Design and Simulation of Micro- size Optical Solar Concentrator

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Abstract

A simulation for the design of micro-size optical concentrator is presented. The software of zemax is implemented to design optical concentrator consists of an array of micro-lenses that focuses sun-light on a glass sheet waveguide, which to be attached to a common PV cell placed at the end edges of the waveguide. Solar concentration using waveguides offers a new design approach for small-scale optics compatible with volume manufacture and assembly. Furthermore, it opens a new design space for high efficiency systems with the potential for cost reduction in both the optics and tracking mechanics.

Key Words: Solar Energy, Optical Concentrator and Micro-optics Design

تصميم ومحاكاة المكثف البصري المايكروي

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الخلاصه

تم محاكاه تصميم مكثف بصرى مايكروى . أستخدم برنامج زيماك (zemax) لتصميم المكثف البصري والذي يشتمل على مصفوفة عدسات مايكرويه تقوم بتركيز اشعه الشمس لتسقط على دليل الموجه (صفيحه زجاجيه)، والتي تلتصق بخليه شمسيه مشتركه واقعه على الحافات الخارجيه لدليل الموجه. استخدام دليل الموجه في مكثفات الاشعه الشمسية يعطى طريقه جديده لتصاميم البصريات ذات الحجوم الصغيرة بتوافق مع التصنيع الحجمى والتجميع. أضافه لذلك، فهى تفتح المجال لتصاميم جديده لمنظومات عاليه الكفاءه وامكانيه تقليل الكلفه الخاصه بالاجزاء البصريه وميكانيك التتبع.

الكلمات المفتاحية : الطاقه الشمسيه، مركزات الاشعه البصريه وتصاميم البصريات الميكرويه .

Introduction

Several design concepts appear in literature considering concentrator photovoltaic (CPV) systems (Benitez and Minano (2004), Cassarly (1995)), that use large area optical components to collect direct sunlight and transfer the energy onto small, high efficiency photovoltaic (PV) cells. High concentration systems incorporate mechanical tracking to maintain alignment with the sun. System designs should include cell alignment tolerances, angular acceptance, flux uniformity (Winston Gordon (2005)), and for CPV systems to be cost effective the complete cost of optics, assembly and mechanical tracking must not exceed the savings gained from using small area PV cells.

Recently a new approach appears that implement a planar concentration systems (Winston and Gordon (2005), Karp, *et al.*, (2010)) which replace the multiple nominating optics and their associated PV cells (Winston *et al.*, (2004) , Gordan (2007), Feuermann and Gordon (2001)) with a single multimode waveguide connected to a shared PV cell. Sunlight collected by each aperture of the arrayed lenses is coupled into a common slab waveguide using localized injection features. Rays that exceed the critical angle defined by Snell's law propagate via total internal reflection (TIR), within the waveguide to the exit aperture, typically at the edge of the slab. TIR is a complete reflection with negligible spectral or polarization dependent losses which enables long propagation lifetimes (Karp, *et al.*, (2010)). Planar wave-guides also provide excellent beam homogenization when coupling diverging illumination into a high number of supported modes (Balanis (1989)). The waveguide transports sunlight collected over the entire input aperture to a single PV cell placed at the waveguide edge. PV alignment becomes trivial since comparatively large cell are cemented to the waveguide edges. Fewer cells reduce connection complexity and allow one heat sink to manage the entire system output.

A simulated design of a planar compact optical concentrator, using micro lens array, suitable coupling prisms and optical waveguide, is handled in this work. The software of zemax (version (2005)) is employed to achieve this simulation, that help getting acquainted with the various design parameters of these rather recent types of optical systems.

Materials and Methods

Principles of Basic Design

Optics for solar concentration typically consists of lenses or mirrors focusing onto secondary elements that eliminate intensity variations at the PV cell. A common approach places dozens of lenses into a shared tracking platform, each focusing onto independent secondary optics and solar cells. The large quantity of components increases mounting, alignment, and electrical connection costs. However, the proposed concentrator design replaces discrete optics with a 2D lens array and a common slab waveguide. Sunlight collected by the array focuses onto localized prisms or mirrors positioned to reflect light at angles that exceed the critical angle for total internal reflection (TIR) and, therefore, couple into the waveguide. Coupled light is homogenized as it propagates towards the exit aperture at the slab edge(s), see Fig.1. The PV cell and heat sink mount directly to the output edge. The coupling prisms are fabricated using simple lithography techniques that make the design compatible with large-scale manufacturing, including roll processing (Karp, *et al.*, (2010)).

The amount of focusing provided by solar concentrators is defined by the geometric-concentration ratio, which describes the ratio of input to output apertures. Optical efficiency is the fraction of light reaching the PV cell. It accounts for surface reflections, material absorption, and losses associated with propagation within the waveguide. The micro-optic concentrator uses 120°-apex prisms placed at each focus that symmetrically reflect and couple sunlight into the waveguide (Karp, *et al.*, (2010)).Fig.2 shows reflective facets tilt light to satisfy TIR and couplers are localized at each lens focus (<1% surface area).Specular reflections provide clearly defined reflection angles at all wavelengths. Reflections from TIR-based prisms or mirror-coated facets placed on the waveguide surface tilt the entire cone of focused sunlight into the waveguide numerical aperture NA.

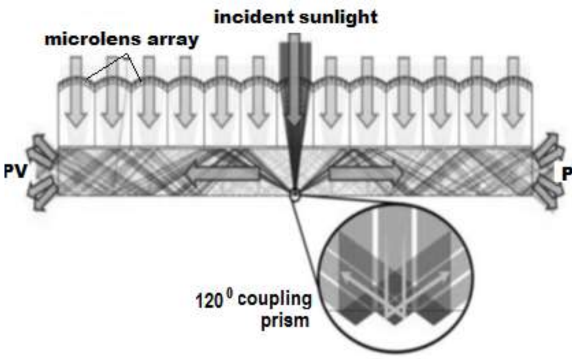

Fig. (1) Micro-optic Concentrators Combine Lens Array and Slab Waveguide. At Each Focus, a 120° Mirrored Prisms Couple Light into the Waveguide (inset) PV: Photovoltaic (Karp, *et al.*, (2010)).

Marginal rays at the lens focus require the largest tilt to TIR at the core/cladding interface.

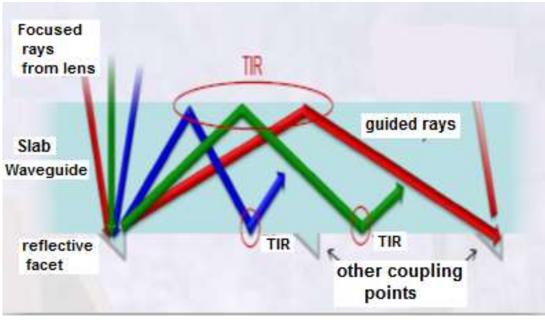

Fig.(2) Waveguide Coupling Facets [Karp, *et al.*, (2010)].

Increasing the NA of the waveguide allows steeper ray angles to guide, however, these rays experience more decoupling and absorption losses due to increased optical path length. Assuming a planar fold mirror, the angle of the steepest marginal ray after reflection limits the lens F/# (F-number) for a given waveguide NA (Karp, *et al.*, (. (2009)).

Design and Simulation of Optical System

The simulated concentrator is about utilizing lens array profiles for light coupling into supported waveguide modes.

Specifying a self-alignment as a fabrication method imposes constraints on the coupler profile. Also, the molding process requires a repeatable, faceted structure since features are not actively placed on the waveguide. A 45° fold mirrors recurring in a triangular or saw tooth manner reflect normal incidence rays at 90°, which immediately strike the adjacent facet, and decouple upon second reflection.

Conversely, as with the presented design 120° apex symmetric prisms have the unique ability to tilt normally incidence light to 60° with respect to the slab surface. This angle is exactly parallel

to the adjacent facet and the ray completely avoids shadowing and decoupling effects (Karp, *et al*,2010.)
The optical efficiency µ is the fraction of light which reaches the output aperture and equals to:

$\mu = S_{flux} / S_{geom}$ . . …….. ……….(1)

where S_{flux} represent the flux concentration, that indicate the concentration level present at the PV cell. And S_{geom} is the geometric concentration ratio, which is equal to:

S_{geom} = waveguide length/waveguide thickness …………………………..(2)

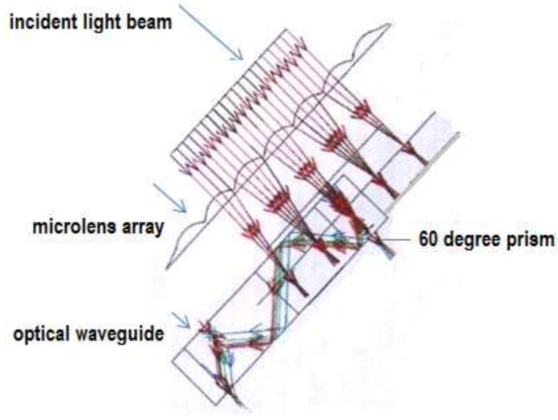

Fig .3 - (A) Results of the Simulation of Optical System Design , Fig(3-B) Show the Multimode Waveguide Part Only.

Results and Discussion

The design of the compact-optic slab concentrator is simulated using the sequential and non-sequential ray tracing of zemax. The lens array simulated is a 1 mm pitch Bk7 glass material, a 1 mm thick Bk7 glass waveguide. The lens array pitch and focal length were designed to form 80 µm spots for coupling into the waveguide. The field extends in 0.26º. Figs.3 (A-B) show the designed optical system with different views.

In the presented design the 60º prism couples radiation into the slab, guiding light only toward one edge of the slab.. In case of implementing a 120º prism, the light would be guided towards two opposite edges. To collect the concentrated light, one simply places PV cells at each output edge. A reflector might be put at one side edge to reflect the light toward the other opposite edge. Therefore, single PV cell could be used.

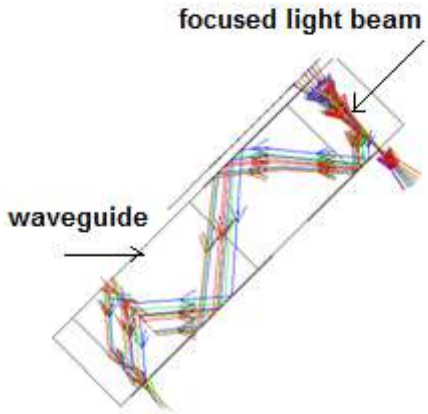

Fig. 3- (B) Continued, Focused light Beam Trapped Inside Multimode waveguide.

Conclusions

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 (lens array) and non-imaging (waveguide) approach, the system becomes essentially planar while opening new design space for CPV.

In this work, the first steps in designing this type of an optical systems are handled. The software of zemax is employed in the design to get the simulation of the optical system presented in Fig.3. A future work is needed to optimize the parameters of the presented design, as focal length, waveguide thickness and material selection that would lead to a variety of potential designs suitable for specific solar energy applications, with demanded optical efficiency.

The importance of the presented work is that it opens the door wide to implement a rather sophisticated optical design software to establish and study a complicated optical systems.

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