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Radial Coupling Method for Orthogonal Concentration within Planar Micro-Optic Solar Collectors

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Abstract: We present an orthogonal concentration method to further confine sunlight within planar solar collectors. Radial-oriented couplers create micro-optic solar concentrators with >375x geometric concentration and a 20% reduction in guiding loss.

OCIS codes: (220.1770) Concentrators; (230.7400) Waveguides, slab

1. Introduction

Concentrator photovoltaic (CPV) systems incorporate large-aperture optical components to collect direct solar energy onto high-efficiency photovoltaic (PV) cells. High concentration systems typically consist of a large primary optic for light collection and a secondary optical element for flux homogenization [1]. Recently, we demonstrated a solar micro-optic concentrator using a two-dimensional lens array and a multimode slab waveguide [2]. Light collected by each element of the lens array is coupled into a common slab waveguide using specular reflections from an associate area of prism facets fabricated at each lens focus. Sunlight propagates within the slab by total internal reflection (TIR) and is guided to a PV cell placed at the waveguide edge(s), as seen in Fig. 1. This configuration transforms the concentrator geometry into a thin, planar system that is potentially compatible with low-cost roll-to-roll manufacture.

The geometric concentration ratio of the micro-optic solar concentrator is defined by the waveguide length divided by the output aperture, typically the waveguide thickness. The optical efficiency is the fraction of light which reaches the output. The concentration in flux is the efficiency multiplied by the geometric concentration ratio. Light entering the system experiences surface reflection losses, material absorption and waveguide decoupling associated with propagation within the slab. Guided light which strikes a subsequent coupling facet may be reflected out of the system as loss. Decoupling loss scales with the quantity of TIR interactions at the back surface of the waveguide, meaning very long or thin slabs result in greater loss.

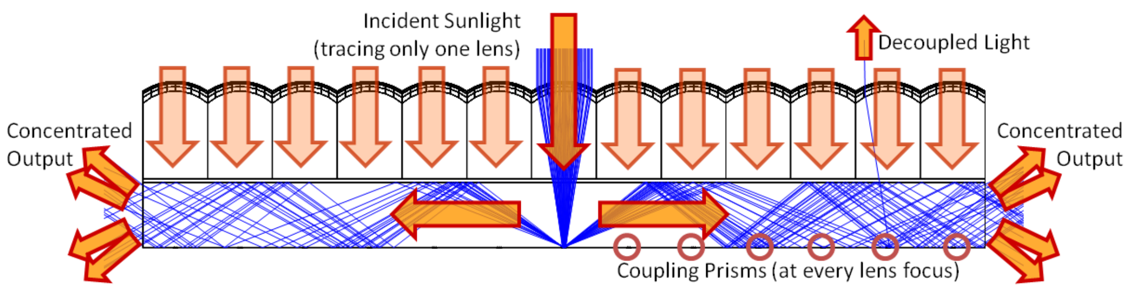

Fig.1. The micro-optic concentrator collects sunlight from a two-dimensional lens array and confines the light within a planar waveguide using reflective facets fabricated at each lens focus. The concentration ratio is the waveguide length divided by two times the thickness.

For the coupling feature, we chose a reflective, 120°-apex symmetric prism structure. These facets tilt normal-incidence rays by 60° and avoid adjacent shadowing effects experienced by many other periodic structures. 120° prisms couple light equally in opposing directions which creates output apertures along two waveguide edges. During assembly, prisms can be molded within a photopolymer and utilize the lens focus to permanently create couplers at desired locations, thereby eliminating active alignment between the lens array and waveguide. With optimized F/2.45 lenses, a simulated design reached 81.9% optical efficiency at 300x geometric concentration with a 1mm thick, 600mm long waveguide and no dependence on waveguide width [3]. This design can be extended to achieve higher concentrations, but longer waveguides result in lower overall efficiency. Here, we present an alternative approach to increasing concentration by orienting the coupling prisms along arms of a circle which point light towards a region along one waveguide edge. Radial coupling incorporates both a concave mirror and tilted waveguide sidewalls to form a V-trough concentrator. Low concentration within the orthogonal dimension is a means to achieve high-flux systems without sacrificing optical efficiency or changing the physical size.

2. Radial Waveguide Coupling

Sunlight incident on the micro-optic concentrator experiences an initial, fixed loss associated with surface reflectivity, followed by material absorption and decoupling losses as it propagates within the slab waveguide. Absorption and decoupling are both functions of path length taken to the PV cell and increase when using long waveguides needed for high concentrations. Radial waveguide coupling provides concentration in the direction orthogonal to propagation by orienting each prism facet along an arm extending from a circle whose center sits just beyond the end of the waveguide. This approach couples light towards a common region along the waveguide width, increasing concentration without extending the path length. The factor of orthogonal concentration is the ratio of original slab width W_1 to the reduced aperture width W_2, as seen in Fig. 2. By increasing the width on the opposing side, the overall input area remains identical to a rectangle of length L and width W_1.

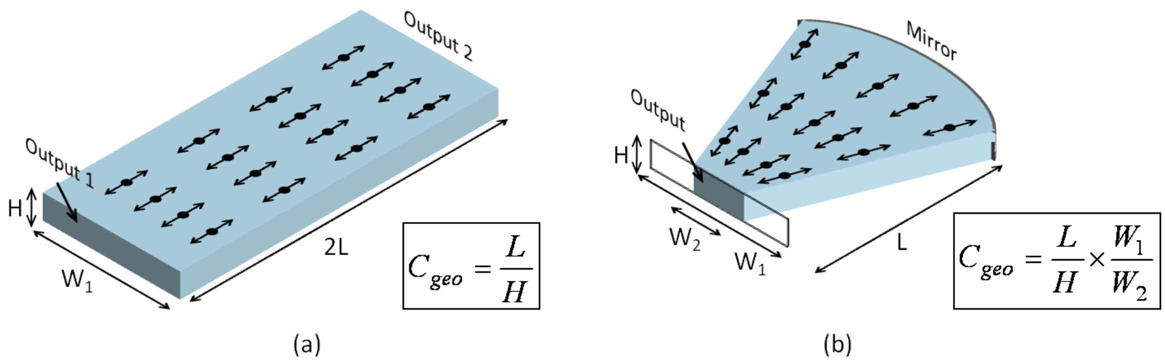

Fig.2. A micro-optic concentrator must extend the optical path length to increase geometric concentration (a). Radial concentration orients the coupling facets towards a common exit aperture to increase concentration without altering path length (b).

The waveguide in the radial concentrator is a circular sector whose length is less than the radius used to define the coupler orientation. The result is a trapezoidal area with tapered sidewalls leading towards the output along the shortest edge. 120° coupling prisms reflect focused light symmetrically into the waveguide, causing only half of the energy to be directed towards the output. A curved mirror with a radius equal to the radius used to define the coupler angle is placed on the opposing waveguide edge. The mirror sits normal in the incident rays, acting as a retroreflector and directing light back towards the PV cell. A variation of this overall structure yields a circular disk with all the light propagating towards a central aperture.

Thus far, we have only considered rays propagating along the arms of a circle, however, the sunlight is first focused by the lens array and then diverges after coupling. The lens F/# defines the divergence angle and limits the amount of orthogonal concentration which can be achieved. The sidewalls of the waveguide can be thought of as V-trough concentrator, used to confine diverging illumination along the slab width. Orthogonal concentration C_{2D} is defined by Eq. 1 and the trough angle φ is calculated using Eq. 2 where δ is the divergence half-angle [4].

$$C_{2D} = \frac{Full\ \ Width}{Reduced\ \ Width} = \frac{W_1}{W_2} \tag{1}$$

$$C_{2D} = 1/\sin(\delta + \varphi) \tag{2}$$

V-troughs typically provide less than 3x concentration and lose efficiency as the trough angle increases. In this geometry, the V-trough performs better since the coupler orientation directs most of the light within the trough angle and does not rely on multiple sidewall reflections to reach the PV cell. Other in-plane designs such as compound parabolic concentrators may be used for 2D concentration, but tend to limit the fill-factor when creating collector arrays. Radial coupler orientation is the primary component of orthogonal concentration as it generally points all coupled light towards a common output area to minimize optical path length, regardless of the existence or profile of waveguide sidewalls.

3. 2D Concentration Performance

To investigate the performance of radial concentration, we carried out non-sequential ray-tracing using ZEMAX EE optical design software. The system used a BK7 glass lens array with 2.38mm diameter, F/2.45 lenses focused onto 78µm coupling regions. Light was focused into a 1mm thick, F2 glass waveguide surrounded by air. Simulations included the weighted AM1.5 spectrum from 0.4 to 1.6µm at ±0.26° field angles. We used 98% silver coatings on all reflective surfaces as well as single layer MgF_2 antireflection coatings on the lens array surface. In Fig. 3a, we replaced the curved edge reflector with a Fresnel mirror to demonstrate how multiple systems cascade to form a linear array.

The concentrator used a 100mm long waveguide which provided 100x geometric concentration prior to any orientation of the coupling facets. Orthogonal concentration reduced the output aperture on one side while the waveguide length and input area remained constant. We compared the optical efficiency to an unbounded aperture micro-optic concentrator whose length increased to reach higher geometric concentrations instead of radial coupling. The results are plotted in Fig. 3b.

At 100x, the extended system was slightly more efficient since it used two output apertures instead of an imperfect mirror along one edge. However, the radial concentrator outperformed the extended system from 150x to 525x, with up to 20.2% less overall loss. Radial concentration reached 82.2% optical efficiency at 375x while the extended but unbounded system achieved 77.7%. The efficiency of the unbounded system decreased linearly since loss is directly proportional to the waveguide length. Radial concentration exhibited less waveguide loss due to the constant path length, however, at concentrations above 5x, rays break TIR at the V-trough interface and lead to additional loss. The efficiency advantage gained from orthogonal concentration is further increased for longer waveguides and higher initial concentrations.

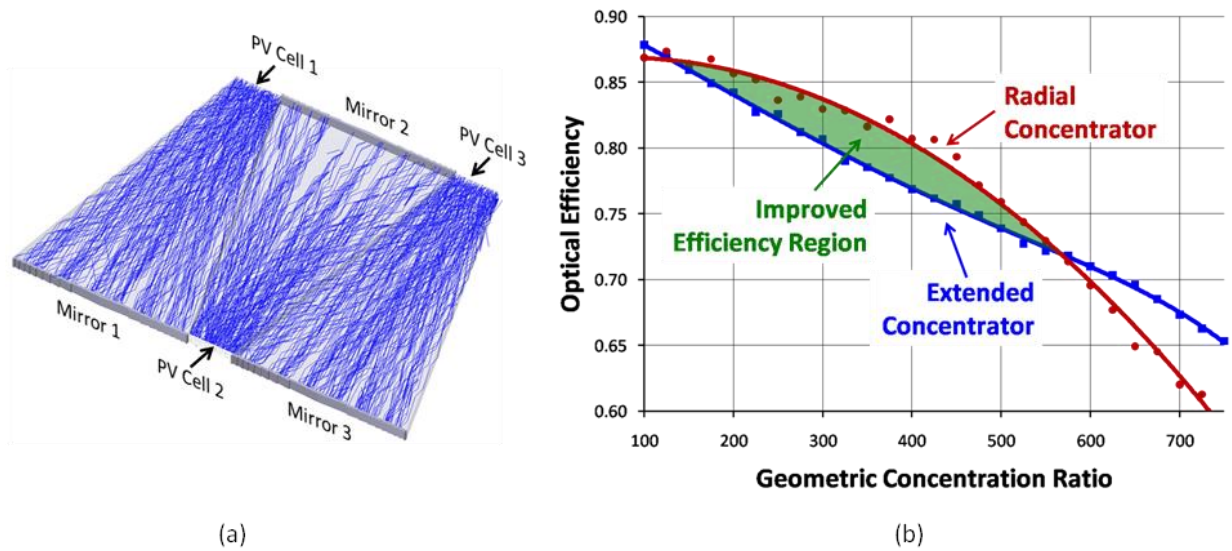

Fig. 3. Raytrace of radial concentrators cascaded in a linear array with independent PV cells (a). Lens arrays have been omitted to highlight ray paths within the waveguides. Optical efficiencies for both the radial and extended systems are plotted against geometric concentration ratio (b).

3. Conclusion

Orienting the coupling facets in a circular pattern points focused sunlight towards a common region along one waveguide edge. This approach to orthogonal concentration increased flux and minimized losses by maintaining the same optical path to the PV cell. A V-trough concentrator within the waveguide worked in conjunction with oriented facets to provide up to 5x orthogonal concentration. Simulations demonstrated a radial concentrator with 82.2% optical efficiency at 375x, which corresponded to a 20% reduction in loss.

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