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Optimization of Coupler Inlet for Planar Solar Concentrator

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Abstract

In this study, we implemented optimization for the coupler inlets of the planar solar concentrator, which was proposed in our prior work. The planar solar concentrator had a waveguide slab to carry an array of light-collecting elements thereon. The light entering the elements is focused on the coupler inlets and guided into the slab with propagating therein through total internal reflection (TIR). Thus, all the light from the elements is guided to the ends of the slab and highly concentrated. Because the coupler inlets couple light into the slab and also decouple the light propagating in the slab in subsequent interactions, they must be optimized to balance between coupling efficiency and decoupling loss. The optimized arrangements of coupler inlets included three types here: uniform-thickness platform, stepped-thickness platform, and stepped-width platform. In the simulation, the three types have the same area of the inlet to keep the concentrator with the same tolerance of the incident angle of light. We analyzed both the optical efficiency and range of the vertical angular distribution of the light reaching the outlet end of the slab; then made a comparison for the three inlet arrangements. The simulation results demonstrate the stepped-thickness and stepped-width platforms provide higher efficiency and concentrated irradiance.

Keywords: planar concentrator, coupler, solar energy, illumination design

1. Introduction

Traditionally, the planar concentrator is equivalent to a device that divides a single large concentrated element into an array of optics (lens) coupled to a common slab waveguide. The light entering each lens is focused on localized coupling microstructures embedded on the bottom of the waveguide and reflected at predicted angles, thereby propagating in the waveguide through total internal reflection (TIR), so the light from all the lenses is guided to the ends of the waveguide [1]. The advantages of the planar concentrator include a compact volume and a light weight. Because the coupling microstructures on the waveguide surface couple light into the waveguide and also decouple the light guided in the waveguide in subsequent interactions, the decoupling loss increases with the waveguide length. To manage the decoupling loss, various designs of the waveguide and coupler geometries were proposed to reduce or eliminate interactions with the coupling microstructure [1-4]. However, these designs require an accurate alignment of the lens array and the coupling microstructure, which is adverse to assemble a large product.

Thus, we proposed a planar solar concentrator in our prior work, which had a waveguide slab to carry an array of TIR light-collecting elements thereon without requiring alignment [5]. The light entering the elements is focused on the coupler inlets and guided into the slab with propagating therein through TIR. Thus, all the light from the elements is guided to the ends of the slab and highly concentrated. Because the coupler inlets couple light into the slab and also decouple the light propagating in the slab in subsequent interactions, we further optimized them to balance between coupling efficiency and decoupling loss in this study.

2. Design concept

A coupler inlet is the junction of each TIR collector and the slab, through which the light focused by the TIR collector enters the slab below. Because the field angle of the sun itself is 0.52^{o}, the sunlight is focused onto a spot, rather than on a point; therefore, the coupler inlet must have an area enough for the focused light to pass through. Moreover, the TIR collector focuses the light within a larger spot area if tracking tolerance is considered. Thus, a coupler inlet with a

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larger area contributes to an increased coupling efficiency. However, a coupler inlet with a larger area also raises the probability of decoupling the light propagating in the slab and thus reduces the propagation efficiency. Because the total optical efficiency depends on the product of the coupling efficiency and the propagation efficiency, securing a balance between them is critical.

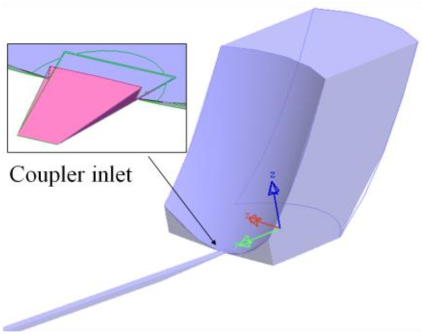

Fig. 1 A TIR collector on a slab with a slope-facet inlet

In our prior work, the tolerance of tracking was set to ±0.5° for the rotation angle of the x-axis and the z-axis (i.e. α and γ, respectively; referring to Fig. 1). The optimal area of the inlet is a trapezoid with two base widths of 0.9 mm and 0.3 mm, and a height of 1.05 mm. In this study, we optimized the arrangements of the inlets to raise the optical efficiency. The arrangements for optimization included three types: uniform-thickness platform (Case A), stepped-thickness platform (Case B), and stepped-width platform (Case C). In Case A, the slab was flat; all the inlets were lined on the same horizontal level. In Case B, the slab had a stepped thickness, and thus the location of the former inlet was higher than the later. In Case C, the slab had a stepped width, and the inlets were on the same horizontal level, but the slab was tiled at a small angle with the line of inlets. The purpose of the arrangements of Case B and C is to prevent the coupled light from leaking out of other inlets ahead. The slab of Case B was the thickest; that of Case C was widest; those of Case A and B had the same width; those of Case A and C had the same thickness. Therefore, Case A had the smallest area of the outlet end of the slab and thus the largest geometric concentration ratio; Case B had the same area as Case C. However, Case B and Case C had the higher propagation efficiency. Moreover, the inlet end of the slab in Case B and C had a slope facet to reduce the range of the vertical angular distribution of the light reaching the outlet end of the slab, which help the light be further concentrated by attaching an extra compound parabolic collector (CPC) to the outlet end. Therefore, we analyzed both the optical efficiency and range of the vertical angular distribution for the three cases under different parameters of the slab; then made a comparison to find the optimal conditions.

3. Results and Discussion

In this study, we established an optical model that had a TIR collector on a narrow slab with a slope-facet inlet. Then, we varied the angle of the slope facet (slope angle) and the thickness of the slab for conducting simulations to find the optimal conditions. Moreover, we made a comparison for the three arrangements of coupler inlets under the optimal condition. In the optical model, the TIR collector had a pitch of 10 mm, a height of 15 mm, and a width of 15 mm; the slab had a width of 1.0 mm, and a length of 60 mm; the TIR collector and slab were made of polymethyl methacrylate (PMMA). The used ray-tracing software was LightTools 8.3.

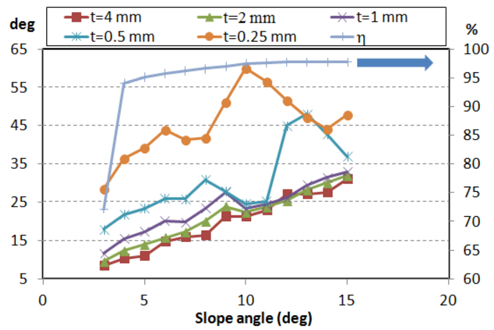

Fig. 2 Slope angles vs. ranges of vertical angular distributions and efficiency

Fig. 2 shows the effects of slope angles on both the optical efficiency and range of vertical angular distributions. The light is incident at an angle (α=0.4, γ=0) with an angular range of 0.26° (half-angle). The range of vertical angular distributions substantially decreases as the slope angle decreases, but increases as the thickness of the slab decreases. Moreover, slope angles have little effects on the efficiency, but the efficiency dramatically drops if the slope angle is below 4°. Furthermore, the efficiency is not affected by the thickness of the slab. Fig. 3 shows the effect of slope angles on the optical efficiency for the light at incident angles of (0, 0), (0.4, 0), (0.4, 0.4), and (0.8, 0). Except the incident angle (0, 0), the other incident angles have the similar trend, dramatic drop in the efficiency when the slope angle below 4°.

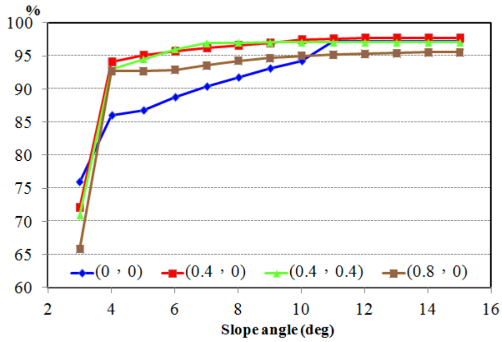

Fig. 3 Slope angels vs. optical efficiency

Finally, we assembled five TIR collectors according to the three types of arrangements for conducting simulation. Case A had a slab with a thickness and width of 1.25 mm and 1 mm, respectively; Case B had a slab with a thickness and width of 2.5 mm and 1 mm, respectively; Case C had a slab with a thickness and width of 0.5 mm and 5 mm, respectively. Case B and C had an inlet with a slope facet of 4°. The irradiance of the outlet end of Case A is 1.9 times that of Case B or C. However, the range of the vertical angular distribution in Case A was 96°; those in Case B and C were 22°, which means Case B and C can be further concentrated 3.8 times Case A by attaching an extra CPC the outlet end of the slab. Overall, Case B and C can provide the concentrated irradiance 2 times Case A at most.

4. Conclusions

In this paper, the arrangements of coupler inlets are analyzed and optimized. As compared with the uniform thickness platform, the stepped-thickness and stepped- width platforms with a slope-facet inlet end of 4° provide higher efficiency and double concentrated irradiance.

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