Field Experiment Of 800× Off-Axis XR-Köhler Concentrator Module On A Carousel Tracker

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Abstract: This paper presents the design and preliminary experimental results of a concentrator-type photovoltaic module based on a free-form off-axis 800×XR-Köhler concentrator. The off-axis XR-Köhler concentrator is one of the advanced concentrators that perform high concentration with a large acceptance angle and excellent irradiance uniformity on a solar cell. As a result of on-sun characterization of the unglazed single-cell unit test rig, the temperature-corrected DC module efficiency was 32.2% at 25 °C without an anti-reflective (AR) coating on the secondary optics, and the acceptance angle was more than ±1.0°. In addition, the non-corrected DC efficiency of an individual cell in a glazed 8-cell unit module mounted on a carousel tracking system was measured. The individual efficiency deviated in the range of 24.3–27.4%, owing to the mirror shape and alignment errors. The resultant series-connected efficiency was approximately 25% at direct normal irradiation (DNI) of 770 W/m^2.

Keywords: Concentrator photovoltaic, Nonimaging, Solar energy

INTRODUCTION

Research and development of an advanced concentrator photovoltaic (CPV) system is an important step toward realizing highly efficient solar energy utilization. The purpose of this work is to conduct the first experiment on a novel high-concentration CPV module based on the off-axis XR-Köhler concentrator developed by Hernandez et al. [1]. A mirror-based CPV can be used to achieve a larger geometrical concentration ratio (C_g) than that obtained by a Fresnel-lens-based CPV. Owing to the high cost of multijunction solar cells, a CPV is desired to have as large a C_g as possible. Generally, a high C_g, greater than 500×, tends to be required to minimize the contribution of the solar cell cost to the total system cost (the contribution of the solar cell cost decreases with the increase in C_g). The off-axis XR-Köhler concentrator is shadow-free and can achieve high optical efficiency, very small secondary glass volume, and high concentration-acceptance product (CAP) at a high C_g of 1000×.

OFF-AXIS XR-KÖHLER CONCENTRATOR DESIGN

Figure 1 shows a perspective view of the patented four-fold (four-channel) off-axis XR-Köhler concentrator designed for a concentration of 800×. In this concentrator, each channel of the primary optical element (POE) is exposed to sunlight and reflects this light to irradiate a corresponding channel on the four-fold secondary optical element (SOE). The light from these four ray bundles coming from the POE mixes inside the SOE after refracting from its surface to irradiate the solar cell. Although we selected a four-fold architecture in order to simplify the design, other numbers of folds can be selected. In this layout, the optics has a plane of symmetry. The channels of the device are designed to perform in a Köhler integrator function in which each micro-lens quadrant provides substantial uniform illumination on the solar cell and spectral integration (no kaleidoscope or prism is needed), which are critical for high-efficiency conversion in multijunction cells.

Figure 2 shows the light path through the concentrator towards the solar cell when the concentrator is illuminated with parallel rays. The figures illustrate the important features of the off-axis XR-Köhler concentrator: (a) The incoming light bundle is split into four channels to illuminate the corresponding part of the SOE. It reduces the power of each light spot inside the SOE, which lowers the risk of solarization and reduces the thermal stress on the SOE; (b) the off-axis layout allows for maximum un-occluded utilization of the aperture area because the SOE and solar cell do not cast a shadow on the POE, a fact that helps decrease the system weight as well as achieve the power output goal with the minimum entry aperture area.

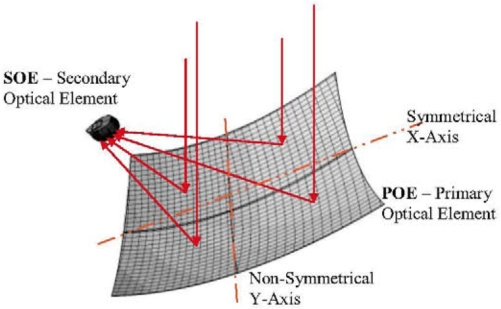


FIGURE 1. Schematic drawing of a free-form off-axis XR-Köhler concentrator module.

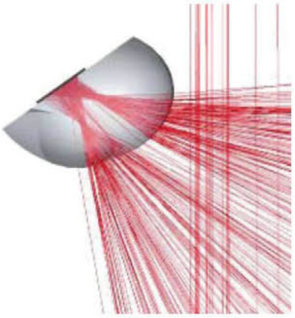
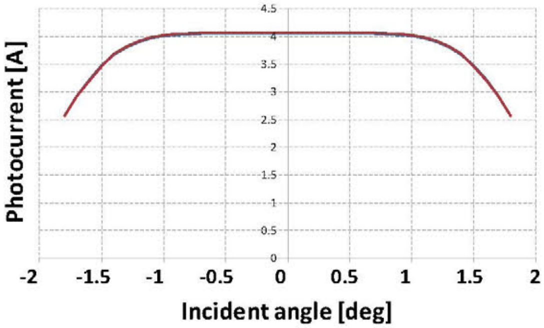


FIGURE 2. Free-form secondary optics.

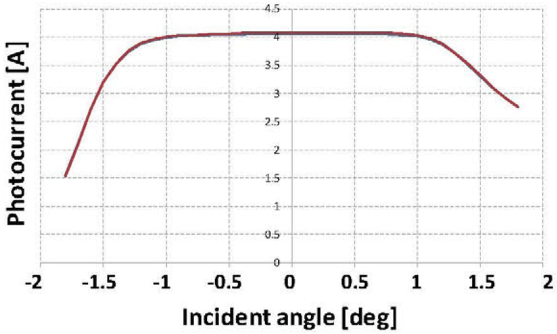
Table 1 shows the ray-tracing simulation result for the 800× off-axis XR-Köhler concentrator, which includes spectral transmissions of the mirror, glass cover without an anti-reflective (AR) coating, B270 glass secondary element without an AR coating, an equivalent quantum efficiency (EQE) of commercial triple-junction solar cells (38% nominal efficiency; cell is covered by index material), 900 W/m^2 output at direct normal irradiance (DNI), and finite sun size. Roughness of the optical elements is not considered. Optical efficiency for the top and middle cells reaches 81.5% and 82.5%, respectively. Cell current of the top and middle cells is 4.06 A and 4.07 A, respectively.

TABLE 1. Optical efficiency of 800× off-axis XR-Köhler concentrator (ray-tracing simulation result).

C_q = 800x Cell area = 49 mm^2	*Simulations results*
Light Incident power	100%
Glass cover transmission (without an AR coating)	91%
POE transmission	95%
SOE transmission (without an AR coating)	94.3%
Geometrical losses	0.0%
Optical Efficiency (%)	81.5/top cell, 82.4/middle cell
Cell currents I_{sc} (A)	4.06/top cell, 4.67/middle cell



(a) *x* direction



(b) *y* direction

FIGURE 3. Incident angle dependency of 800× off-axis XR-Köhler concentrator (ray-tracing simulation result).

Figure 3 shows the *x* (symmetrical) and *y* (non-symmetrical) sections of the photocurrent generated by the concentrator as function of the incidence angle for both top and middle cells (although they are overlapped). From the curve, we can determine the acceptance angle, defined as the incidence angle at which the concentrator collects 90% of the on-axis power. The smallest incidence angle observed is considered the acceptance angle of the concentrator. The resultant acceptance angle of 800× off-axis XR-Köhler concentrator is ±1.33°, which means *CAP* = 0.66.

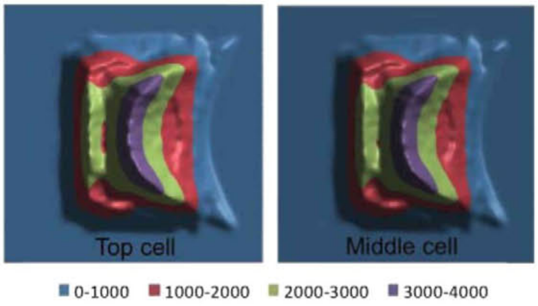


FIGURE 4. Spectral irradiance distribution on the cell of the 800× off-axis XR-Köhler concentrator (ray-tracing simulation result).

Figure 4 shows spectral irradiation distribution on the solar cell when the concentrator is perfectly facing the sun. Distribution on the top cell is not significantly different from that on the middle cell, as in the incident angle calculations.

EXPERIMENT

A single-cell unit of the designed 800× off-axis XR-Köhler CPV module was manufactured for on-sun characterization experiment. The singe unit module has been tested in Japan. The unglazed module test rig shown in Figure 5 had a temperature-corrected DC module efficiency of 32.2% at 25 ºC without an AR coating on the secondary optics. Figure 6 shows the obtained *I-V* curve. By using the same test rig, we also tested the acceptance angle and identified it to be wider than approximately ±1°. The 2.3-kW demonstration array system was built as shown in Figure 7 for a mid-term continuous-operation test. The glazed 8-cell unit module was mounted on a carousel tracker. Up to 24 modules can be mounted on the tracker (12 modules in the picture). The *I-V* curve of each individual cell unit in the first prototype module was measured and compared. Figure 8 shows instant DC efficiency of each individual cell unit at DNI to be 770 W/m^2 without temperature correction. The highest efficiency of 27.4% appears at the center of the module, while the lowest efficiency of 24.3% was at the edge of the module. The resultant series-connected module efficiency was approximately 25%. The cause of this efficiency deviation is currently under investigation.

ACKNOWLEDGMENTS

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FIGURE 5. Single-cell unit module test rig of the 800× off-axis XR-Köhler CPV module.

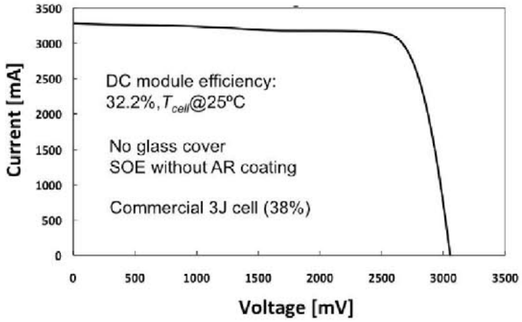

FIGURE 6. *I-V* curve of the single-cell unit module test rig on sun measurement.

FIGURE 7. Field demonstration 2.3-kW array mounted on a carousel-type tracking system.

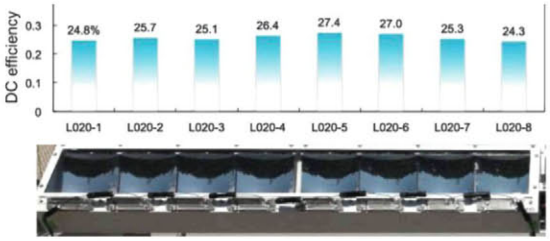

FIGURE 8. DC efficiency of individual cell units in the first prototype 8-cell unit module (without temperature correction, 770W/m^2 at DNI without an AR coating on the SOE or the glass cover).

REFERENCES

1. M. Hernandez et al., 1000× shadow-free mirror-based Köhler concentrator, *Proc. of SPIE* **V01**. 8468 84680C (2012).