IV-6(a). The change in index of refraction required for this performance is around 0.3, as shown in Figure IV-6(b).
However, the critical metric is the performance of the system over a large angular range. With the size and position of the high index region optimized for each configuration (discrete angular input), the overall optical efficiency can be measured as in Figure IV-7, with the Matlab code used to generate these figures given in Appendices A.A and A.B. These systems could be used either in a static panel or a polar-tracked system. The total annual accepted energy for the singlet system in San Diego is found to be 25% for static panels and 60% in a polar-tracked system. For the doublet, these figures increase to 28% and 83%, respectively.
Figure IV-7: Optical efficiency over the total range of possible angular input for a) the prototype, with inset showing a close-up, b) the reactive singlet, and c) the reactive doublet [11].

IV.C Material System

The simulated performance of the reactive system is strong, but requires a large response of 0.3 increase in index of refraction. This response must also be fast, reversible, and occur in response to focused sunlight. One way to accomplish this response is through localized concentration of high-index particles in a low-index suspension. An elegant solution is to use optical trapping from the focused sunlight to trap particles [21]. This would enable the material response without adding additional elements to the overall system. This concept is illustrated in Figure IV-8. This general mechanism is used in spatial soliton generation [22]. The trapping force from an optical intensity gradient [21], where $a$ is the particle radius, $m$ is the ratio of index of
refraction between the particles and the medium, \( c \) is the speed of light, and \( I \) is the optical intensity is

\[
F_{\text{trap}} = \frac{2\pi a^3}{c} \left( \frac{m^2 - 1}{m^2 + 2} \right) \nabla \cdot I.
\]

Figure IV-8: Reactive cladding using direct optical trapping [11]

The principal force opposing optical trapping is diffusion. The particle flux \( j \) as a function of the concentration \( C \), the diffusion constant \( D \), and the mobility \( \nu \), which is equal to \( D/kT \) where \( k \) is the Boltzmann constant and \( T \) is the temperature in Kelvin, is given by [23]

\[
\vec{j} = -D \nabla C + \nu \vec{F} C.
\]

Combining this equation with this previous one and solving for the steady-state solution results in the concentration as a function of intensity [23]:

\[
C = C_0 \exp \left( \frac{I}{I_0} \right), \quad I_0 = \frac{ckT}{2\pi a^3} \frac{m^2 + 2}{m^2 - 1}.
\]

The average index of refraction can be found from the concentration by using the Bruggeman model, the preferred model for high concentration by volume. For the particle concentration \( C \), the permittivity of the particle \( \varepsilon_1 \), the permittivity of the medium \( \varepsilon_2 \), and the overall permittivity of the suspension \( \varepsilon \) [24],

\[
C \frac{\varepsilon_2 - \varepsilon}{\varepsilon_2 + 2\varepsilon} + (1-C) \frac{\varepsilon_1 - \varepsilon}{\varepsilon_1 + 2\varepsilon} = 0
\]

Unfortunately, the mathematics indicates that this approach will not achieve the required response, as shown in Figure IV-9, with code shown in Appendix A.C. Because the optical
trapping force scales with the particle’s size, in order to reach 0.3 change in index, the particle must have a radius of well over 200 nm. This is on the order of the size of the wavelength of visible light, causing significant scattering, and too large to stay in suspension. Another approach is needed.

Another potential mechanism is optically-induced dielectrophoresis (DEP). DEP is the motion of uncharged particles in a non-uniform electric field [25][26]. Ming Wu’s group at UC Berkeley demonstrated the concentration of particles using this effect in response to a laser beam. Their results showed an equivalent response to direct optical trapping with 100,000 times less optical density [27]. This increased magnitude in force makes this phenomenon ideal for the purpose of this project. The actual trapping force of DEP is given by

\[ F_{DEP} = 2\pi\varepsilon_m a^3 K\nabla E_0^2, \quad K = \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + \varepsilon_m}. \]

It is a common misconception the DEP can only be used with AC fields. While AC-DEP has the advantages of phased arrays and minimal damage to biological cells, DEP does work with DC fields, and there is research into this area [27].
Optically-induced DEP is more difficult to model than direct optical trapping since there are inherently more forces at play. In addition to the DEP trapping force, there is also the electrothermal force and electro-osmosis [29][30]. Electrothermal motion is due to the localized heating in the area of non-uniformity. This thermal gradient induces a current flow with the colloid. This can actually aid in particle concentration, since the direction of flow brings particles in toward the heated area. This kind of system has an electrically-charged surface open to the colloid. The presence of this charged surface will collect ions of opposite from the neutral fluid and induce an additional electric field. The interplay of these forces is extremely dependent on the exact system.

Possible mechanisms for using focused sunlight to induce the non-uniform electric field are shown in Figure IV-10. One option is to mimic the geometry of Wu’s work. A photoconductor with an applied bias will respond to the sunlight with a decrease in resistance. This will cause the voltage to drop over the colloidal region rather than the photoconductor, and induce a local non-uniformity. This configuration is likely to work, but does require the use of an external power source. Another option is to implement a very thin layer of an organic photovoltaic [31]. This organic photovoltaic can be tuned such that it only absorbs a small region of the solar spectrum with allowing the vast majority of light to pass through. Through the photovoltaic effect, the absorbed light will induce a voltage and thus a local non-uniformity in the electric field. For both these options, there is no current needed and, as the gap is very small, even a low voltage will create a large electric field [11].
IV. D  Materials Characterization

In order to demonstrate the plausibility of optically-induced DEP change in index of refraction for use in a reactive solar concentrator, the first step is to demonstrate the mechanism working. Initial tests leave out the optically-induced aspect and simply aim to demonstrate DEP-induced change in index of refraction.
The experimental setup went through several iterations before finding the optimal system. The first-pass experiment just to see an effect used gold pins glued into a washer, as seen in Error! Reference source not found.(a). The center was filled with aqueous polystyrene particles and a signal was applied across the pins. The sample was placed in one branch of a Mach-Zehnder interferometer in order to observe the fringes shift with a change in index of refraction as shown in Figure IV-12. As an initial proof-of-concept, this setup showed a change in index, but not in response to the desired geometry.

Figure IV-12: I used a Mach-Zehnder interferometer to measure the change in index of the material. Shown here are a diagram of the optical system (left) and the actual setup (right). (Image reversed to match diagram)
The next iteration of the experiment used a pin-plate geometry, as shown in Figure IV-13. Patterned gold electrodes with pointed, circular, and squared tips at varying distances from a common plate carry the signal over the colloid sample. The change in index could clearly be seen with the shift in fringes, but could not be exactly calculated. Since the concentration isn’t necessarily taking place throughout the entire depth of material, it’s not possible to know the exact thickness experiencing the change in index.

Figure IV-13: A gold pin-plate geometry demonstrated dielectrophoresis, but the interferograms could not be used to calculate the change in index of refraction, as the electric field was orthogonal to the optical axis.

The final iteration to generate a DEP-induced change in index of refraction is shown in Figure IV-14. I used lithography to create patterned indium tin oxide (ITO) electrodes on a glass microscope slide. Additional glass slides were coated entirely with ITO. Since ITO is a transparent conducting oxide, an applied bias across the two ITO coated slides produces a non-uniformity in the electric field similar to what would result from the designs in Figure IV-10. With a colloidal material in this gap, DEP will attract particles to the area of highest magnitude electric field.
As with the first two iterations, this entire setup was placed within one branch of a modified Mach-Zehnder interferometer. This is the advantage of using transparent electrodes: the region of interest can clearly be imaged along the same axis as the direction of the electric field. Observing the shift of fringes in the interferogram with the application of the electric field enables the calculation of the change in index of refraction. We used 60 nm polystyrene particles suspended in water as the test medium. Although the dynamic range is low, as the difference in index between the particle and fluid is less than 0.3, this material is stable and readily available. Initial tests used a DC voltage, as the ideal system would use DC, but issues with the space-charge effect made the effect unrepeatable. Also, excessive DC voltage could cause electrolysis in the sample material. For the sake of replicable data, the applied signal was changed to a 60 Hz square wave with varying voltage.
Figure IV-15: Interferograms before (a) and after (b) a 2V 60 Hz square wave signal applied for 60 seconds, with a total shift of 1.5 fringes [11].

Figure IV-15 shows an example shift. A 2 V signal is applied for 60 seconds, and then removed. Within about 45 seconds, the peak shift of 1.5 fringes is reached. When the signal is removed, the fringes return to flat within a few minutes. The overall results are shown in Figure IV-16. The average response seen at 2 V corresponded to a 0.033 change in index of refraction. While this is an order of magnitude lower than the required response to make the simulated system work, the aqueous polystyrene was never going to show a large change in index. A more relevant metric is that the particle concentration by volume increased from 10% to 23%. Given a high-index material such as titanium dioxide [32] and a low-index perfluorocompound suspension, the same increase in volume would result in a change in index of 0.157. Starting from a higher initial volume or achieving a slightly higher relative increase can easily get this figure to the necessary 0.3.
Figure IV-16: Experimental results: measured fringe shifts and calculated change in index of refraction for a varying voltage 60 Hz square wave signal applied for 60 seconds [11].

The text in Chapter 4 is in part a reprint of material appearing in K.A. Baker, J.H. Karp, E.J. Tremblay, J.M. Hallas, and J.E. Ford, “Reactive self-tracking solar concentrators: concept, design, and initial materials characterization,” Appl. Opt. 51, 1086-1094 (2012). The dissertation author was the primary researcher and author on this paper.
Chapter V:

Conformal Cladding and Fabrication

V.A Conformal Cladding

Karp’s fabrication process worked well for creating a laboratory prototype [1]. The most difficult part of this process was to create the mirrored micro-prisms. The experimentally determined procedure is as follows. First, SU-8 photoresist is spun onto a 3 inch by 2 inch microscope slide and pre-baked. Next, a PDMS mold of the prism shape is pressed into the photoresist, weighted down, and baked again. The UV exposure is performed with a solar simulator, including the angular divergence of the sun, which is exposed onto the molded photoresist through the lenslets, ensuring that the size of the prism feature is correct. In Karp’s prototype, he then sputtered aluminum over the entire surface, followed by development of the uncured photoresist. This resulted in circular regions of prisms coated with aluminum, with the rest of the slide left blank. However, this part of the process had significant downsides. In order to develop the photoresist beneath the layer of sputtered aluminum, the slide had to be both heated and sonicated until the aluminum started to develop small cracks. These cracks could appear in
the aluminum intended to be kept. Furthermore, the tearing of the aluminum from the parts to be discarded from the coating of the permanent prisms also resulted in defects. These can be seen in Figure V-1. Furthermore, this process does not scale well to mass fabrication for commercial production.

![Defects](image)

Figure V-1: The existing fabrication procedure resulted in significant defects in the aluminum coating.

Developing the SU-8 and then coating the entire surface with aluminum would result in fewer defects, but each reflection off the waveguide surface would result in loss associated with the reflectance of the material. We want to maintain the total internal reflection at that boundary which is virtually lossless. Instead, I examined a different approach, using a conformal cladding. This concept is illustrated in Figure V-2. The SU-8 is deposited, molded, and exposed as in Karp’s previous work. However, the photoresist is lifted off without the aluminum there, leaving circular regions of molded prisms. Next, a cladding is deposited over the entire surface, with a low enough index of refraction to maintain TIR for light coupled into the waveguide. The entire cladding is then coated with an aluminum layer. The light focused onto the prisms will propagate through the cladding to the mirror, and correctly deflect into guided modes. This method simplifies the entire fabrication procedure and avoids the problems that led to defects in the original process.
V.B Sol Gel Derived Cladding

One obstacle for this concept is identifying an acceptable material. This material must have a very low index of refraction in order to be an effective cladding for inexpensive glasses like BK-7 (n=1.52). Sol gel derived aerogels present an appealing option. Sol gel is a deposition process that involves starting from a dissolved material, or sol, and depositing this liquid coating through spin-coating, dip-coating, or spraying. This liquid will gel, and as the solvents dry, leave behind a solid coating. If the gel is dried under supercritical conditions, then the structure of the solid will maintain the cavities from the solvent in the gel, resulting in an aerogel that is mostly air by volume [34]. This material has an extremely low index of refraction, based on the exact volume of air, also known as the porosity p. The relationship can be approximated linearly, with \( n = 1.458 - .458p \) [34]. Researchers in the last 15 years have been investigating alternate approaches to sol gel processing that result in porous aerogels without requiring supercritical drying. These include surface derivatization that causes the porous structure to spring back after...
drying [35] and using a non-volatile cosolvent ethylene glycol to control the porosity [36]. These techniques have been used to create aerogels with a refractive index as low as 1.1, excellent for use as an optical cladding [37].

The required thickness of the cladding depends on the exact index of refraction of the aerogel. If the layer is too thin, the metallic coating will frustrate total internal reflection. The necessary thickness and refractive index of the cladding layer can be found through use of characteristic matrices representing the reflectance from a thin film [38]. The code for this is found in Appendix A.D. The results are shown in Figure V-3. At a thickness of 1 um, with a beam propagating at 53˚through a BK-7 substrate, the refractive index should ideally be less than 1.15 for low loss. A silica aerogel at 70% porosity has an index of 1.14, and is a low enough porosity that metal can adhere to it [36].

![Figure V-3: Reflectance at a BK-7 and cladding interface as a function of cladding index and thickness.](image)

Existing research from Rensselaer Polytechnic Institute has developed a recipe for a silica aerogel with these properties [39]. The thickness and texture are shown in Figure V-4. A material with these characteristics should meet all requirements needed for the conformal cladding.
Silica aerogel deposition followed the procedure laid out by Nitta et al [39]. First, 11.3 mL ethanol, 11.3 mL triethyl orthosilicate, 7.9mL ethylene glycol, and 2.0 mL 1M hydrochloric acid were added to a volumetric flask, in that order. The mixture was reacted on a stirring hot plate at 60° C for 90 minutes. 10 mL of the solution was mixed with 1 mL of .05 M ammonium hydroxide. 2mL of this mixture was filtered through a .2um filter attached to a syringe and deposited on a 3 by 2 inch glass microscope slide in a spin coater. Spinning conditions were 200 rpm, acceleration 7, and 12 seconds of operation. The slide was then left still for 45 minutes to allow initial gelling. The coated slide was aged in a solution of 20% .05 M ammonium hydroxide and 80% ethanol for 18 hours. The slide was then rinsed in ethanol, and placed in a solution of 98% hexane and 2% trimethylchlorosilane for one hour. (This step provides the surface derivatization to enable high porosity.) The slide was rinsed in hexane and ethanol, and then baked in an oven at 60° ramping up to 80°C.

The results of this process did not successfully replicate the results produced by Nitta et al, as shown by the SEM images in Figure V-5. This is most likely due to differences in
temperature, pressure, and air turbulence conditions in our fumehood. The sol gel process, particularly when attempting high porosity aerogels without using supercritical drying, is extremely sensitive to environmental variables. My attempts were highly uneven and did not effectively function as a cladding.

![SEM images of aerogel deposition](image)

Figure V-5: Silica aerogel deposition at UCSD did not successfully replicate RPI results, likely due to differences in lab conditions.

Our next step was to seek out collaboration without material scientists on the silica aerogel deposition. Paul Clem and colleagues at Sandia National Lab are experts in the area of aerogel fabrication \[40\][41]. They had the capabilities to deposit a layer of aerogel with the desired characteristics.

In addition to sending plain microscope slides to Sandia to be coated with aerogel, I also sent slides with the patterned prism features in order to determine if the aerogel could conform to the prism shapes and to measure the overall performance of the concentrator. I fabricated the prisms by adapting the process laid out by Karp. Details are listed in Appendix C. The final slides with both 50 um and 5 um pitch prisms are shown in Figure V-6.
V.D Results

Clem and colleagues at Sandia first dip-coated the patterned slides to deposit a porous silica aerogel around 1 um thick. Next, they sputtered 80 nm aluminum over the aerogel cladding. These slides were then returned to me at UCSD for testing. As shown in Figure V-7, these coatings conformed to the shape of the injection features, indicating that aerogel meets the conformal requirement of this cladding.

The next test was to measure the reflectance of the material over a range of angular inputs. The experimental setup for this measurement is shown in Figure V-8. This test used plain microscope slides with the aerogel coating and differing metallic layers. The slides were index-matched onto a right-angle prism, and laser light over a wide range of angles was reflected off the interior mirror surface. I set up an iris to block extraneous reflections from additional surfaces within the setup and measured the reflected power with a Newport power detector. The results are shown in Figure V-9 and Figure V-11.
Figure V-7: Aerogel and aluminum forma conformal cladding over a 50 um pitch injection feature (left) and a 5 um pitch injection feature (right)

Figure V-8: The coated slides are index-matched onto a prism. Incoming laser light is reflected of the interior mirror surface at a range of incoming angles, and the reflected power is measured. A diagram is shown on the left, and the experiment is shown on the right.
The aerogel was measured uncoated, with 40, 80 and 200 nm aluminum coatings, and with an 80 nm silver coating. For reference, slides coated with 80 nm of silver and aluminum were also tested, as was the prism without any slide affixed. The slide with aerogel and no mirror shows quite similar results to the bare prism. This is as expected. The aerogel coated by 80 nm aluminum by Sandia did not show optimal results. The reflected power shows a marked decrease with decreasing angle, indicating that TIR has not been achieved. Further, the reflected power at low angles is quite low, indicating that the reflectivity of the mirror itself is low.

![Graph](image)

**Figure V.9:** Reflected power as a function of input angle for aluminum coatings

The reflectivity of the mirror could potentially be improved with a different thickness of mirror or a more reflective material. However, the aerogel must be mechanically sound enough to withstand this metallization. The images in Figure V-10 show both the top surface of the mirror and a cross-sectional view for aerogel with no metal coating and with 40, 80, and 200 nm of...
aluminum. The metal closely adheres to the pore size in the thinner coatings, but the 200 nm coating covers the pores more thoroughly. All four cross-sections show approximately the same thickness, indicating that the aerogel is reasonably robust and can withstand a thicker mirror. The reflectance from these samples was also shown in Figure V-9. The 200 nm coating in particular does show an improvement in reflectivity at smaller angles, though it is still low.

![SEM images of aerogel with different metal coatings](image)

Figure V-10: SEM images show the top surface (top row) and cross-sectional view (bottom row) of unmirrored aerogel and aerogel coated with 40, 80, and 200 nm of aluminum.

Another approach is to change to a silver coating. Silver has higher reflectivity across the visible spectrum than aluminum does, though it is more costly. Results from silver-coated aerogel are shown in Figure V-11. The samples with silver coating appear to support TIR at large angles, with higher reflectivity than the silver control slide. The smaller angle reflectivity is higher than that of aluminum, though not high enough to be effective in the concentrator. The SEM image in Figure V-12 gives a sense of what’s going on. The aerogel has a very small pore size, much smaller than the wavelength of solar light. However, the silver has deposited in an uneven way, creating larger scattering areas. Given that TIR is supported at higher angles and the cladding
adequately conforms to the shape of the prisms, if the metallization problem can be solved, this approach could still be successful.

Figure V-11: Reflected power as a function of angle for silver coatings.

Figure V-12: Cross section of 130 nm silver coated aerogel
Although the reflectivity of the 80 nm aluminum was low, the coated patterned slides could still be tested as concentrators. Both the 50 um prism slide and the 5 um prism slide were used in the experimental setup designed by Karp. The slide is glued onto a 5-axis stage, allowing precision alignment. An Oriel light source acts as a solar simulator, and the light passes through a lens to give it the correct angular divergence. A photodetector is used to measure the efficiency. The 50 um version had an average efficiency of 4.8%. However, the epoxied edges reduced the intensity output at the edges of the exit facet. If the intensity at the center of the slide were uniform over the whole surface, the efficiency would be 5.8%. This general performance corresponds to a flux concentration of around 2. While the performance is low, it does still concentrate light. The 50 um prism version demonstrated an efficiency of 1.1%, which indicates a flux concentration of less than one. This prototype did not effectively function as a concentrator.

Figure V-13: The patterned concentrators coated with aerogel and aluminum were measured in Karp’s testbed.
Chapters 5 is, in part, currently being prepared for submission for publication of the material in K.A. Baker, J.M. Hallas, J.H. Karp, P. Clem, and J.E. Ford, “Alternate approaches to planar micro-optic solar concentration” (*in preparation*). The dissertation author was the primary researcher and author on this paper.
Chapter VI:

Conclusion

This thesis presents work on two different applications of non-imaging optics to small-scale systems. The first involves illumination. A video laryngoscope suitable for extremely low birth weight infants will vastly improve intubation of premature infants, but proper illumination is crucial to enable an adequate image. The second task involves concentration. A planar micro-optic solar concentrator can be used for either CPV or CSP use, but careful thought must be given to tracking.

In the illumination project, we first identified a commercial camera small enough for use in the laryngoscope tip. Next, I characterized the camera and identified the illumination requirements. I designed an acrylic blade to act both as a waveguide for a remote light source and a mechanical structure for the laryngoscope. I then fabricated the waveguide and built the complete prototype. This prototype was tested by the medical researchers on infant manikin, and the illumination was sufficient to allow the camera to image the larynx properly. This project showed the importance of non-imaging illumination systems even in the context of an imaging medical device.

The non-imaging concentrator systems were approached in several different ways. First of all, I took the basic planar micro-optic solar concentrator design developed by Karp and
reoptimized it for 1-dimensional polar mechanical tracking. This included looking at various geometries for the lenslets, as well as examining both passive optical tracking and mechanical micro-tracking of the type investigated by Hallas. The most efficient design is the refractive micro-tracked configuration, although the micro-tracking does add complexity to the system. The most efficient passive design uses cylindrical reflective lenslets.

Solar concentration isn’t limited to photovoltaic systems. Concentrators can also be implemented in solar thermal applications. However, for this waveguide-based system to work in CSP, the light must be decoupled from the waveguide and redirected to a thermally-conductive micro-channel. I created several designs for this purpose, and analyzed them with the results of the polar tracking design study. The output coupler with one TIR surface is the most efficient coupler, and the micro-tracked refractive design remains the optimal concentrator. However, the refractive passive design outperforms the reflective passive design for this application, as the output couplers cause significant shadowing for the reflective geometry.

I also explored a completely different approach to concentrator tracking. Adding a nonlinear cladding material to the basic solar concentrator design enables a concentrator that can self-track without moving parts beyond the limits of étendue. I simulated the optical system in Zemax to define the optical requirements of the system. I found a candidate phenomenon to accomplish the needed 0.3 change in index, and then tested the system experimentally to demonstrate DEP-induced change in index. Although the magnitude measured was much lower than 0.3, the experiment still demonstrates the plausibility of the system, and new materials system can reach the needed response.

Additionally, I examined an alternative to the fabrication procedure developed by Karp. The exposure-metallization-liftoff part of the process resulted in significant defects in the mirror coating. Instead, I used a conformal cladding over the SU-8 prisms that enabled the entire surface to be metallized. Collaborators at Sandia National Labs created a silica aerogel to serve as this
low-index cladding. The conformal nature of the material worked well and it provided an effective low index. However, the metallization resulted in a very low reflectivity mirror. Further process improvements could make this system feasible.

These systems show the versatility of non-imaging concentrator systems, even when looking at a common application of solar power. It’s possible to adapt this concentrator in many ways. Altogether, non-imaging systems, whether for illumination or concentration, are extremely adaptable and useful in a variety of applications.
Appendix A:

Source Code

A.A AnglevConcPlot.m

% clear
angledata = load('AngleEffDataPrototypeFinal.txt');

[a b] = size(angledata);

Eff_1 = angledata;
Eff_2 = flipdim(Eff_1, 2);
Eff_2 = Eff_2(:, 1:(b-1));
Eff_3 = flipdim(flipdim(Eff_1, 1), 2);
Eff_3 = Eff_3(1:(a-1), :);
Eff_4 = flipdim(Eff_1, 1);
Eff_4 = Eff_4(1:(a-1), 2:b);
Eff = [Eff_3 Eff_4; Eff_2 Eff_1];

phimax = 40;
thetamax = 30;

phi = -phimax:10/3:phimax;
theta = -thetamax:10/3:thetamax;

% figure(1), surf(phi,theta,Eff)
% figure(13), imagesc(phi,theta,Eff,[0 .8]); colormap jet; colorbar;

phi3 = -phimax:1:phimax;
theta3 = -thetamax:1:thetamax;

phi2 = 0:10/3:phimax;
theta2 = 0:10/3:thetamax;

phi4 = 0:1; phimax;
theta4 = 0:1:thetamax;

Eff_interp = zeros(length(phi3),length(theta3));

% figure(2), surf(phi2, theta2, Eff_1)
%   shading interp

for i = 1:length(phi3)
  for j = 1:length(theta3)
    Eff_interp(i,j) = interp2(phi,theta,Eff,phi3(i),theta3(j));
  end
end

for i = 1:length(phi4)
  for j = 1:length(theta4)
    Eff_intensity(i,j) = interp2(phi2,theta2,Eff_1,phi4(i),theta4(j));
  end
end

Eff_intensity = padarray(Eff_intensity, [90-phimax,90-thetamax], 'post');

Eff_interppad = padarray(Eff_interp, [90-phimax, 90-thetamax]);

% figure(14), imagesc(theta3,phi3,Eff_interp, [0 .8]); colormap jet; colorbar;

% figure(2), surf(-90:90,-90:90,Eff_interppad)
%   shading interp

Eff_display = imrotate(Eff_interppad, 90);
figure(18),imagesc(-90:90,-90:90,Eff_display, [0 .8]); colormap jet; colorbar;

[p q] = size(Eff_interppad);

IntensityIntegral = 0;
for m = 1:p
  for n = 1:q
    IntensityIntegral = IntensityIntegral + Eff_interppad(m,n);
  end
end
% clear all

%% Location and Panel Properties

% San Diego
Lat = 32.7;
Long = -117.2;
Meridian = -120;
A = 0;

% Panel
Tilt = Lat;
b0 = Tilt - Lat;

chart=zeros(91,91);
chart2=zeros(91,91);
T=zeros(181,181);
SunEnergy = 0;
CaptEnergy = 0;
SunEnergyUniform = 0;
CaptEnergyUniform = 0;

%% Equation of time - correction to solar noon

for n=1:1:365;
    % for n = [80 173 356]
    mark =0;
    for time=12:1/60:20;
        B=360*(n-81)/364;
        E=9.87*sind(2*B)-7.53*cosd(B)-1.5*sind(B);  %Eq of time (min)
        t=time*60+4*(Meridian-Long)+E;  %solar time (min)
        hour=(t/60-12)/(4/60);  %hour angle

        % Declination angle - Tip of the earth wrt sun
        decline=-sind(23.45)*cosd(360*(n+10)/365.25);
        declinep=-sind(23.45)*cosd(360*(90)/365.25);
        decline=asind(decline);  %declination angle
        declinep=asind(declinep);

        % Solar Altitude
        altitude=cosd(Lat).*cosd(decline).*cosd(hour)+sind(Lat).*sind(decline);
        altitude=asind(altitude);
northanglesun = (-cosd(hour).*tand(Lat) + 
tand(decline))/(cosd(hour)+tand(decline).*tand(Tilt));
northanglesun = atand(northanglesun);
northangletrack = -tand(Tilt);
northangletrack = atand(northangletrack);

%% Solar Azimuth
azimuth=cosd(decline).*sind(hour)./cosd(altitude);
if azimuth>0.99999
  mark=1;
end
if mark==1
  azimuth=asind(azimuth);
  azimuth=90+(90-azimuth);
elseif mark==0
  azimuth=asind(azimuth);
end

%% Angle Between Sun and surface normal
angleEW = (cosd(decline)*cosd(hour)*cosd(Lat) + 
sind(decline)*sind(Lat))/sqrt(1-(sind(decline)*cosd(Lat)-
cosd(decline)*cosd(hour)*sind(Lat))^2);
angleEW = acosd(angleEW);
angleNS = (cosd(decline)*cosd(hour)*cosd(b0)-
sind(decline)*sind(b0))/sqrt(1-(cosd(decline)*sind(hour))^2);
angleNS = acosd(angleNS);
% trackNS = (cosd(declinep)*cosd(hour)*cosd(b0)-
sind(declinep)*sind(b0))/sqrt(1-(cosd(declinep)*sind(hour))^2);
% trackNS = acosd(trackNS);
if northanglesun < northangletrack
  angleNS = -angleNS;
end

%% Solar Irradiation
Io=1372.7; %Solar Const W/m2
%Clear Day Model (Rabl, p.63)
r0=.97; r1=.99; rk=1.02;
a0=r0*(0.4237-0.00821*(6-A)^2);
a1=r1*(0.5055+0.00595*(6.5-A)^2);
k=rk*(0.2711+0.01858*(2.5-A)^2);
Ieff=Io*(1+0.033*cosd(360*n/365.25)); %Solar Power Variation
if altitude>0
  I=Ieff*(a0+a1*exp(-k*cosd(90-altitude)));
else
  I=Ieff*(a0+a1*exp(-k*cosd(90+altitude)));
end
theta = sqrt(angleNS^2+angleEW^2);
I = I * cosd(theta);

%% Graphing
angleEW=round(angleEW*1);
angleNS=round((angleNS*1);
SunEnergy = SunEnergy + I*60/1000;
SunEnergyUniform = SunEnergyUniform + 1*60/1000;
if angleEW>0 && angleNS>0 && angleEW<90 && angleNS<90
   chart(angleNS,angleEW)=I;
   CaptEnergy = CaptEnergy +
   I*60*Eff_intensity(angleEW,angleNS)/1000;
   CaptEnergyUniform = CaptEnergyUniform +
   l*60*Eff_intensity(angleEW,angleNS)/1000;
   if mod(time,1)==0
      T(angleNS,angleEW)=NaN;
   end
%                 imagesc([0:180],[0:180],flipud(chart),[0 1000]);
   colorbar; pause(.01);
%                 imagesc([0:180],[0:180],chart,[0 1000]); colorbar;
   pause(.01);
   end
   if angleEW>0 && angleNS<=0 && angleEW<90 && angleNS>-90
      chart2(-angleNS+1,angleEW)=I;
%         imagesc([0:180],[0:180],flipud(chart2),[0 1000]); colorbar;
       pause(.001);
      CaptEnergy = CaptEnergy + I*60*Eff_intensity(angleEW,-
      angleNS+1)/1000;
      CaptEnergyUniform = CaptEnergyUniform +
      l*60*Eff_intensity(angleEW,-angleNS+1)/1000;
   end
end
end
% close all;

alt=[-90:90];
azi=[-90:90];
chart2=flipud(chart);
chart=padarray(chart,[0 size(chart,2)],'symmetric','pre');
chart2=padarray(chart2,[0 size(chart2,2)],'symmetric','pre');
chart_fin = [chart2;chart];
% imagesc(azi,alt,chart_fin,[0 850]); colormap gray; colorbar; grid on;
T=flipud(T);
T=padarray(T,[0 size(T,2)],'symmetric','pre');
% figure;
%    imagesc(azi,alt,chart+T,[0 850]); colormap jet; colorbar; grid on;

% surf(azi,alt,chart_fin
%This program will analyze the response of a colloid to light intensity.

clear

%Physical Constants
g = 9.8;
c = 3e8;
k = 1.3806504e-23;
T = 300;

%Particle Data

%Titanium Dioxide
% a = 150e-9; % particle radius in meters
dp = 4.098e3; % density in kg/m^3
np = 2.4;
ep = np^2;

%Polystyrene
% dp = 1.05e3;
% np = 1.59;
% ep = np^2;

% Medium Data

% Water
% dm = 997.1;
% nm = 1.331;
% em = nm^2;

% Ethanol
% dm = 789;
% nm = 1.36;
% em = nm^2;

% FC - 70 (Perfluoro-tri-n-pentalymine)
dm = 1.93e3; % density in kg/m^3
% kv = .14; % kinematic viscosity in Stokes
% dv = kv*.00001*dm; % dynamic viscosity in Pa*s
% Am = 4.4e-23*6*pi; % Hamaker Constant in Joules
% eps = 1.98; %dielectric constant
nm = 1.303;
em = nm^2;

a = 0:1e-9:320e-9;

m = np/nm;
\[ W = 0.44; \] % Concentration by Weight
\[ C_0 = \frac{1}{1+(1-W)/W*dp/dm}; \] % Calculates Background Concentration by Volume

\[ I_0 = c*k*T*(m^2+2)/(2*pi*a^3*(m^2-1)); \] % Calculates Critical Intensity

\[ I = 0:1e7:1.4*I_0; \] % Plots Based on Critical Intensity
\[ I = 2e7; \] % Plots Based on User-Defined Value

\[ f = C_0; \]
\[ e_{coll0} = \frac{3}{4}f*(ep-em)-\frac{1}{4}(ep-2*em)+\frac{1}{4}(9*f^2*(ep-em)^2-6*f*(ep-2*em)*(ep-em)+(ep+2*em)^2)^{(1/2)}; \]
\[ n_0 = \sqrt{e_{coll0}}; \]

\texttt{for} p = 1:length(a)
\[ I_0(p) = c*k*T*(m^2+2)/(2*pi*a(p)^3*(m^2-1)); \]
\[ C(p) = C_0*exp(I/I_0(p)); \]
\[ f = C(p); \]
\[ e_{coll}(p) = \frac{3}{4}f*(ep-em)-\frac{1}{4}(ep-2*em)+\frac{1}{4}(9*f^2*(ep-em)^2-6*f*(ep-2*em)*(ep-em)+(ep+2*em)^2)^{(1/2)}; \]
\[ n(p) = \sqrt{e_{coll}(p)}; \]
\[ \text{deltan}(p) = n(p) - n_0; \]
\texttt{end}

\[ \text{neededn} = \text{zeros}(1, \text{length(deltan)}) + 0.3; \]

\texttt{figure(1),plot(a/1e-6,deltan,a/1e-6,neededn, 'r')}
\% title('Change in Refractive Index as a Function of Particle Size for Set Intensity')
\% xlabel('Particle Radius')
\% ylabel('Change in Index of Refraction')

\texttt{subplot(3,1,1),plot(I,C)}
\% title('Concentration as a function of input intensity; Background Concentration = ',num2str(C0),')
\% xlabel('Intensity in W/m^2')
\% ylabel('Concentration')
\texttt{subplot(3,1,2),plot(I,n)}
\% title('Effective Refractive Index as a Function of Intensity, 300nm particle')
\% xlabel('Intensity')
\% ylabel('Index of Refraction')

\textbf{A.D CladdingDepth.m}

% This program finds the reflectance of a thin film cladding between two
% layers of glass
clear all

% Universal Constants
e0 = 8.854e-12;
u0 = 4*pi*1e-7;
c0 = 3e8;

% Materials Constants
n0 = 1.62; %glass substrate
n1 = 1.0; %cladding
n2 = 5; %extra medium
lambda = 500e-9; %wavelength
d = 0:10e-9:2000e-9;

theta_d = 50; %propagation in substrate
theta0 = theta_d*pi/180;
theta1 = asin(n0/n1*sin(theta0));
%theta2 = asin(n1/n2*sin(theta1));
theta2 = theta0;
Eta0s = e0*c0*n0*cos(theta0);
Eta1s = e0*c0*n1*cos(theta1);
Eta2s = e0*c0*n2*cos(theta2);
Eta0p = e0*c0*n0/cos(theta0);
Eta1p = e0*c0*n1/cos(theta1);
Eta2p = e0*c0*n2/cos(theta2);

% Find the phase factor delta
for m = 1:length(d)
    delta(m) = 2*pi*n1*d(m)*cos(theta1)/lambda;
    Ys(m) = (Eta2s*cos(delta(m))+i*Eta1s*sin(delta(m)))/(cos(delta(m))+i*(Eta2s/Eta1s)*sin(delta(m)));
    Qs(m) = (Eta0s - Ys(m))/(Eta0s+Ys(m));
    Rs(m) = Qs(m)*conj(Qs(m));
    Yp(m) = (Eta2p*cos(delta(m))+i*Eta1p*sin(delta(m)))/(cos(delta(m))+i*(Eta2p/Eta1p)*sin(delta(m)));
    Qp(m) = (Eta0p - Yp(m))/(Eta0p+Yp(m));
    Rp(m) = Qp(m)*conj(Qp(m));
    Rav(m) = (Rs(m)+Rp(m))/2;
end

plot(d,Rav)
hold on
Appendix B:

Zemax Prescriptions

B.A Cylindrical Reflective System, Nonsequential Prescription

OBJECT DATA DETAIL:

There are 17 objects:

Object 1 : NumLens
Object Type : Null Object (NSC_NULL)
Reference Object : 0
Inside Of : 0
XYZ Position : 125 0 0
Tilt About XYZ : 0 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 1.25000000E+002
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 0.00000000E+000
Material :
Index at 0.425000 µm = 1.00000000
Index at 0.465000 µm = 1.00000000
Index at 0.505000 µm = 1.00000000
Index at 0.545000 µm = 1.00000000
Index at 0.585000 µm = 1.00000000
Index at 0.625000 µm = 1.00000000
Index at 0.665000 µm = 1.00000000
Index at 0.705000 µm = 1.00000000
Index at 0.745000 µm = 1.00000000
Index at 0.785000 µm = 1.00000000
Index at 0.825000 µm = 1.00000000
Index at 0.865000 µm = 1.00000000
<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.905000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>0.945000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>0.985000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.025000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.065000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.105000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.145000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.185000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.225000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.265000</td>
<td>1.00000000</td>
</tr>
<tr>
<td>1.305000</td>
<td>1.00000000</td>
</tr>
</tbody>
</table>

Object 2: Lens Diameter

Object Type: Null Object (NSC_NULL)

Reference Object: 0

Inside Of: 0

XYZ Position: 2 0 0

Tilt About XYZ: 0 0 0

Position Matrix:

<table>
<thead>
<tr>
<th>R11</th>
<th>R12</th>
<th>R13</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00000000E+000</td>
<td>0.00000000E+000</td>
<td>0.00000000E+000</td>
<td>2.00000000E+000</td>
</tr>
<tr>
<td></td>
<td>1.00000000E+000</td>
<td>0.00000000E+000</td>
<td>0.00000000E+000</td>
</tr>
<tr>
<td></td>
<td>0.00000000E+000</td>
<td>1.00000000E+000</td>
<td>0.00000000E+000</td>
</tr>
</tbody>
</table>

Material:

<table>
<thead>
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Object 3: Illuminated Lenses

Object Type: Null Object (NSC_NULL)

Reference Object: 0

Inside Of: 0

XYZ Position: 125 0 0

Tilt About XYZ: 0 0 0

Position Matrix:

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Material:

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<td>1.305000</td>
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Index at 0.945000 µm = 1.00000000
Index at 0.985000 µm = 1.00000000
Index at 1.025000 µm = 1.00000000
Index at 1.065000 µm = 1.00000000
Index at 1.105000 µm = 1.00000000
Index at 1.145000 µm = 1.00000000
Index at 1.185000 µm = 1.00000000
Index at 1.225000 µm = 1.00000000
Index at 1.265000 µm = 1.00000000
Index at 1.305000 µm = 1.00000000

Object 4 : Num Lenses Wide
Object Type : Null Object (NSC_NULL)
Reference Object : 0
Inside Of : 0
XYZ Position :
Tilt About XYZ :
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 1.00000000E+001
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 0.00000000E+000
Material :
Index at 0.425000 µm = 1.00000000
Index at 0.465000 µm = 1.00000000
Index at 0.505000 µm = 1.00000000
Index at 0.545000 µm = 1.00000000
Index at 0.585000 µm = 1.00000000
Index at 0.625000 µm = 1.00000000
Index at 0.665000 µm = 1.00000000
Index at 0.705000 µm = 1.00000000
Index at 0.745000 µm = 1.00000000
Index at 0.785000 µm = 1.00000000
Index at 0.825000 µm = 1.00000000
Index at 0.865000 µm = 1.00000000
Index at 0.905000 µm = 1.00000000
Index at 0.945000 µm = 1.00000000
Index at 0.985000 µm = 1.00000000
Index at 1.025000 µm = 1.00000000
Index at 1.065000 µm = 1.00000000
Index at 1.105000 µm = 1.00000000
Index at 1.145000 µm = 1.00000000
Index at 1.185000 µm = 1.00000000
Index at 1.225000 µm = 1.00000000
Index at 1.265000 µm = 1.00000000
Index at 1.305000 µm = 1.00000000

Object 5 : Array Length
Object Type : Null Object (NSC_NULL)
Reference Object : 0
Inside Of : 0
XYZ Position :
Tilt About XYZ :
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 2.50000000E+002
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 0.00000000E+000
Material :
Index at 0.425000 µm = 1.00000000
Index at 0.465000 µm = 1.00000000
Index at 0.505000 µm = 1.00000000
Index at 0.545000 µm = 1.00000000
Index at 0.585000 µm = 1.00000000
Index at 0.625000 µm = 1.00000000
Index at 0.665000 µm = 1.00000000
Index at 0.705000 µm = 1.00000000
Index at 0.745000 µm = 1.00000000
Index at 0.785000 µm = 1.00000000
Index at 0.825000 µm = 1.00000000
Index at 0.865000 µm = 1.00000000
Object 6 : Waveguide
Object Type : Rectangular Volume (NSC_RBLK)
Face 0 : Side Faces
Face Is : Object Default
Coating : (none)
Scattering : None
Face 1 : Front Face
Face Is : Object Default
Coating : 1.99
Scattering : None
Face 2 : Back Face
Face Is : Object Default
Coating : 1.99
Scattering : None
Reference Object : 0
Inside Of : 0
XYZ Position : 0 0 0
Tilt About XYZ : 0 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 0.00000000E+000
Material : BK7
Index at 0.425000 µm = 1.52782658
Index at 0.465000 µm = 1.52401238
Index at 0.505000 µm = 1.52108692
Index at 0.545000 µm = 1.51877729
Index at 0.585000 µm = 1.51690776
Index at 0.625000 µm = 1.51536070
Index at 0.665000 µm = 1.51405476
Index at 0.705000 µm = 1.51293214
Index at 0.745000 µm = 1.51195080
Index at 0.785000 µm = 1.51107956
Index at 0.825000 µm = 1.51029485
Index at 0.865000 µm = 1.50957859
Index at 0.905000 µm = 1.50891670
Index at 0.945000 µm = 1.50829808
Index at 0.985000 µm = 1.50771390
Index at 1.025000 µm = 1.50715702
Index at 1.065000 µm = 1.50662164
Index at 1.105000 µm = 1.50610300
Index at 1.145000 µm = 1.50559716
Index at 1.185000 µm = 1.50510082
Index at 1.225000 µm = 1.50461122
Index at 1.265000 µm = 1.50412600
Index at 1.305000 µm = 1.50364318
X1 Half Width : 5
Y1 Half Width : 125
Z Length : 2.5
X2 Half Width : 5
Y2 Half Width : 125
Front X Angle : 0
Front Y Angle : 0
Rear X Angle : 0
Rear Y Angle : 0

Object 7 : Lenslets
Object Type              : Lenslet Array 1 (NSC_LET1)
Face 0                   : Side Faces
Face Is                  : Object Default
Coating                  : (none)
Scattering               : None
Face 1                   : Front Face
Face Is                  : Object Default
Coating                  : I.995
Scattering               : None
Face 2                   : Back Face
Face Is                  : Reflective
Coating                  : (none)
Scattering               : None
Face 3                   : Inside Faces
Face Is                  : Object Default
Coating                  : (none)
Scattering               : None
Reference Object         : 0
Inside Of                : 0
XYZ Position             : 0 0 0.02
Tilt About XYZ           : 0 180 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000 2.00000000E+000
Material                 : BK7
Index at    0.425000 µm = 1.52782658
Index at    0.465000 µm = 1.52401238
Index at    0.505000 µm = 1.5208692
Index at    0.545000 µm = 1.51877729
Index at    0.585000 µm = 1.51690776
Index at    0.625000 µm = 1.51536070
Index at    0.665000 µm = 1.51405476
Index at    0.705000 µm = 1.51293214
Index at    0.745000 µm = 1.51195080
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Index at    0.825000 µm = 1.51029485
Index at    0.865000 µm = 1.50957859
Index at    0.905000 µm = 1.50891670
Index at    0.945000 µm = 1.50829808
Index at    0.985000 µm = 1.50771390
Index at   1.025000 µm = 1.50715702
Index at   1.065000 µm = 1.50662164
Index at  1.105000 µm = 1.50610300
Index at  1.145000 µm = 1.50559716
Index at  1.185000 µm = 1.50510082
Index at  1.225000 µm = 1.50461122
Index at  1.265000 µm = 1.50412600
Index at  1.305000 µm = 1.50364318
X Half-Width             : 5
Y Half-Width             : 1
Thickness                : 2.032712
Radius                   : -9.1821941
Conic                    : 0.023664661
Is Toric?                : 1
Toric R                  : 0
Lines/µm                 : 0
Diff Order               : 0
Coeff y^2                : 1.7517265e-006
Coeff y^4                : -1.018341e-007
Coeff y^6                : 8.5626061e-005
Coeff y^8                : -6.9894976e-005
Coeff y^10               : 0
Coeff y^12               : 0
Coeff y^14               : 0
Coeff y^16               : 0
Decenter X               : 0
Decenter Y               : 0
Number In X               : 1
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<td>Scattering</td>
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</table>
Face 2                  : Back Face
Face Is                  : Object Default
Coating                  : (none)
Scattering                : None
Reference Object         : 8
Inside Of                : 7
XYZ Position             : 0 -0.010278119                  0
Tilt About XYZ           : 0 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 1.23989722E+002
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 0.00000000E+000 1.00000000E+000 2.50000000E+000
Material                 : BK7
Index at 0.425000 µm = 1.52782658
Index at 0.465000 µm = 1.52401238
Index at 0.505000 µm = 1.52108692
Index at 0.585000 µm = 1.51690776
Index at 0.625000 µm = 1.51536070
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Index at 1.145000 µm = 1.50559716
Index at 1.185000 µm = 1.50510082
Index at 1.225000 µm = 1.50461122
Index at 1.265000 µm = 1.50412600
Index at 1.305000 µm = 1.50364318
X1 Half Width            : 10
Y1 Half Width            : 0.0051390596
Z Length                 : 0.0029652374
X2 Half Width            : 10
Y2 Half Width            : 0
Front X Angle            : 0
Front Y Angle            : 0
Rear X Angle             : 0
Rear Y Angle             : 0

Object 10              : PrismFeature 3
Object Type              : Rectangular Volume (NSC_RBLK)
Face 0                  : Side Faces
Face Is                  : Reflective
Coating                  : (none)
Scattering                : None
Face 1                  : Front Face
Face Is                  : Object Default
Coating                  : (none)
Scattering                : None
Face 2                  : Back Face
Face Is                  : Object Default
Coating                  : (none)
Scattering                : None
Reference Object         : 8
Inside Of                : 7
XYZ Position             : 0 0.010278119                  0
Tilt About XYZ           : 0 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000 1.24010278E+002
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 2.50000000E+000
Material                 : BK7
Index at 0.425000 µm = 1.52782658
Index at 0.465000 µm = 1.52401238
Index at 0.505000 µm = 1.52108692
Index at 0.545000 µm = 1.51877729
Index at 0.585000 µm = 1.51690776
Index at 0.625000 µm = 1.51536070
Index at 0.665000 µm = 1.51405476
Index at 0.705000 µm = 1.51293214
Index at 0.745000 µm = 1.51195080
Index at 0.785000 µm = 1.51107956
Index at 0.825000 µm = 1.51029485
Index at 0.865000 µm = 1.50957859
Index at 0.905000 µm = 1.50891670
Index at 0.945000 µm = 1.50829808
Index at 0.985000 µm = 1.50771390
Index at 1.025000 µm = 1.50715702
Index at 1.065000 µm = 1.50662164
Index at 1.105000 µm = 1.50610300
Index at 1.145000 µm = 1.50559716
Index at 1.185000 µm = 1.50510082
Index at 1.225000 µm = 1.50461122
Index at 1.265000 µm = 1.50412600
Index at 1.305000 µm = 1.50364318

X1 Half Width : 10
Y1 Half Width : 0.0051390596
Z Length : 0.0029652374
X2 Half Width : 10
Y2 Half Width : 0
Front X Angle : 0
Front Y Angle : 0
Rear X Angle : 0
Rear Y Angle : 0

Object 11 : Prism Array
Object Type : Array (NSC_ARRA)
Face 0 : Defined by Object 8 Face 0
Face 1 : Defined by Object 8 Face 1
Face 2 : Defined by Object 8 Face 2
Reference Object : 8
Inside Of : 0
XYZ Position : 0 0 0
Tilt About XYZ : 0 0 0

Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 1.24000000E+002
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 2.50000000E+000

Material :
Index at 0.425000 µm = 1.00000000
Index at 0.465000 µm = 1.00000000
Index at 0.505000 µm = 1.00000000
Index at 0.545000 µm = 1.00000000
Index at 0.585000 µm = 1.00000000
Index at 0.625000 µm = 1.00000000
Index at 0.665000 µm = 1.00000000
Index at 0.705000 µm = 1.00000000
Index at 0.745000 µm = 1.00000000
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Index at 0.945000 µm = 1.00000000
Index at 0.985000 µm = 1.00000000
Index at 1.025000 µm = 1.00000000
Index at 1.065000 µm = 1.00000000
Index at 1.105000 µm = 1.00000000
Index at 1.145000 µm = 1.00000000
Index at 1.185000 µm = 1.00000000
Index at 1.225000 µm = 1.00000000
Index at 1.265000 µm = 1.00000000
Index at 1.305000 µm = 1.00000000
Parent Object #: 8
Number X': 1
Number Y': 125
Number Z': 1
Delta1 X': 1
Delta1 Y': -2
Delta1 Z': 1
X’ - x: 1
X’ - y: 0
X’ - z: 0
Y’ - x: 0
Y’ - y: 1
Y’ - z: 0
Z’ - x: 0
Z’ - y: 0
Z’ - z: 1
Tilt x: 0
Tilt y: 0
Tilt Z: 0
Draw Limit: 500
Draw Boundary: 0
Delta2 X': 0
Delta2 Y': 0
Delta2 Z': 0
Delta3 X': 0
Delta3 Y': 0
Delta3 Z': 0
Delta4 X': 0
Delta4 Y': 0
Delta4 Z': 0
Maximum X': 0
Maximum Y': -248
Maximum Z': 0
Object 12: Prism Array 2
Object Type: Array (NSC_ARRA)
Face 0: Defined by Object 9 Face 0
Face 1: Defined by Object 9 Face 1
Face 2: Defined by Object 9 Face 2
Reference Object: 9
Inside Of: 0
XYZ Position: 0 0 0
Tilt About XYZ: 0 0 0
Pos. Mtrx. R11 R12 R13 X: 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y: 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000 1.23989722E+002
Pos. Mtrx. R31 R32 R33 Z: 0.00000000E+000 0.00000000E+000 1.00000000E+000 2.50000000E+000
Material:
Index at 0.425000 µm = 1.00000000
Index at 0.465000 µm = 1.00000000
Index at 0.505000 µm = 1.00000000
Index at 0.545000 µm = 1.00000000
Index at 0.585000 µm = 1.00000000
Index at 0.625000 µm = 1.00000000
Index at 0.665000 µm = 1.00000000
Index at 0.705000 µm = 1.00000000
Index at 0.745000 µm = 1.00000000
Index at 0.785000 µm = 1.00000000
Index at 0.825000 µm = 1.00000000
Index at 0.865000 µm = 1.00000000
Index at 0.905000 µm = 1.00000000
Index at 0.945000 µm = 1.00000000
Index at 0.985000 µm = 1.00000000
Index at 1.025000 µm = 1.00000000
Index at 1.065000 µm = 1.00000000
Index at 1.105000 µm = 1.00000000
Index at 1.145000 µm = 1.00000000
Index at 1.185000 µm = 1.00000000
Index at 1.225000 µm = 1.00000000
Index at 1.265000 µm = 1.00000000
Index at 1.305000 µm = 1.00000000
Parent Object # : 9
Number X' : 1
Number Y' : 125
Number Z' : 1
Delta1 X' : 1
Delta1 Y' : -2
Delta1 Z' : 1
X' - x : 1
X' - y : 0
X' - z : 0
Y' - x : 0
Y' - y : 1
Y' - z : 0
Z' - x : 0
Z' - y : 0
Z' - z : 1
Tilt x : 0
Tilt y : 0
Tilt Z : 0
Draw Limit : 500
Draw Boundary : 0
Delta2 X' : 0
Delta2 Y' : 0
Delta2 Z' : 0
Delta3 X' : 0
Delta3 Y' : 0
Delta3 Z' : 0
Delta4 X' : 0
Delta4 Y' : 0
Delta4 Z' : 0
Maximum X' : 0
Maximum Y' : -248
Maximum Z' : 0

Object 13 : Prism Array 3
Object Type : Array (NSC_ARRA)
Face 0 : Defined by Object 10 Face 0
Face 1 : Defined by Object 10 Face 1
Face 2 : Defined by Object 10 Face 2
Reference Object : 10
Inside Of : 0
XYZ Position : 0 0 0
Tilt About XYZ : 0 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 1.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 2.50000000E+000
Material :
Index at 0.425000 µm = 1.00000000
Index at 0.465000 µm = 1.00000000
Index at 0.505000 µm = 1.00000000
Index at 0.545000 µm = 1.00000000
Index at 0.585000 µm = 1.00000000
Index at 0.625000 µm = 1.00000000
Index at 0.665000 µm = 1.00000000
Index at 0.705000 µm = 1.00000000
Index at 0.745000 µm = 1.00000000
Index at 0.785000 µm = 1.00000000
Index at 0.825000 µm = 1.00000000
Index at 0.865000 µm = 1.00000000
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Index at 0.945000 µm = 1.00000000
Index at 0.985000 µm = 1.00000000
Index at 1.025000 µm = 1.00000000
Index at 1.065000 µm = 1.00000000
Index at 1.105000 µm = 1.00000000
Index at 1.145000 µm = 1.00000000
Index at 1.185000 µm = 1.00000000
Index at 1.225000 µm = 1.00000000
Index at 1.265000 µm = 1.00000000
Index at 1.305000 µm = 1.00000000
Parent Object # : 10
Number X' : 1
Number Y' : 125
Number Z' : 1
Delta1 X' : 1
Delta1 Y' : -2
Delta1 Z' : 1
X' - x : 1
X' - y : 0
X' - z : 0
Y' - x : 0
Y' - y : 1
Y' - z : 0
Z' - x : 0
Z' - y : 0
Z' - z : 1
Tilt x : 0
Tilt y : 0
Tilt Z : 0
Draw Limit : 500
Draw Boundary : 0
Delta2 X' : 0
Delta2 Y' : 0
Delta2 Z' : 0
Delta3 X' : 0
Delta3 Y' : 0
Delta3 Z' : 0
Delta4 X' : 0
Delta4 Y' : 0
Delta4 Z' : 0
Maximum X' : 0
Maximum Y' : -248
Maximum Z' : 0
Object 14 : Ray Rotator (NSC_ROTA)
Reference Object : 0
Inside Of : 0
XYZ Position : 0 0 2.8
Tilt About XYZ : 0 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 1.00000000E+000 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 1.00000000E+000 2.80000000E+000 0.00000000E+000 0.00000000E+000
Material :
Index at 0.425000 µm = 1.00000000
Index at 0.465000 µm = 1.00000000
Index at 0.505000 µm = 1.00000000
Index at 0.545000 µm = 1.00000000
Index at 0.585000 µm = 1.00000000
Index at 0.625000 µm = 1.00000000
Index at 0.665000 µm = 1.00000000
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Index at 0.745000 µm = 1.00000000
Index at 0.785000 µm = 1.00000000
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Index at 0.945000 µm = 1.00000000
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Index at 1.065000 µm = 1.00000000
Index at 1.105000 µm = 1.00000000
Index at 1.145000 µm = 1.00000000
Index at 1.185000 µm = 1.00000000
Index at 1.225000 µm = 1.00000000
Index at 1.265000 µm = 1.00000000
Index at 1.305000 µm = 1.00000000
X Half Width : 5
Y Half Width : 125
Rotate Z : 0
Rotate Y : 23.45

Object 15 :
Object Type : Source Two Angle (NSC_SR2A)
Reference Object : 0
Inside Of : 0
XYZ Position : 0 0 3
Tilt About XYZ : 180 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 -1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 0.00000000E+000 0.00000000E+000 -1.00000000E+000 3.00000000E+000
Source uses system wavelengths
# Layout Rays : 50
# Analysis Rays : 5000
Power(Watts) : 1.53
Wavenumber : 0
Color # : 0
X Half Width : 0
Y Half Width : 125
X Half Angle (deg) : 0.26
Y Half Angle (deg) : 0.26
Spatial Shape : 0
Angular Shape : 0
Uniform Angle : 0

Object 16 :
Object Type : Detector Rectangle (NSC_DETE)
Face 0 : All Faces
Face Is : Object Default
Coating : (none)
Scattering : None
Reference Object : 6
Inside Of : 6
XYZ Position : 0 124.999 1.25
Tilt About XYZ : 90 0 0
Pos. Mtrx. R11 R12 R13 X : 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000
Pos. Mtrx. R21 R22 R23 Y : 0.00000000E+000 0.00000000E+000 -1.00000000E+000 1.24999000E+002
Pos. Mtrx. R31 R32 R33 Z : 0.00000000E+000 1.00000000E+000 0.00000000E+000 0.00000000E+000 1.25000000E+000
Material : ABSORB
X Half Width : 5
Y Half Width : 1.25
# X Pixels : 1
# Y Pixels : 1
Data Type : 0
Color : 0
Smoothing : 0
Scale : 0
Plot Scale : 0
Front Only : 0
PSF Wave # : 0
X Angle Min : -90
X Angle Max : 90
Y Angle Min : -90
Y Angle Max : 90
Polarization : 0
Mirroring : 0

Object 17 :
Object Type : Detector Rectangle (NSC_DETE)
Face 0 : All Faces
Face Is : Object Default
Coating : (none)
Scattering: None
Reference Object: 6
Inside Of: 6
XYZ Position: 0, -124.999, 1.25
Tilt About XYZ: 90, 0, 0
Pos. Mtrx.: R11 R12 R13 X: 1.00000000E+000 0.00000000E+000 0.00000000E+000 0.00000000E+000 1.24999000E+002
Pos. Mtrx.: R21 R22 R23 Y: 0.00000000E+000 1.00000000E+000 0.00000000E+000 -0.00000000E+000 1.25000000E+000
Pos. Mtrx.: R31 R32 R33 Z: 0.00000000E+000 0.00000000E+000 1.00000000E+000 1.25000000E+000
Material: ABSORB
X Half Width: 5
Y Half Width: 1.25
# X Pixels: 1
# Y Pixels: 1
Data Type: 0
Color: 0
Smoothing: 0
Scale: 0
Plot Scale: 0
Front Only: 0
PSF Wave #: 0
X Angle Min: -90
X Angle Max: 90
Y Angle Min: -90
Y Angle Max: 90
Polarization: 0
Mirroring: 0

COATING DEFINITIONS:

SOLVE AND VARIABLE DATA:

Surf 1 NSC Object 3 Position X: Solve, ZPL Macro justin/num lens
Surf 1 NSC Object 6 Parameter 1: Pickup From 4 Scale 5.0000E-001 Offset 0.0000E+000 Column X
Surf 1 NSC Object 6 Parameter 2: Pickup From 5 Scale 5.0000E-001 Offset 0.0000E+000 Column X
Surf 1 NSC Object 6 Parameter 4: Pickup From 6 Scale 1.0000E+000 Offset 0.0000E+000 Column Parameter 1
Surf 1 NSC Object 6 Parameter 5: Pickup From 6 Scale 1.0000E+000 Offset 0.0000E+000 Column Parameter 2
Surf 1 NSC Object 7 Parameter 1: Pickup From 4 Scale 5.0000E-001 Offset 0.0000E+000 Column X
Surf 1 NSC Object 7 Parameter 2: Pickup From 2 Scale 5.0000E-001 Offset 0.0000E+000 Column X
Surf 1 NSC Object 7 Parameter 3: Variable
Surf 1 NSC Object 7 Parameter 6: Variable
Surf 1 NSC Object 7 Parameter 7: Variable
Surf 1 NSC Object 7 Parameter 12: Variable
Surf 1 NSC Object 7 Parameter 13: Variable
Surf 1 NSC Object 7 Parameter 14: Variable
Surf 1 NSC Object 7 Parameter 15: Variable
Surf 1 NSC Object 7 Parameter 23: Pickup From 1 Scale 1.0000E+000 Offset 0.0000E+000 Column X
Surf 1 NSC Object 8 Position Y: Solve, ZPL Macro kate/SetPrismSpacing
Surf 1 NSC Object 8 Parameter 2: Variable
Surf 1 NSC Object 8 Parameter 3: Pickup From 8 Scale 5.7700E-001 Offset 0.0000E+000 Column Parameter 2
Surf 1 NSC Object 8 Parameter 4: Pickup From 8 Scale 1.0000E+000 Offset 0.0000E+000 Column Parameter 1
Surf 1 NSC Object 9 Position Y: Solve, ZPL Macro kate/Set2ndaryPrismSpacing
Surf 1 NSC Object 9 Parameter 1: Solve, ZPL Macro kate/Set2ndaryPrismSpacing
Surf 1 NSC Object 9 Parameter 2: Variable
Surf 1 NSC Object 9 Parameter 3: Pickup From 8 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 9 Parameter 9: Pickup From 8 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 10 Position Y: -1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 10 Parameter 1: Pickup From 8 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 10 Parameter 2: Pickup From 9 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 10 Parameter 3: Pickup From 9 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 11 Parameter 3: Pickup From 1 Scale 1.0000E+000 Offset 0.0000E+000 Column X
Surf 1 NSC Object 11 Parameter 6: Pickup From 2 Scale -1.0000E+000 Offset 0.0000E+000 Column X
Surf 1 NSC Object 12 Parameter 3: Pickup From 1 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 12 Parameter 6: Pickup From 11 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 13 Parameter 3: Pickup From 1 Scale 1.0000E+000 Offset 0.0000E+000 Column X
Surf 1 NSC Object 13 Parameter 6: Pickup From 2 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 15 Parameter 6: Pickup From 2 Scale 1.0000E+000 Offset 0.0000E+000 Column Current
Surf 1 NSC Object 15 Parameter 7: Pickup From 5 Scale 5.0000E-001 Offset 0.0000E+000 Column X
B.B Singlet for Reactive Tracking

SURFACE DATA SUMMARY:

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SURFACE DATA DETAIL:

Surface OBJ STANDARD
Aperture : User Aperture
Aperture File : HEXAGON_UNIT1.UDA
Aperture Scale : 0.5
User Aperture Data : 0.25 -0.4330127
User Aperture Data : -0.25 -0.4330127
User Aperture Data : -0.5 3.8285687e-016
User Aperture Data : -0.25 0.4330127
User Aperture Data : 0.25 0.4330127
User Aperture Data : 0.5 -1.2098029e-015
User Aperture Data : 0 0

Surface STO EVENASPH
Coefficient on r^2 : 0.21881795
Coefficient on r^4 : 0.67184285
Coefficient on r^6 : -3.6322686
Coefficient on r^8 : -8.4388985
Coefficient on r^10 : 25.755269
Coefficient on r^12 : 122.71977
Coefficient on r^14 : 79.297691
Coefficient on r^16 : -1813.6937
Aperture : User Aperture
Aperture File : HEXAGON_UNIT1.UDA
Aperture Scale : 0.5
User Aperture Data : 0.25 -0.4330127
User Aperture Data : -0.25 -0.4330127
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User Aperture Data : -0.25 0.4330127
User Aperture Data : 0.25 0.4330127
User Aperture Data : 0.5 -1.2098029e-015
User Aperture Data : 0 0

Surface 2 STANDARD
Aperture : Circular Aperture
Minimum Radius : 0
Maximum Radius : 2

Surface 3 STANDARD
Aperture : Circular Aperture
Minimum Radius : 0
Maximum Radius : 2

Surface IMA STANDARD
Aperture : Circular Aperture
Minimum Radius : 0
Maximum Radius : 2

COATING DEFINITIONS:

SOLVE AND VARIABLE DATA:
Curvature of 1 : Variable
Thickness of 1 : Variable
Semi Diameter 1 : Fixed
Conic of 1 : Variable
Parameter 1 Surf 1 : Variable
Parameter 2 Surf 1 : Variable
Parameter 3 Surf 1 : Variable
Parameter 4 Surf 1 : Variable
Parameter 5 Surf 1 : Variable
Parameter 6 Surf 1 : Variable
Parameter 7 Surf 1 : Variable
Parameter 8 Surf 1 : Variable

B.C Doublet for Reactive Tracking

SURFACE DATA SUMMARY:

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SURFACE DATA DETAIL:

Surface OBJ STANDARD
Aperture : User Aperture
Aperture File : HEXAGON_UNIT1.UDA
Aperture Scale : 0.5
User Aperture Data : 0.25 -0.4330127
User Aperture Data : -0.25 -0.4330127
User Aperture Data : -0.5 3.8285687e-016
User Aperture Data : -0.25 0.4330127
User Aperture Data : 0.25 0.4330127
User Aperture Data : 0.5 -1.2098029e-015
User Aperture Data : 0 0

Surface STO EVENASPH lens 1
Coating : L95
Coefficient on r^2 : -0.16661235
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COATING DEFINITIONS:

SOLVE AND VARIABLE DATA:

Curvature of 1 : Variable
Thickness of 1 : Variable
Conic of 1 : Variable
Parameter 1 Surf 1 : Variable
Parameter 2 Surf 1 : Variable
Parameter 3 Surf 1 : Variable
Parameter 4 Surf 1 : Variable
Parameter 5 Surf 1 : Variable
Parameter 6 Surf 1 : Variable
Parameter 7 Surf 1 : Variable
Parameter 8 Surf 1 : Variable
Thickness of 2 : Variable
Curvature of 3 : Variable
Thickness of 3 : Variable
Conic of 3 : Variable
Parameter 1 Surf 3 : Variable
Parameter 2 Surf 3 : Variable
Parameter 3 Surf 3 : Variable
Parameter 4 Surf 3 : Variable
Parameter 5 Surf 3 : Variable
Parameter 6 Surf 3 : Variable
Parameter 7 Surf 3 : Variable
Parameter 8 Surf 3 : Variable
Semi Diameter 4 : Fixed
Semi Diameter 5 : Fixed
Appendix C:

Self-Aligned Fabrication Process

Prism Coupler Fabrication (Adapted from Karp’s process [42] and SU-8 processing guidelines [43])

1. Glass Cleaning
   - Sonicate for 1 minute each in acetone and methanol
   - Rinse with isopropanol and deionized water. Dry with nitrogen.
   - Bake at 200°C for 5min to dehydrate glass
   - Remove from heat. Allow to cool to ~30°C before SU-8 deposition

2. Spin-Coating and Soft Bake
   - For 5 um pitch prisms
     a. Pour half dollar-sized amount of SU-8 2002 onto glass (covers chuck ring)
     b. 10s at 500rpm, acceleration = 100rpm/s
     c. 30s at 3000rpm, acceleration = 300rpm/s
     d. Bake for 1 minute at 95°C
   - For 50 um pitch prisms
     a. Pour half dollar-sized amount of SU-8 2015 onto glass (covers chuck ring)
     b. 10s at 500rpm, acceleration = 100rpm/s
     c. 30s at 2100rpm, acceleration = 300rpm/s
     d. Bake for 3.5 minutes at 95°C

3. Prism Molding (Vacuum Oven)
   - Preheat vacuum oven to 60°C
   - Place PDMS mold onto spun photoresist layer (do not press)
   - Place 1kg aluminum block on top of PDMS mold
   - Insert into oven, raise thermostat to 95°C (~30min transition)
   - Pull vacuum (20-25 inHg)
   - Bake for a total of 45min
- Vent chamber and let cool to ~30°C with mold still in contact

4. UV Exposure
   - Turn on Hg arc lamp and exhaust fan. Warm up for ~15min
   - Place glass, SU-8 and mold onto exposure stage
   - Place lens array over glass and gently secure with clamps
   - Set Newport 818-ST to power integration (mJ/cm²)
   - Exposure Parameters
     a. For 5 um prisms: 40 mJ/cm²: 4-6 minutes
     b. For 50 um prisms: 70 mJ/cm²: 7-10 minutes

5. Post Bake (on hotplate)
   - Bake with PDMS mold in place to prevent resist reflow
   - For 5 um prisms, bake 2 minutes at 95°C
   - For 50 um prisms, bake 4.5 minutes at 95°C
   - Turn off hotplate and let cool to ~30°C
   - Remove PDMS mold

6. Development and Liftoff
   - Rinse in PGMEA developer for 1.5 minutes
   - Rinse with isopropanol, and dry with nitrogen
Bibliography


[38] H. A. MacLeod, Thin-Film Optical Filters (Hilger, Bristol, 1986).


