Planar micro-optic solar concentration using multiple imaging lenses into a common slab waveguide

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ABSTRACT

Conventional CPV systems focus sunlight directly onto a PV cell, usually through a non-imaging optic to avoid hot spots. In practice, many systems use a shared tracking platform to mount multiple smaller aperture lenses, each concentrating light into an associated PV cell. Scaling this approach to the limit would result in a thin sheet-like geometry. This would be ideal in terms of minimizing the tracking system payload, especially since such thin sheets can be arranged into louvered strips to minimize wind-force loading. However, simply miniaturizing results in a large number of individual PV cells, each needed to be packaged, aligned, and electrically connected. Here we describe for the first time a different optical system approach to solar concentrators, where a thin lens array is combined with a shared multimode waveguide. The benefits of a thin optical design can therefore be achieved with an optimum spacing of the PV cells. The guiding structure is geometrically similar to luminescent solar concentrators, however, in micro-optic waveguide concentrators sunlight is coupled directly into the waveguide without absorption or wavelength conversion. This opens a new design space for high-efficiency CPV systems with the potential for cost reduction in both optics and tracking mechanics. In this paper, we provide optical design and preliminary experimental results of one implementation specifically intended to be compatible with large-scale roll processing. Here the waveguide is a uniform glass sheet, held between the lens array and a corresponding array of micro-mirrors self-aligned to each lens focus during fabrication.

1. INTRODUCTION

Concentrator photovoltaic (CPV) systems combine large, light-collecting apertures with high efficiency semiconductor photovoltaic (PV) materials to convert solar photons directly into electricity. III-V multijunction PV cells provide efficiencies surpassing 40%, but only when illuminated with high solar flux (up to 500x)[1-3]. These cells are significantly more expensive than crystalline silicon or thin film solar cells, however, optical concentration results in a dramatic reduction in the cell's physical area. Combining small-area, high-efficiency PV cells with inexpensive concentrator optics can potentially decrease costs as well as reducing the system footprint.

All CPV optics collect direct insolation while high flux systems actively tracking the sun's daily position. Large-aperture concentrators are typically difficult to mount for tracking due to their considerable physical weight and volume, and due to wind-loading forces on the extended surface. Nevertheless, most CPV systems rely on bulky optics such as parabolic dishes or imaging lenses[4,5]. These elements produce demagnified images of the sun and can yield high levels of concentration (>1000x), but produce nonuniform flux distributions and require very accurate alignment[6]. To minimize overall CPV system cost, our goal was to identify a manufacturable optical system that can provide high collection efficiency and 100-500x concentration with a thin physical footprint. The planar geometry lends well to a tilt/roll tracking approach with concentrators mounted into louvered strips, like those of Venetian blinds[7].

A straightforward method to reduce optical volume is segmenting a single large aperture into an array of smaller, individual apertures mounted on a common tracking system [8]. However, this approach can only be extended to a degree until the assembly (alignment) and electrical connectivity costs of multiple PV cells becomes cost prohibitive. Nonimaging optical design yields entirely different optical systems optimized for energy collection, as opposed to image

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formation. Optics like compound parabolic concentrators approach the thermodynamic limit for concentration, but become lengthy when generating high flux[9], and so do not meet our form constraint. Design methods based on the edge-ray principle or simultaneous multiple surface construction produce free-form optics which maximize angular acceptance, beam uniformity and efficiency[10]. These systems have enormous flexibility, but can be hindered by fabrication difficulties when creating large apertures. Luminescent solar concentrators incorporate fluorescent or phosphorescent dyes into a waveguide to absorb and reemit photons which may be guided within a high-index slab[11,12]. This approach is elegant in concept and completely eliminates the need for tracking, but also have inherent loss mechanisms including initial wavelength conversion, emission into unguided modes, and re-absorption.

Here we describe a hybrid system that combines the waveguide structure with an efficient light injection technique. The micro-optic slab concentrator combines an array of lenses with a multimode slab waveguide. Each lens element forms a focus within the guide and is redirected into guided modes propagating laterally within the slab. All light exits from the slab edge directly onto a PV cell. Efficient coupling into the waveguide is possible using small area reflective microstructures located at each lens focus, where the image of the sun is formed. The configuration has additional benefits of producing a uniform intensity distribution at the PV cell as well as passing diffuse illumination for possible collection using flat-panel cells.

Alignment between the lens focus and coupling mechanism is critical for capturing incident sunlight. Our proposed technique uses self-aligned photolithography, enabling the coupling structure to be molded in photoresist and polymerized at each focus using the lens array as a mask. This guarantees accurate alignment between the lens array and coupling features. The process can potentially yield very large, inexpensive concentrators when performed using roll-to-roll manufacture. We detail the design, tradeoffs and potential performance of the system as well as present fabrication methods and functioning prototypes.

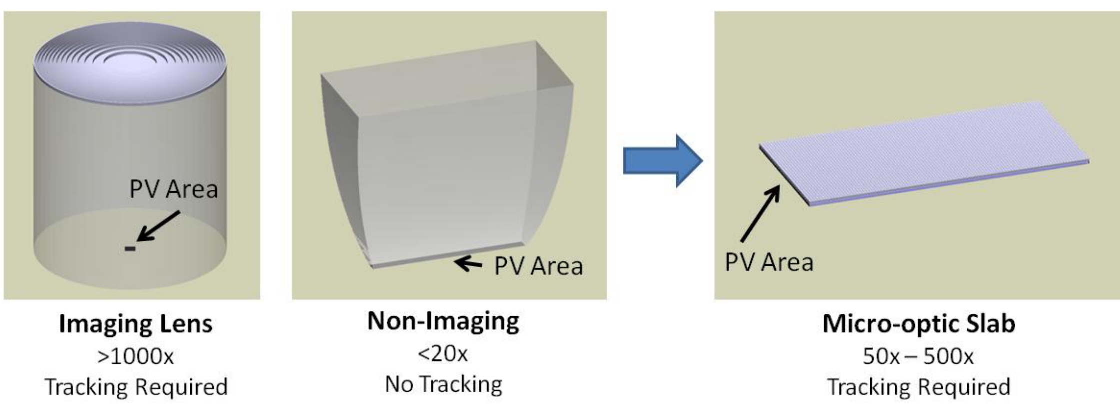

Figure 1: Existing imaging and nonimaging concentrators occupy large optical volumes (left). The micro-optic slab concentrator combines imaging and nonimaging techniques to form a planar system (right).

2. MICRO-OPTIC SLAB CONCENTRATOR

The micro-optic slab concentrator acts as a hybrid imaging/nonimaging optical system by combining an imaging lens array with a multimode slab waveguide. The optical system consists of three main components. The first is a two-dimensional lens array acting as the upward facing aperture to collect incident solar radiation. Each lens forms a demagnified image of the solar disk which subtends ±0.26° (4.7mrad)[13].

A high refractive index slab waveguide, the second element, sits beneath the lens array. Localized structures embedded on the backside of the waveguide reorient focused light into guided modes that travel via total internal reflection (TIR) transversely within the slab. The top surface of the waveguide is separated from the lenses by a thin layer of low-index cladding. Large index contrasts between the core and cladding promote greater numbers of guided modes and allow steep marginal rays to TIR at the interface. The nonimaging nature of the slab waveguide allows light to be collected from several lens apertures at large ray angles.

The third and last component of the concentrator is the mechanism that efficiently couples light into the waveguide. Gratings and holograms have previously been used for waveguide coupling, however, the broad spectrum of sunlight prevents such solutions from being as efficient as needed[14,15]. Instead, specular reflections from small fold mirrors can reorient the sunlight into angles which exceed the critical angle between the guiding slab and cladding interface and therefore, guide by TIR.

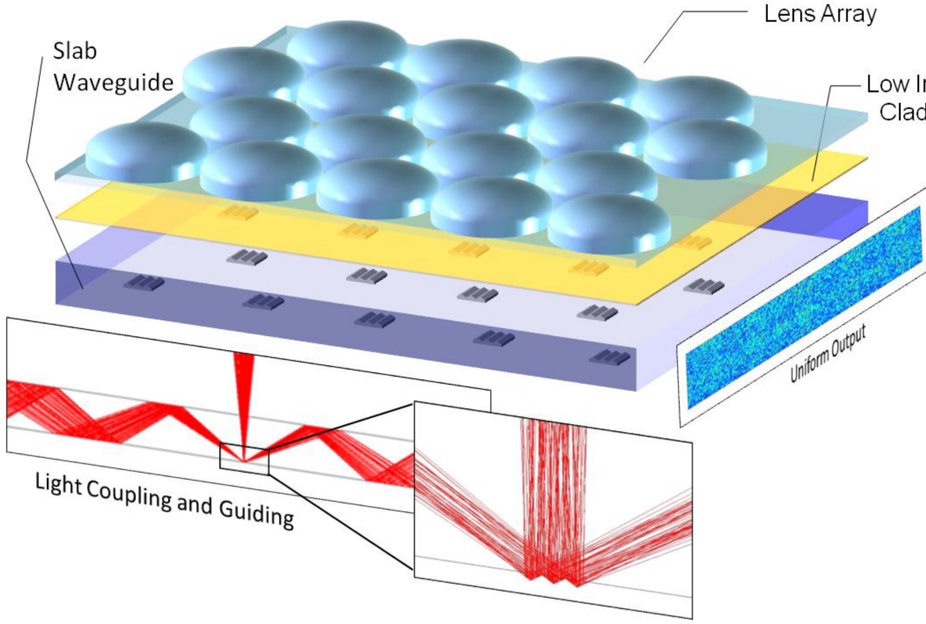

Figure 2: Exploded perspective of the main components of the micro-optic slab concentrator. Waveguide couplers are aligned at each lens focus to reorient light into guided modes.

Fabrication and alignment techniques, which are covered in Section 4, place restrictions on light-coupling designs. Since fold mirrors are not actively placed at each lens focus, a continuous structure must be used to enable molding and facet formation at any location. A simple 45° fold mirror blocks light already in the waveguide upon second incidence. A noteworthy example that does enable guiding is a 120° apex angle, symmetric prism array with a metallic coating. Light at normal incidence reflects at 60°; an angle that exceeds the critical angle for many optical material interfaces. The tilt is also parallel to the adjacent facet in the array and avoids shadowing effects. Marginal rays that reflect at shallower angles also avoid shadowing; while steeper angles encounter a second grazing reflection, but still satisfy the TIR criteria. Defining a continuous structure enables the coupling facets to be placed anywhere within the lens focus. No attention is needed towards which portion(s) of the facet is producing the reflection. Since this prism structure is symmetric, light travels laterally in both directions.

It is essential that the coupling facets exist only at each lens focus as guided light is decoupled upon second illumination. The area occupied by each lens focus is <0.1% of the total surface area of the waveguide. Though not lossless, the waveguide appears >99.9% reflective allowing light to propagate hundreds of lens diameters before being decoupled by a subsequent facet. The light exiting the slab appears uniform in intensity due to divergence after the focus. A PV cell is placed at the slab edge to collect light from the entire lens array.

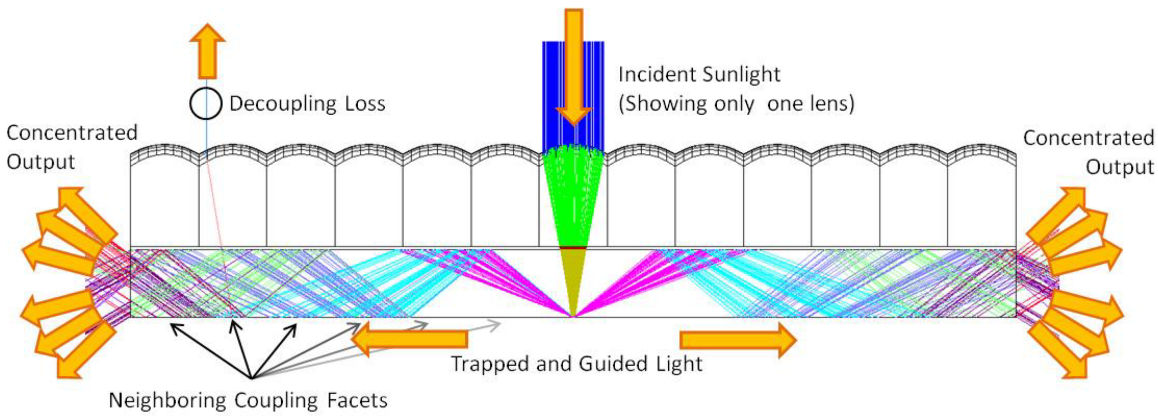

Figure 3: Annotated raytrace depicting the light path entering a single lens element. The coupling facet at each lens focus reorients sunlight into guided modes, however, becomes a source of loss when struck a second time.

3. CONCENTRATOR DESIGN AND PERFORMANCE

The geometric concentration ratio is defined as the ratio of areas between the collecting and emitting apertures. With regards to the micro-optic slab concentrator, the ratio is simply the waveguide length divided by its thickness, assuming no concentration in the orthogonal direction. Flux concentration is more indicative of concentrator performance and is computed by multiplying the geometric ratio by the optical efficiency.

Several loss mechanisms affect the performance of the slab concentrator. Most obvious are surface reflections between the lens array, cladding and waveguide layers. Additionally, dielectric or metallic coatings on the coupling facets are imperfect, leading to fixed-percentage losses. Guiding light within a dielectric medium always leads to some loss from material absorption, however high-quality optical glasses can be very transparent over several centimeters of thickness. F2, a common flint glass, has high internal transmission (τ_{25mm}=0.998 at λ=546nm) and index of refraction (n_d=1.62)[16]. Light can be guided in the material for a meter length and still maintain 92% of its original energy.

The most interesting source of loss is decoupling of light from striking successive facets visible from within the waveguide. The size/spacing of the facets is governed by the optical design and not materials, opening a new design space for solar concentrators. Tradeoffs between lens diameter, focal length, waveguide thickness and desired flux output all affect the performance of a particular design.

Lens focal length determines the image size of the solar disk, thereby dictating the required coupling facet area. Short focal lengths form smaller images of the sun. Large diameter lenses produce fewer points of coupling/decoupling at the costs of system thickness and the severity of aberrations when moving towards short focal lengths. Furthermore, the numerical aperture of the lens array plays an important role in matching the modes which may be guided within the slab. Increasing the index contrast between the slab and cladding supports lenses with high numerical apertures, yet non-paraxial rays experience increased paths lengths while guiding towards the slab edge. The physical thickness of the slab waveguide impacts the number of TIR interactions with the lossy bottom surface. Thick waveguides minimize the likelihood of stripping light by reducing the amount contact with the potentially lossy surface. Decreased loss per unit length also diminishes the geometric concentration ratio.

We simulate the performance of the micro-optic slab concentrator using Matlab as well as nonsequential raytracing in Zemax. First, we selected the system materials and thicknesses. As an example, we simulate a 2mm pitch acrylic lens array (n_d=1.49), 1mm thick F2 glass waveguide (n_d=1.62) and NuSil LS-2233 fluoropolymer cladding (n_d=1.33). The lens array pitch and focal length were designed to form 75µm spots for coupling into the waveguide. The optical efficiency is plotted in Figure 4 for concentrator lengths up to 1000mm. This length corresponds to 500x geometric concentration at each exit aperture, since light exits the slab from two, 1mm edges. We incrementally add loss mechanisms to depict the impact of material absorption, imperfect mirror reflectivity, and a single layer MgF_2 antireflection coating. 300x flux concentration occurs using a 740mm concentrator. The system achieves 81% optical efficiency when including all losses. For comparison, one 457mm acrylic Fresnel lens achieved only 62x flux concentration with 81% optical efficiency when considering surface reflections, material absorption and geometrical losses[17]. Changing system materials and thicknesses can lead to other flux concentrations and footprints which may be suitable for different small and large scale CPV applications.

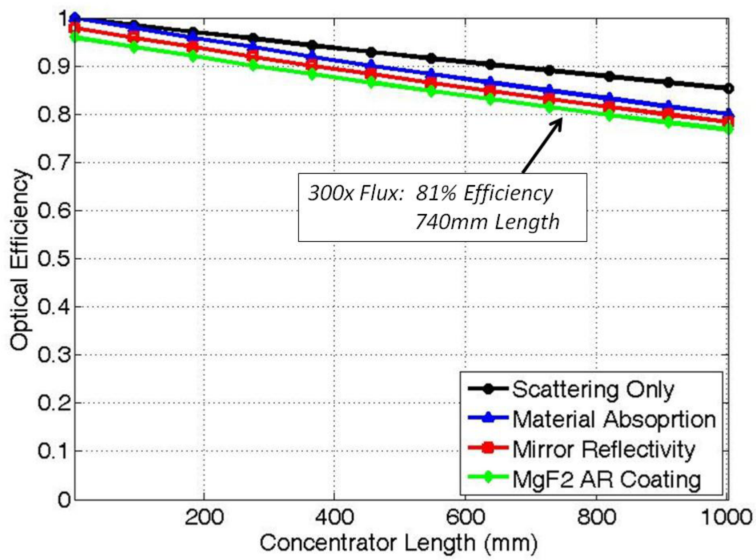

Figure 4: Analysis of a 2mm diameter lens array and 1mm slab waveguide symmetrically coupling light to both edges. Systems up to 1000mm (500x geometric concentration) are plotted with curves depicting loss sources.

4. ALIGNMENT AND FABRICATION

The micro-optic concentrator is able to guide light long distances with high efficiency only because the coupling points occupy a small fraction of the waveguide surface. Each of the potentially thousands of injection points must be accurately aligned to the focus of each lens element. For example, a 1m x 0.5m concentrator sheet with 75µm coupling facets requires <37µm lateral alignment tolerance and <0.01° (0.2mrad) rotational accuracy. These levels of precision are exceptionally difficult and expensive to achieve over large areas, and defeat the initial justification for CPV.

Our approach to assembly avoids active alignment by imposing proper positioning of the lens focus and couplers during the fabrication process. Through self-alignment, the coupling structure is molded onto the backside of the slab with SU-8 photoresist and crosslinked using light at the lens focus. SU-8 is a common, photocurable polymer well suited for micro-optical replication because of its mechanical robustness, chemical resistance and operational temperatures above 200°C once crosslinked[18]. It also exhibits favorable optical characteristics including a refractive index of 1.60 to closely match that of F2 (n_d=1.62) glass, and excellent light transmittance for high power applications (>92%)[19].

SU-8 is formulated with gamma butyrolactone to maintain a liquid state for spin coating. The solvent must be removed before molding to prevent void formation during solvent evaporation. Standard processing for a single layer of SU-8 includes softbaking to remove the solvent, however, baking causes the resist to solidify at ambient temperatures. Raising the resist temperature above the glass transition temperature (T_g) of 50°C returns it to a pliable state which can be molded[20]. Minor polymer shrinkage (<0.5%) has been observed using vacuum molding. No impact on UV crosslinking has been observed using this process[21].

Prism fabrication is depicted in Figure 5. A single layer of SU-8 is spun onto the guiding slab for molding. Standard softbaking times are extended 20% to ensure almost all of the solvent is removed prior to coming in contact with the mold. A flexible prism master is placed in contact with the resist along with a small 1kg weight. The slab, resist and prism master are baked above T_g while under vacuum to remove any trapped air. The assembly is removed from the vacuum chamber and allowed to cool prior to separation from the mold.

The localized coupling features are formed by exposing UV light through the lens array. Making the light source mimic the angular extent of the sun produces coupling regions which match the spot size occurring from solar illumination. We constructed a UV light source from a mercury-arc lamp imaged through an adjustable iris, and collimated by a parabolic mirror. The divergence angle of the illumination can be controlled by changing the diameter of the iris.

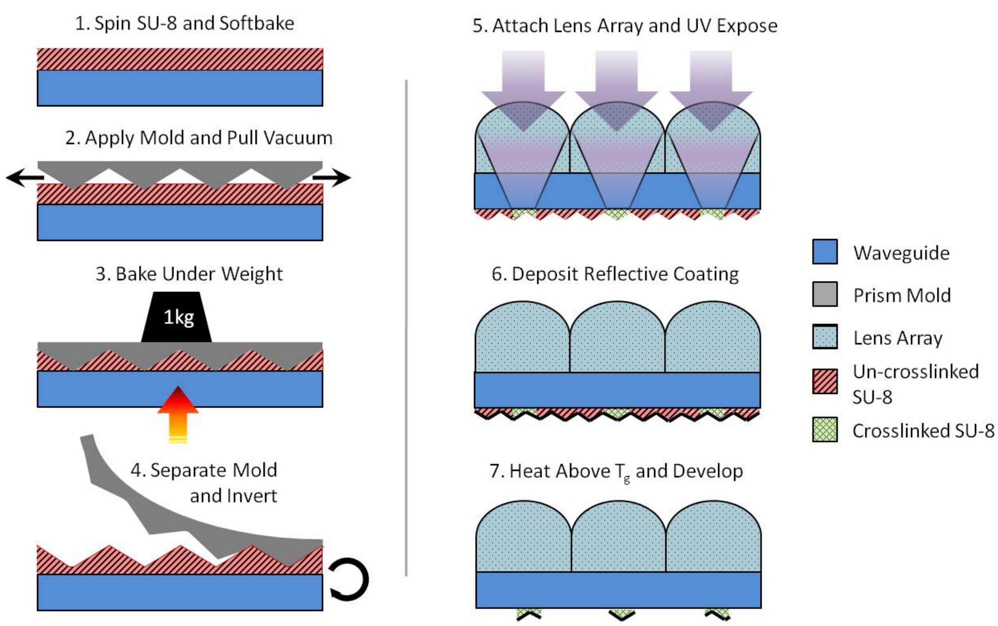

Figure 5: Process for vacuum molding prism couplers in SU-8 and the self-alignment approach for crosslinking.

A cladding material is placed on the opposite side of the guiding slab with respect to the molded resist. Liquid claddings such as fluoropolymers (NuSil LS-2233) can be spray coated or air-gap claddings may be defined using precision spacers. The lens array is placed on top of the cladding and held in place with two-part epoxy at the edges. 200mJ/cm^2 dosage of filtered UV light (365-435nm) is deposited at each lens focus to crosslink the SU-8. The resist undergoes standard post-exposure baking to complete the molding process.

Prior to development, the molded and crosslinked facets are made reflective via metallic deposition of aluminum. The un-crosslinked resist must be removed from the device along with portions of the metallic coating, leaving only polymerized, reflective facets. Standard development in SU-8's developer (propylene glycol monomethyl ether acetate, PGMEA) is unable to penetrate the continuous aluminum coating covering the uncured resist. Prior to immersion in PGMEA, the sample is heated above T_g which softens the underlying polymer, creating cracks in the metal surface. The system is then developed in PGMEA in conjunction with ultrasonics to aid in lift-off. The waveguide surface is rinsed with IPA and dried with compressed nitrogen.

5. RESULTS AND DISCUSSION

The 120° prism master used for molding has a 50µm period and 14.5µm depth embossed on flexible acrylic (WaveFront Technology Inc.). SU-8 10 (MicroChem Corp.) is spun onto a 1mm thick F2 glass slab at 2500 RPM to yield a 20µm layer for molding. The resist is baked for 2 min at 65°C, ramped to 95°C, and baked for 6 additional minutes. The prism mold is set into the resist and placed in a vacuum oven at 95°C for 45 min.

We selected a 2.3mm pitch, F/1.1 hexagonal lens array (Fresnel Technologies Inc, Part #300) as the upward facing aperture of the concentrator. For initial experimental testing, the lens array is not permanently attached to the slab and will be aligned after fabrication using micrometers to measure alignment tolerances. After UV exposure and post-exposure baking (5 min at 95°C), a 300nm aluminum coating is applied using DC sputtering, covering both polymerized and un-crosslinked resist. The sample is heated to 70°C on a hotplate to soften the uncured regions and developed for 2 min in PGMEA with ultrasonics.

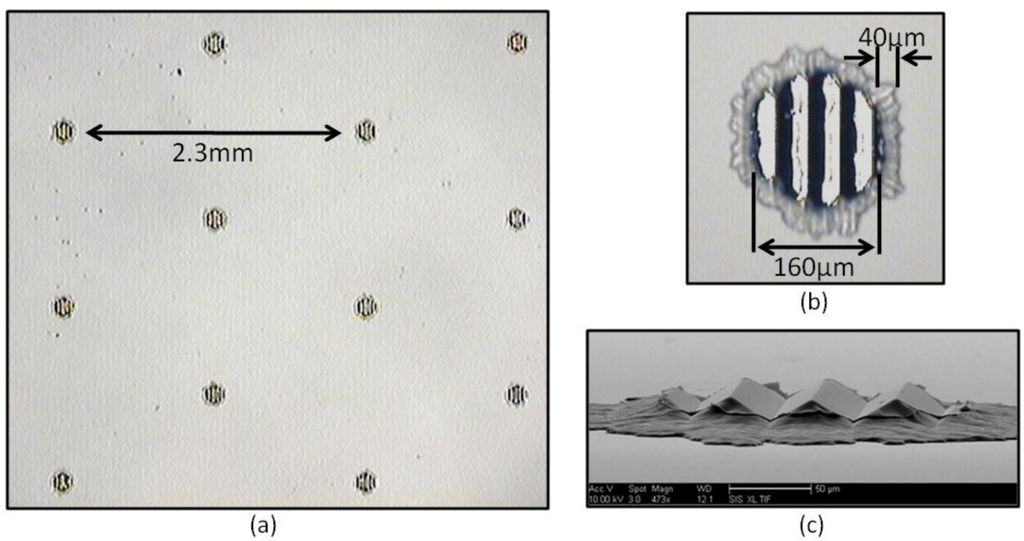

Figure 6: Coupling prisms are formed in SU-8 at each focus of a hexagonal lens array using the self-alignment technique (a,b). SEM of the coupler (c).

This specific lens array is capable of crosslinking SU-8 into 160µm diameter spots. Each lens aperture focuses incident light by 170x which sets the upper limit for potential flux concentrations. Spherical aberration stemming from the very low F/# optics constrains the performance of the current lens array. Additionally, a 40µm annulus of partially-cured resist surrounds each molded prism. This excess region lacks the metallic coating and will contribute to decoupling losses within the waveguide. We are investigating adjustments to the processing parameters to minimize or eliminate this boundary region for more efficient guiding. 40µm or smaller spots are possible by switching to F/2 lenses. Decreased coupler area enables the slab concentrator to theoretically achieve >500x concentrations in flux, though the practical optimum depends on the desired length, thickness and material specifications of the system.

We realigned the lens array to the slab waveguide after fabrication to demonstrate light coupling. Lateral and rotational tolerances are very tight even with relatively small, 50mm x 75mm concentrator prototypes. We use a collimated white light source for alignment and to demonstrate waveguide coupling. With the slab aligned at the lens focus, light is seen emitting symmetrically from two opposing slab edges. The concentrated output appears uniform in intensity due to divergence occurring after each lens focus. We transported the setup outside and oriented it towards the sun to verify light coupling. We are currently performing a full characterization to determine the overall optical efficiency and quantify points of loss.

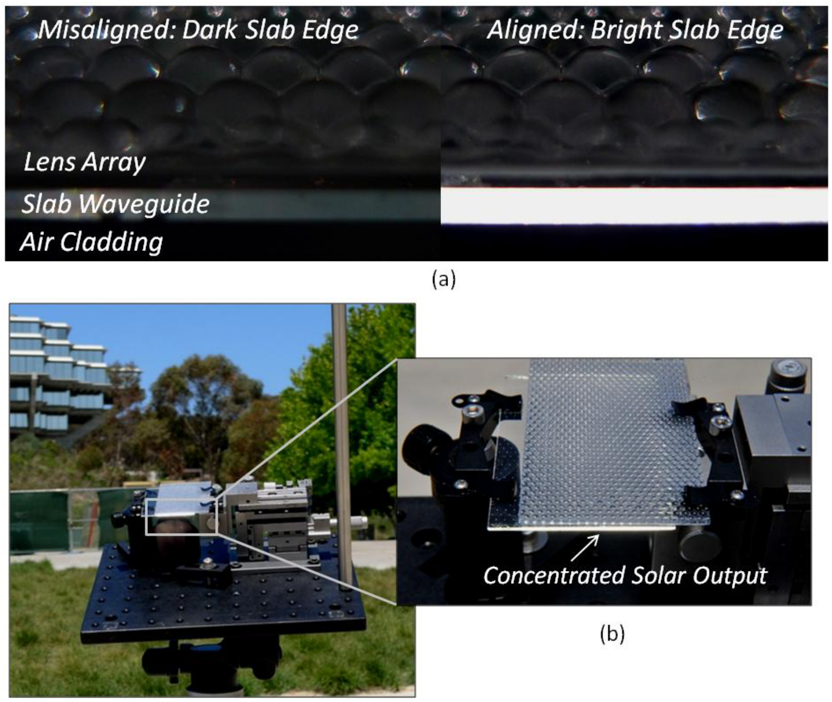

Figure 7: Accurate alignment between the light source and concentrator is necessary for strong coupling (a). The prototype concentrator displays intense output when illuminated by the sun (b).

Alignment of the assembled concentrator towards direct insolation imposes another tolerance constraint common to all CPV systems. In the case of the micro-optic slab concentrator, solar alignment is governed by the coupling area covering the backside of the waveguide. Using the self-alignment technique, the spot size produced by each lens can be adjusted by changing the characteristics of UV light source. High efficiency systems utilize small faceted spots fabricated from light matching the divergence angle of the sun. Minimum spot size requires exact alignment to the sun since any small tilt causes the lens focus to partially or completely miss the waveguide coupler. Solar alignment constraints can be relaxed by creating larger spots during fabrication at the expense of optical efficiency. Tailoring the spatial extent and divergence of the UV illumination source can create slab concentrators with increased angular acceptance, yielding another parameter in the overall system design.

The 120° prism design symmetrically couples radiation into the slab, guiding light towards two opposing edges. To collect the concentrated light, one simply places PV cells at each output edge. However, a reflective coating can be applied to one of the edges to direct all radiation towards one side of the guiding slab. This single-sided configuration can still be very efficient despite the increased path length because of low losses within the waveguide. Additionally, using one PV cell doubles the geometric concentration ratio, allowing systems to become physically shorter while still providing identical levels of flux. Furthermore, two, counter-propagating single-sided concentrators can be integrated, allowing light from each system to travel towards a common central region and emit into one PV cell. Output coupler designs are currently being investigated to combine multiple micro-optic systems for both high flux concentrations and high optical efficiency.

Facet molding and self-alignment techniques can be modified to fabricate very large area solar concentrators using continuous roll-to-roll manufacturing. Roll processing is already capable of accurately fabricating micro-optics such as diffraction gratings, lens arrays, holographic diffusers and prismatic films[22,23]. Rigid glass components used in the micro-optic concentrator can be substituted for flexible polymers to conform to drum rollers. Sol-gel materials replace SU-8 and can be molded directly versus under vacuum. Lastly, a one-dimensional UV line source can illuminate the photo-sensitive molding agent through a traveling lens array. The ability to produce large, alignment-free solar concentrators in a continuous manner offers enormous cost savings, which complement the original justification for CPV.

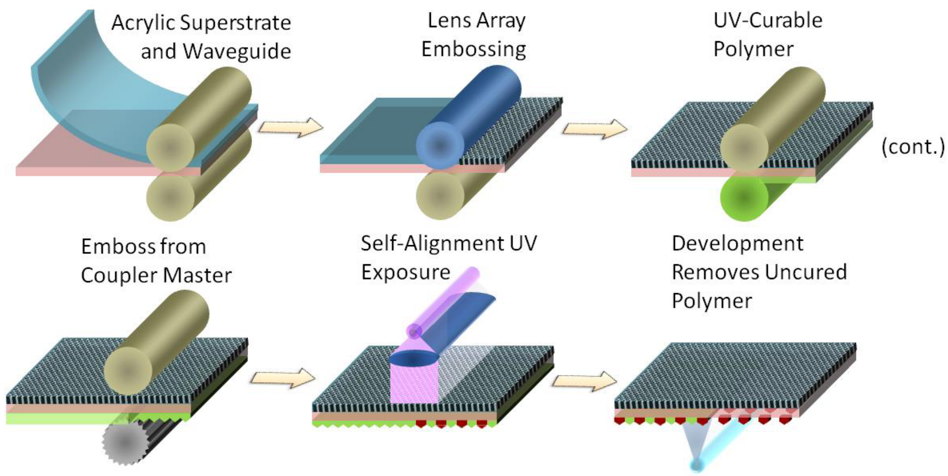

Figure 8: The slab concentrator can be fabricated using continuous roll-to-roll manufacture by switching to flexible polymers for the lens array and guiding slab.

6. CONCLUSION AND FUTURE DIRECTIONS

Today's high efficiency solar cells reach record conversion efficiencies with high flux concentrations. Despite significant advances in solar cell design and fabrication, conventional high-flux concentrators rely on imaging mirrors and lenses that impose alignment and assembly difficulties. In contrast, the micro-optic slab concentrator integrates multiple, focusing apertures with a common, multimode waveguide to direct solar energy to a single PV cell. Using the hybrid, imaging/nonimaging approach, the system becomes essentially planar while opening a new design space for CPV. Focal length, waveguide thickness and materials selection lead to a variety of potential designs suitable for small and large-scale applications. We outline design tradeoffs, points of loss, as well as simulate an example system achieving 300x flux concentration with 81% optical efficiency.

The self-alignment fabrication process uses UV-curable polymers to permanently attach coupling features at each lens focus during the molding process. Furthermore, the exposure procedure can solar relax alignment by creating couplers tailored in size to improve angular acceptance. All fabrication steps are compatible with high-volume roll-to-roll manufacture considering modifications to the optical materials. Prototype concentrators have been fabricated and aligned to the sun to demonstrate light coupling and guiding within the device.

The micro-optic slab is the first of many unconventional concentrator designs based on new fabrication and molding technologies. Several other embodiments explore input and output coupling structures, as well as arrayed configurations cascading multiple concentrator systems. Flexibility within the design and the unique tradeoffs associated with the micro-optic concentrator may lead to new optical systems with advantages over simple imaging concentrators used for CPV.

7. ACKNOWLEDEMENTS

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