Multiband Solar Concentrator using Transmissive Dichroic Beamsplitting

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ABSTRACT

Significant efficiency increases in photovoltaic power conversion are due to improved absorption over the broad spectrum of the sun. Semiconductors have an efficiency peak at a specific wavelength associated with the material band gap. The current trend towards high-efficiency photovoltaics involves multi-junction cells where several semiconductors are grown on top of one another creating a layered device with a broad spectral response. Fabrication is a difficult and expensive process that results in small area solar cells. An alternative approach uses dielectric mirrors to optically separate the incident light by reflecting one spectral band while transmitting another.

Spectral splitting is simulated within a 10x non-imaging concentrator. The optical system may be concatenated into large arrays and incorporates two separated ray paths exiting at a common plane. Optimized photovoltaic cells can be interleaved on a single circuit board, improving packaging and thermal management compared to orthogonal arrangements. The entire concentrator can be molded from glass or acrylic and requires a dichroic coating as the only reflector. Average collection efficiencies above 84% are realized within 40°x16° angular acceptance.

Keywords: solar concentrator, multi-junction photovoltaics, solar beamsplitting

1. INTRODUCTION

The need for clean, renewable energy has placed enormous attention on solar power to provide the world's energy, despite currently supplying only 0.1% of generated electricity[1]. Two approaches of power generation aim to utilize either the sun's thermal energy or photon energies to excite the photoelectric effect in semiconductor materials. Photovoltaics (PV) can provide point-of-use power eliminating large scale distribution problems and expenses.

Photovoltaic cells are commonly connected into large area, rigid solar panels used to cover upward-facing rooftops. These systems require large volumes of high-purity mono- or polycrystalline silicon and provide power conversion efficiencies well below 20%. The high material cost and low output levels elevate the cost per Watt to over $5 which is currently four to five times higher than grid-based power generation[1].

Tandem and multi-junction PV cells are constructed by layering semiconductors with different absorption characteristics to convert a larger portion of the incident solar spectrum. These devices can achieve efficiencies above 40%, however are small in physical area and cost orders of magnitude more than simple silicon cells[2]. Multi-junction solar cells hope become cost effective by using concentrating optics to capture large areas of illumination and increase the flux onto small areas.

The geometric concentration ratio is defined as the incident illumination area divided by the area of the absorber. Solar concentrators are classified into three regimes: high concentration (>100x), medium concentration (>10x) and low concentration (<10x)[3]. The highest efficiency solar cells reach their peak performance under high concentration, but require strict alignment to the sun accuracy and intense cooling arrangements. Low concentration optical geometries have significant benefits since cell performance improves under increased flux[4], less semiconductor material lowers cost and solar tracking is not necessary.

A significant portion of cost for multi-junction cells comes from the difficult fabrication involving the layered growth of several materials with different lattice constants. Strain and interface defects reduce the yield and overall performance of the cell[5]. Solar splitting can also be achieved using dichroic mirrors which appear transparent for certain wavelengths and reflective at others. Designing dichroics into the already required concentrator incorporates various single-junction PV cells of differing materials instead of complicated, multi-junction cells. The proposed optic has the unique ability of using two dichroic reflections to provide 10x concentration onto interleaved PV cells placed on a common circuit board. The structure is cascaded into an array aiding in packaging and thermal management.

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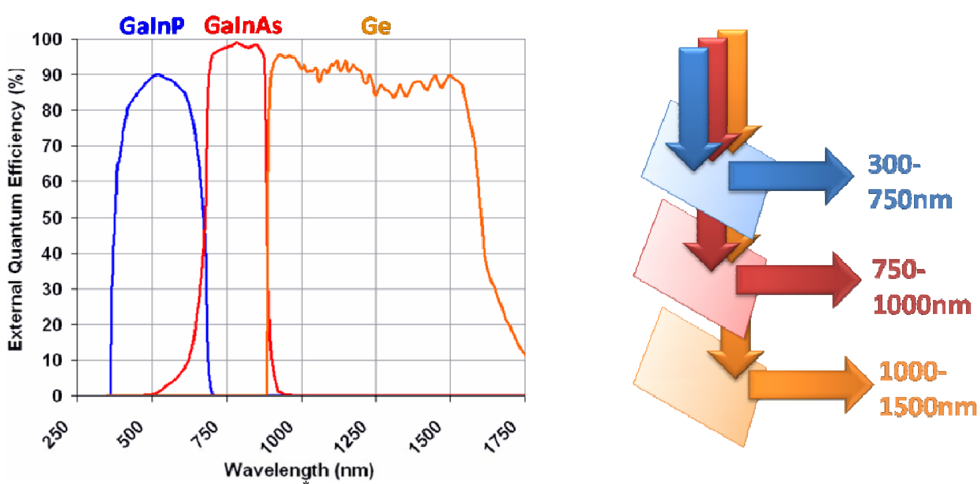
2. SPECTRAL SPLITTING

The sun is a 5760K black body radiator depositing an average of 1372 W/m2 on the earth's surface[6]. The atmosphere causes specific ultraviolet and infrared spectral nulls due to absorption and scattering from water vapor, ozone, CO_2, clouds and dust. 97.5% of the resulting spectrum exists between 380nm and 2130nm[6]. The PV material should maximize its response to this very broadband illumination. Unfortunately, the photovoltaic effect requires specific photon energies above the material band gap to generate a photocurrent. Photons greater than the band gap contain too much energy and lead to excess heat from phonons while low energy photons cannot generate electron-hole pairs. This makes PV materials truly efficient at only one specific wavelength.

The solar spectrum has an irradiance peak at 885nm, corresponding to an ideal 1.4eV material band gap[4]. Silicon is the most widely-used PV material, though has a band gap of 1.12eV shifting its absorption further towards lower energy infrared photons. III-V semiconductor compounds such as gallium arsenide (GaAs) with 1.42eV band gaps are better suited for single-junction solar cells, but provide only modest efficiency gains over silicon and add significant material costs[4].

Since the incident illumination spans 0.5-3eV, several semiconductor materials can be used in tandem to effectively convert a large portion of the incident illumination. This is the motivation for multi-junction solar cells which layer different band gap semiconductors to form a composite, high-efficiency PV cell. Double-junction, or tandem devices have demonstrated efficiencies over 35%[7] while triple-junction cells hold the current record of 40.7%[8]. Multi-junction cells are very expensive compared to crystalline silicon due to the complicated growth necessary for lattice matching, buffer layers and terminal connection. The devices are typically small in area and are used in space applications where collection area is limited and conversion efficiency is paramount.

Spectral splitting is an alternative approach using dichroics to separate sunlight bands instead of tunneling seen in multi-junction cells. Filters formed using thin-film dielectrics can be designed to transmit a specific spectral band while reflecting another. Hot mirrors are commercial examples passing visible light while reflecting infrared. Optically splitting incident sunlight allows the use of different, single-junction devices, eliminating fabrication concerns associated with lattice matching and tunnel junctions.



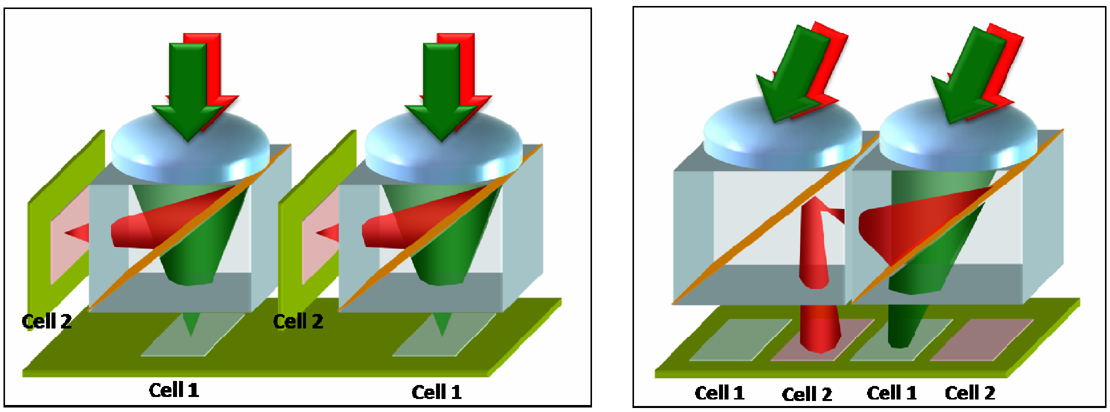
(a)* (b)

Figure 1: Multi-junction PV cells grow several different semiconductors on a common substrate material to respond to the solar spectrum (a)*. Dichroic mirrors can be used to spectrally split and direct sunlight onto monolithic PV cells (b).
*Spectrolab C1MJ_CDO-100. http://www.spectrolab.com/prd/terres/cell-main.htm

The optical geometry and design of a two band, solar splitting concentrator comprises the main area of focus. Creating more than two distinct ray paths within a common optic leads to unnecessary concentrator length and complexity, requiring multiple dichroic mirrors. Optimized single-junction or multi-junction PV cells can be placed at the exit aperture of the device to maximize solar absorption.

The simplest form of spectral splitting uses a lens to collect incoming sunlight and a dichroic beamsplitter prior to the focused spot. The dichroic divides the light into orthogonal spots, each incident on their respective PV cell[9]. Practical packaging problems exist due to the vertical orientation of the second cell. Thermal management concerns arise from the undesirable cell arrangement since concentrated photovoltaics require a heat sink to maintain efficient, long-term operation. Lastly, the overall geometry has a poor fill-factor since the orthogonal cell occupies potential upward-facing area with its positioning and heat sink.

Our proposed solution considers spectral splitting from an array of repeated lens/dichroic systems, using two mirror reflections to orient multiband light onto a single plane. Light is reflected orthogonally as with the cube beamsplitter, however the divided light is incident on a second dichroic existing within the adjacent focusing system. Upon second illumination, the light is reflected again, now propagating parallel, but laterally shifted, to the light passed by the dichroic. This enables both PV cells to be interleaved on a common circuit board, simplifying packaging and thermal management by using a single heat sink for all cells. Maximizing the area behind each lens suggests off-axis input illumination which can be accomplished by tilting the system with respect to normal illumination from the sun. Designing decentered lenses or placing a prism structure above the input can also generate an off-axis focus. These considerations will be discussed further in the following optical design section.



(a) (b)

Figure 2: Single-reflection spectral splitting places the second PV cell orthogonal to the first making packaging and thermal management difficult (a). The adjacent dichroic reorients the separated band to the same plane as the transmitted band (b).

3. OPTICAL DESIGN

The dichroic mirror is integrated into a 10x non-imaging concentrator. Our target specifications call for >80% optical efficiency from 40° acceptance East to West and 16° from North to South. The wide entrance angles allow the system to perform efficiently without active alignment during the peak hours of sunlight. The design points are well-suited to use a compound parabolic concentrator (CPC). A CPC is a modification to the cone concentrator and consists of parabolic sidewalls tilted to the extreme entrance angle, reflecting indent rays towards the exit aperture with a single bounce. The optical path length within the CPC differs based on ray positioning within the entrance pupil, leading to non-imaging concentration.

The CPC tends to be excessive in length, especially as the concentration ratio surpasses 5x. The fundamental method for overcoming physical size is to incorporate refractive elements to converge the angle of extreme rays. This involves placing a lens at the entrance as well as filling the CPC with a dielectric material. The curvature of the lens can be chosen such that the parabolic shape of the CPC regresses to a straight line creating planar sidewalls[3]. These improvements simplify the fabrication and allow the walls to reflect by total internal reflection (TIR).

Effective use of the area behind the lens/CPC is essential when attempting to place two PV cells next to one another. Normal illumination forms a focus directly behind the lens, leaving little continuous area for the second PV cell to reside. Off-axis illumination laterally shifts the focus creating space for both cells behind the lens. Tilting the incident sunlight is executed by tilting the entire lens system with respect to the sun or placing a prism array at the entrance pupil. Both scenarios have drawbacks of dispersion and off-axis lens aberrations. Creating decentered lens elements also causes shadowing effects as the sun arcs across the sky. Since the system is not forming an image of the sun, chromatic and off-axis aberrations have minimal impact on low concentration systems.

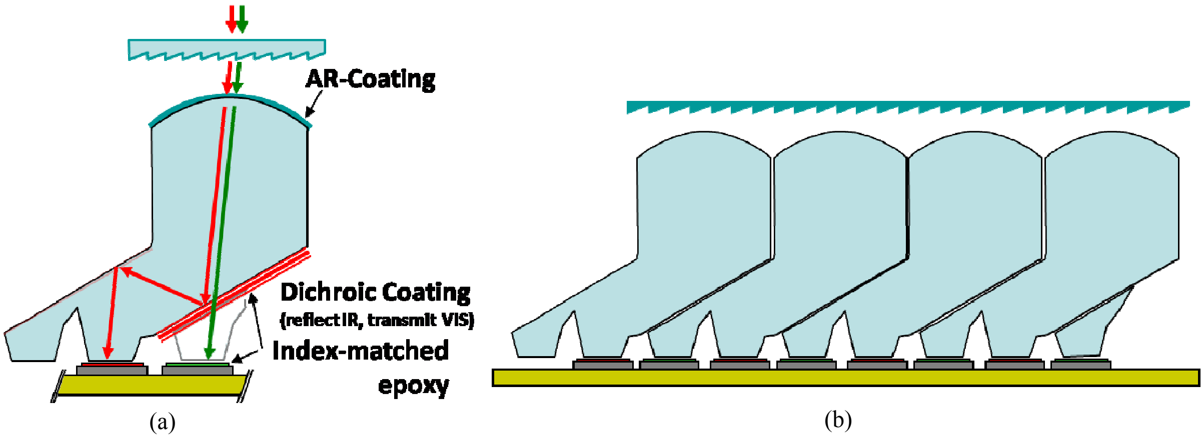


Figure 3: The double-reflection multiband concentrator exists as a single, molded optical element containing all required optical surfaces (a). Each lens/dichroic system connects with adjacent elements to form an entire array with all PV cells interleaved on a common circuit board (b).

Spectral splitting uses two dichroic reflections for one path and none for the other creating a significant difference between the optical path lengths. The refractive lens is designed to focus at a location in between these differing tracks. Transmitted rays reach the exit aperture prior to coming to a focus while the reflection path occurs just after focus. Optical power is placed on the dichroic mirror to help maintain a confined ray bundle throughout the reflection path.

The dichroic mirror is placed within the CPC to spectrally split the incident illumination. The reflector shape is formed from a set of Zernike polynomials. These circularly symmetric functions create unique curvatures allowing a single reflector design to perform well under the two illumination scenarios. Off-axis illumination places the bulk of the incoming rays on the bottom two-thirds of the reflector leaving freedom in the top portion. The specific design of the reflector is key in maintaining high optical efficiency over large acceptance angles. The dichroic mirror is formed using a circular aperture, yet only a central region is actually used within the CPC sidewalls.

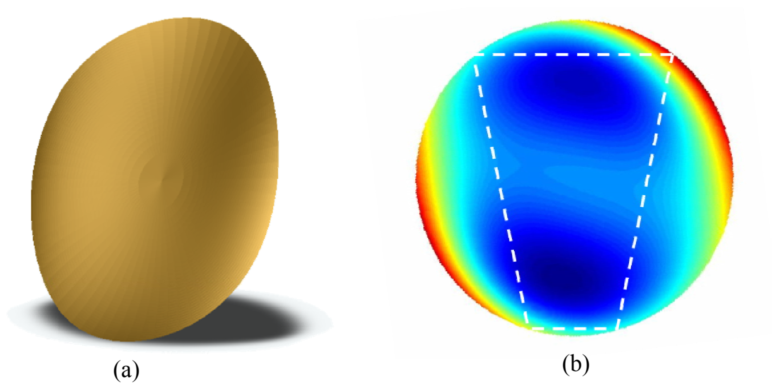
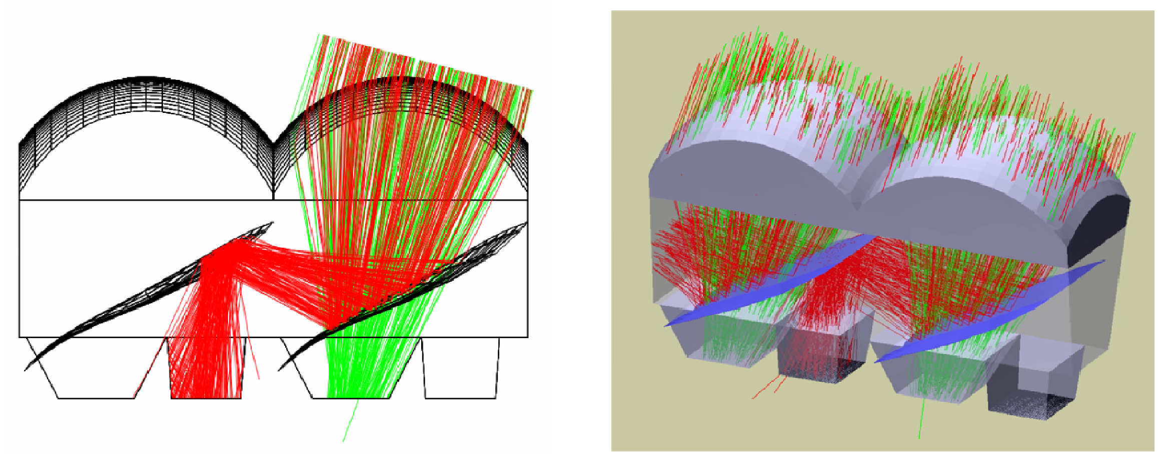


Figure 4: Circularly symmetric Zernike polynomials shape the dichroic reflector (a). Only the highlighted central region of the shape is seen by incoming rays (b).

PV cells made from semiconductor materials have refractive indexes above 3.5. The high index difference requires multi-layer antireflection coatings that only perform well over a specified angle range. Additional tapered sidewalls are designed around each exit aperture to TIR diverging rays and maintain 10x concentration. The angular extent of the exiting rays is limited to <±45° to maximize optical coupling into the PV cell. All rays incident on the sidewalls undergo total internal reflections preventing expensive and imperfect metallic reflectors.



(a) (b)

Figure 5: 2D optical ray trace (a) of the multiband dichroic concentrator (does not include all input angles). 3D optical ray trace shwoing placement of reflective sidewalls (b).

4. PERFORMANCE

The sun subtends a 0.5° full angle and changes its elevation in the sky throughout the year. A stationary collector must accept 71° full angle to collect direct sunlight for 7 hours per day[6]. This statistic can be misleading in that the most intense sunlight occurs from 10:00am to 2:00pm while the morning and evening sun provide less solar insolation because of increased atmospheric absorption. The multiband concentrator is designed to collect these peak sunlight hours without requiring two-axis solar tracking.

Sunlight is efficiently collected over 40°x16° illumination cone. The incident rays are divided into two propagation directions referred to as the transmission and reflection paths. The transmission path sees concentration from the lens and CPC sidewalls and passes through the dichroic reflector to the exit aperture. The reflection path undergoes two reflections from the primary and neighboring dichroics with additional TIR at the tapered sidewalls around the PV cell. Optical power is placed on the reflector to constrain ray divergence within the reflection path.

The overall system was designed and simulated using Zemax Non-Sequentials. The presented results are for a 10x concentrator with a 5x5mm entrance pupil and 6.5mm physical depth; however, all dimensions can be scaled to any arbitrary size. The aspect ratio of the PV cell placed at the exit aperture of the transmission path is 1.12:1 and 1.5:1 for the reflection geometry. Incident illumination enters at 14.8° off axis. Shallower entrance angles are realized by extending the optical track; however, increased thicknesses adversely affects efficiency due to material absorption.

Collection efficiency maps for both paths are shown in Figure 6 with the on-axis origin referring to the source tilted at the designed off-axis angle. The transmission path provides 87% average collection efficiency through the 40° x 16° angular acceptance while the reflection path yields 84% average from the same input range. The transmission path has better overall performance characteristics allowing concentration at angles beyond 44°x24° with >40% optical efficiency. The reflection path experiences sharper roll-offs at extended angles due to the more complicated optical track. Light which is not collected typically leaks from the sidewalls when the critical angle for TIR is not satisfied.

These results do not consider surface reflections or losses incurred from material absorption. One simulated example is constructed from UV-transparent acrylic (n=1.491) and yields average optical efficiencies of 82% and 76% for the transmission and reflection paths respectively over the specified acceptance angles. This includes a first-surface anti-reflection coating and material absorption characteristics for 365-1014nm wavelengths. The reflection path shows increased loss due to the absorption from the extended path length. Higher refractive index materials such as F2 glass (n=1.62) increase the range of TIR angles and can lead to increased angular acceptance with minor adjustments to the lens and dichroic mirror curvatures. However, high-index materials tend to have poor optical transmission at shorter wavelengths and increased cost compared to moldable acrylic.

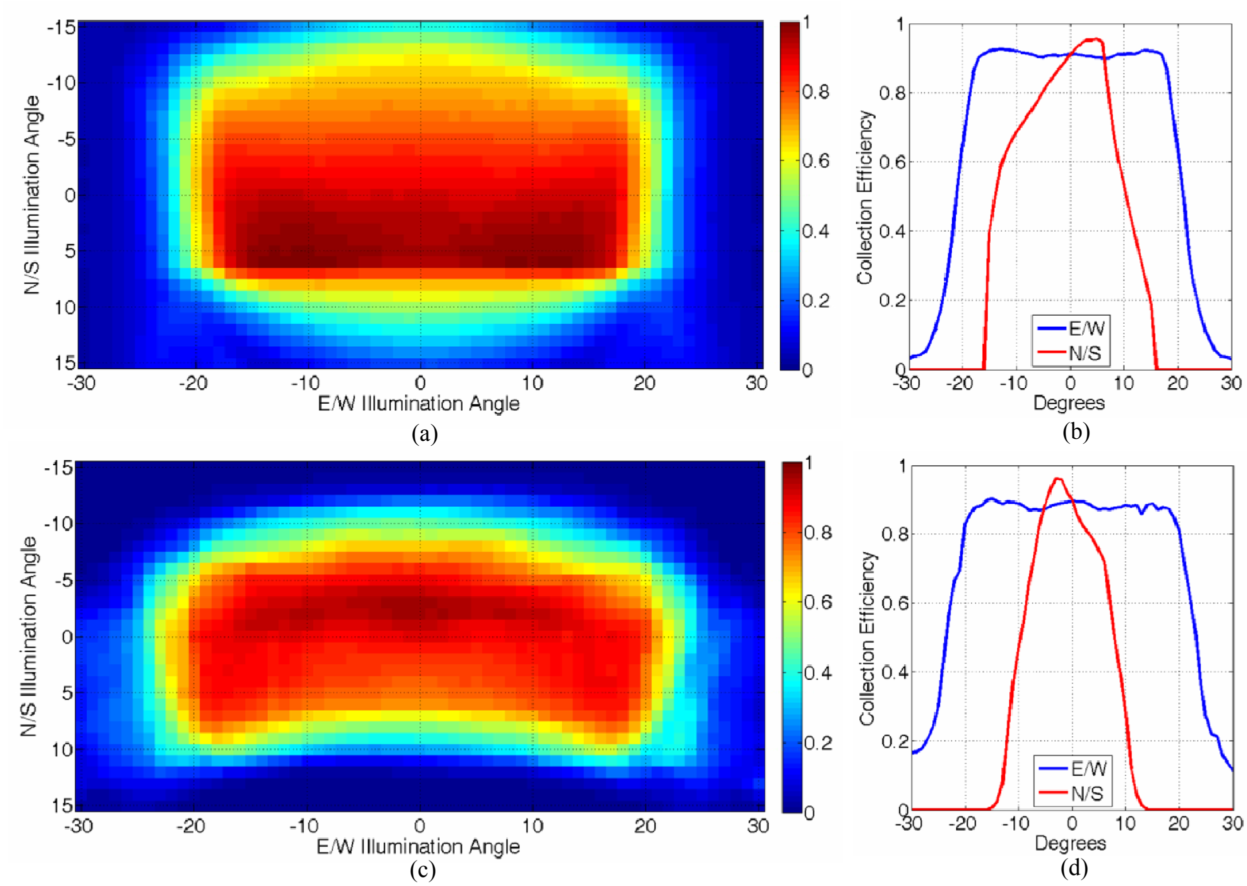


Figure 6: Collection efficiency maps for the transmission (a) and reflection paths (c). >80% collection efficiency occurs within the 40°x16° acceptance range. Cross sections through the origin are plotted for each path in (b) and (d).

The concentrator is oriented so the daily arc of the sun occurs orthogonal to the interleaved PV cells. The non-imaging sidewalls enable the wide-angle light to remain within the concentrator body. Seasonal elevation changes are much more difficult to collect since only the trapezoidal reflectors around the exit pupil confine the light in the North-South direction. Seasonal adjustments or single-axis tracking will help provide efficient solar collection year round.

Non-uniform illumination hinders PV cell performance and is of particular concern in concentrated photovoltaics. Localized, high-intensity hot spots can lead to cell shunting and cracking which lead to cell failure[5]. The proposed concentrator system incorporates non-imaging reflections and defocus, eliminating regions of gradient flux.

5. ASSEMBLY

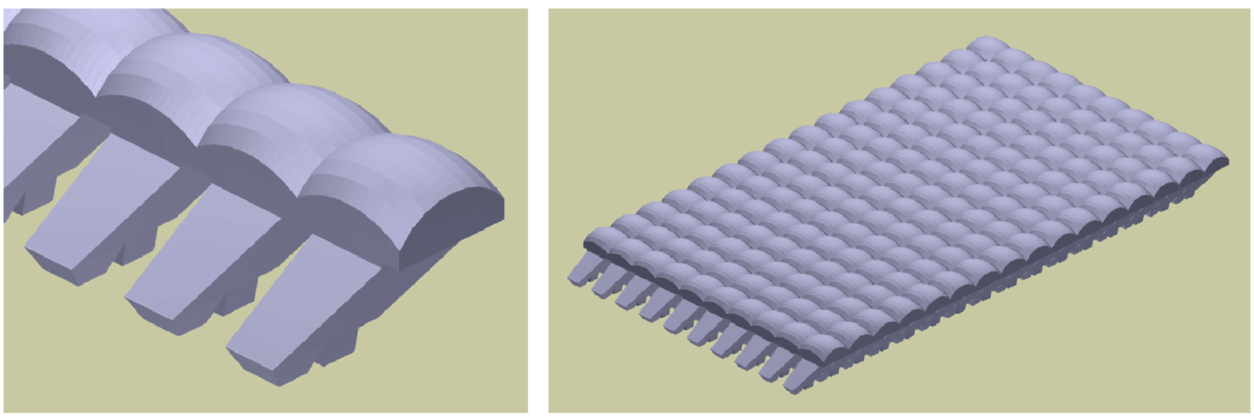
The complete system is designed for concatenation into large arrays. Each subassembly may be injection molded from UV-transparent acrylic for low-cost volume manufacture. One-dimensional arrays formed in long rows are fitted together along the dichroic mirror to create a large two-dimensional concentrator. Two PV cells are interleaved on a common circuit board and attached directly to the output apertures of the concentrator array. Refractive index-matching epoxy is applied along the dichroic and exit apertures to create a single, bonded optic to the interleaved PV cells.

Two different PV cells coexist on a single output plane to collect each of the wavelength bands. Cells with an optimum band gap constructed from a single material can be placed at the exit aperture to avoid complicated and expensive fabrication associated with multi-junction solar cells. The superior performance of the transmission path should incorporate ~1.6eV material to collect higher energy photons from visible wavelengths while using a lower band gap semiconductor at the exit of the reflection path for near infrared. The two cells alternate on a common circuit board which may contain hundreds of individual modules when large concentrator arrays are constructed. Cells of a common material may be connected in series, as in flat-plate solar modules, to increase the output voltage.

Because Zernike Polynomials are all circularly symmetric, the complicated shape of the dichroic reflector may be fabricated as a master using diamond turning. The refractive lens incorporates aspheric terms and may also be diamond machined. All other concentrator surfaces are planar and uncoated. A full manufacturing tolerance analysis is yet to be completed as this has been primarily an optical design study. Angular intersections, especially those close to the exit apertures, may need to be evaluated in order to create a moldable structure.

Multilayer dielectric thin-films are deposited on the Zernike reflector. A custom dichroic design is required to address the wavelength transition characteristics and wide-angle response. Filters containing upwards of 100 dielectric depositions can be designed to meet these specifications[10], however simpler coatings may be preferable for cost considerations. The upward-facing refractive lens also requires a dielectric coating to minimize first-surface reflection and should consider acceptance angles and illumination wavelengths.

Off-axis illumination is important to enable both PV cells to reside behind a common lens. A micro-prism above the refractive lens can tilt the incoming sunlight, however requires its own anti-reflection coatings on both the entrance and exit facets. Orienting the entire concentrator at the desired angle provides the simplest solution, however the upward-facing area is reduced by the cosine of the tilt. If this approach is pursued, the tilt angle should be minimized to provide greater collection area.



(a) (b)

Figure 7: 3D rendering of a single multiband concentrator molded as a 1-D subassembly (a). The specific curvature of the dichroic reflector is omitted and represented as planar. The subassembly may be connected into large 2D arrays to share the adjacent dichroic (b).

6. Conclusion

Approaches to improve solar energy collection and efficiency require extended spectral absorption. Multi-junction PV cells have demonstrated high efficiencies using III-V semiconductors with different band gaps layered on top of one another. These devices are hundreds of times more expensive than crystalline silicon modules due costly fabrication using deposition processes. Spectral splitting from thin-film dielectric mirrors offers an optical approach to multiband solar power.

The double-reflection geometry of the multiband solar concentrator improves packaging and thermal dissipation by placing both spectral bands on a common plane. Two optimized PV cells are interleaved onto the same circuit board with the concentrator bonded to the surface. The optical subassembly is designed for concatenation into a large array by sharing the neighboring dichroic mirror.

A refractive first surface is combined with non-imaging sidewalls to accept light from a 40°x16° illumination cone. Zernike polynomials shape the dichroic reflector to place optical power at specific locations for primary and secondary illumination. The system provides 87% and 84% average collection efficiency for the transmission and reflection paths respectively.

The dichroic concentrator can be fabricated through injection molding of inexpensive plastics or polymers. Each subassembly has a thin-film dielectric mirror and is mated to adjacent concentrators with index-matched epoxy to form the concentrator array. The optical properties of acrylic were used to optimize dimensions for the specified acceptance angles. Higher index materials provide increased design freedom regarding the illumination cone and TIR angles at the sidewall interfaces. Dichroic concentrators incorporating the double-reflection design may enable multiband solar power using monolithic PV cells instead of costly multi-junction modules.

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