HCPV MODULES WITH COMBINED LENS/GUIDE SECONDARIES

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ABSTRACT: We report on a new design of the secondary optical element. This element consists of two parts: a flat-convex lens being in optical contact with front surface of an intermediate glass sheet, and a cylindrical light guide being in contact with rear side of the glass. The output edge of the light guide is placed on the top of a solar cell with a small air gap. The cylindrical light guide serves as a distributor of light along a cell surface reducing the local concentration ratio, but keeping wider off-orientation properties of the concentrator module. The photocurrent measurements were performed using high concentration triple-junction InGaP/GaAs/Ge and one-junction AlGaAs/GaAs solar cells. That was necessary to check influence of the chromatic aberrations in the primary/secondary optical system on PV output parameters of the concentrator modules. It was found that insertion of the 3÷5 mm in length light guides leads to effective distribution of light along the cell surface, whereas shorter and longer guides produce stronger illumination in the cell center.
Keywords: Concentrator module; Secondary optics; Characterization.

1 INTRODUCTION

The secondary optical elements make softer the accuracy requirements on assembly, alignment, and tracking technology for the high-concentration photovoltaic (HCPV) modules [1-3]. For instance, the use of plane-convex lenses playing the role of the secondary elements allows widening the off-normal curve of the HCPV modules approximately in two times from 0.5 angular degree on the 0.9 level of photocurrent drop up to 1 degree [4-5]. This takes place for the cost of a decrease in concentrated light spot diameter. However, the central zone of the photosensitive cell area is illuminated by highly concentrated light, which, in turn, may have a negative effect on the cell efficiency due to increased influence of the internal ohmic losses.

We report on a new design of the secondary optical element. This element consists of two parts– a flat-convex secondary lens (SL) and a cylindrical light guide (LG). Both these elements are in an optical contact with the intermediate glass sheet playing the role of a base element for arrangement of the lenses and light guides. The cylindrical light guide serves as a distributor of light along the cell surface (light homogenizer) reducing the local concentration ratio, but keeping wider off-orientation properties of the concentrator module. This work is devoted to usage of this type secondaries in the HCPV modules based on small-aperture area primary silicone-on-glass (SoG) Fresnel lenses and triple-junction InGaP/GaAs/Ge cells [6-7]. In a module, the Fresnel lenses of 40x40 mm² in aperture area are integrated into a primary lens panel. The panel of secondaries is placed in front of solar cells. The cells with passive copper heat spreaders are placed on the outer side of the secondary panel, so that this panel is a common protective cover glass for cells. The local sun concentration ratios on the cell surface, the acceptance angle at off-normal module positioning and the I-V curve fill factor in test HCPV modules have been measured indoors with the help of a specially developed solar simulator.

2 DESIGN OF THE SECONDARY OPTICAL ELEMENTS

The aim of the investigations was to determine an optimum geometry of the optical parts in the case of a HCPV module based on a primary SoG Fresnel lens and triple-junction InGaP/GaAs/Ge cell. The Fresnel lens was 40x40 mm² in aperture area with the focal distance of 70 mm. The smooth-surface secondary lenses of 12 mm in diameter made of glass, have been glued on the front side of a glass sheet 4 mm thick used as a base for the secondary minilens panel. The solar cells were placed behind the glass sheet being, in turn, mounted on the heat sinking troughs. In the gap between the glass sheet and the cell, the cylindrical light guides were installed. They had different lengths along the optical axis: from 0 (no light guide) to 12 mm. The photosensitive cell diameter was 2.3 mm, the same, as the LG diameter. Measured parameters for three versions of the HCPV modules have been compared: without secondaries; with secondary lens; with combined SL+LG secondary element. Optical diagrams of the modules under investigation are shown in Figure 1.

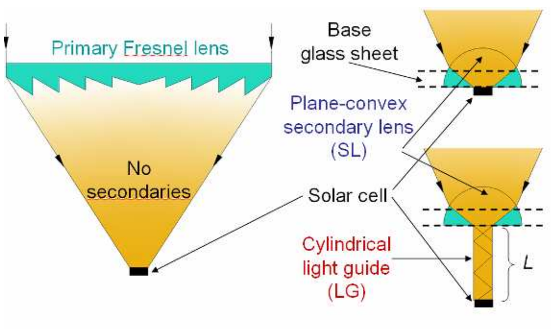

Figure 1: Optical diagrams of the concentrator PV modules under investigation:
- without secondaries, Fresnel lens is 40x40 mm^2;
- with plane-convex secondary lens;
- with lens in combination with a short light guide of 2.3 mm in diameter and *L* mm in length.

3 EXPERIMENTAL EQUIPMENT

Main parts of the measurement set-up were as follows: a xenon flash light source with a calibrated hole;

a parabolic objective mirror (aberrationless collimator, the hole was located in focal plane of the mirror); holders of the optical elements in a concentrator system supplied with independent translators. Set-up parameters ensured simulation of the sunlight: the beam divergence of 32'; 1-sun spectrum AM 1.5D; intensity of 1000W*cm-2. Off-center scanning of the cell surface with respect to the light intensity distribution was done by a computer controlled translation mechanism. The sun concentrating system as a whole could be swung in angle from normal position by a computer controlled rotation mechanism, so that off-normal curves could be recorded as well.

The photocurrent measurements were performed using high concentration triple-junction InGaP/GaAs/Ge and one-junction AlGaAs/GaAs solar cells. That was necessary to check the influence of the chromatic aberrations in the primary/secondary optical system on the PV output parameters of the concentrator modules.

The lay-out of the measurement system parts in the case of characterizing concentrator modules with combined secondary optical elements is shown in Figure 2. In the lower part of the Figure, the optical diagram of the practical secondary structure consisting of plane-convex lenses glued as a panel to the upper surface of the base glass sheet and panel of the short light guides glued to the lower surface are shown.

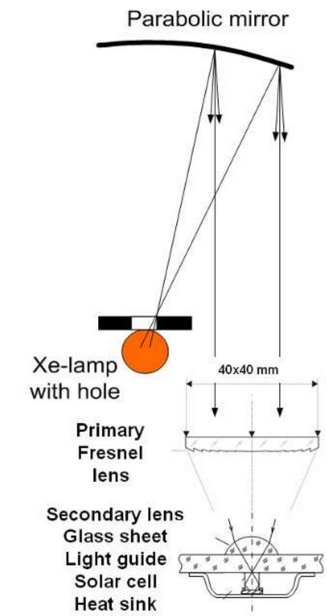

Figure 2: On the top– a lay-out of the measurement system parts in the case of characterizing concentrator modules with combined secondary optical elements. On the bottom– an optical diagram of the practical secondary structure consisting of plane-convex lenses glued as a panel to the upper surface of the base glass sheet and panel of the short light guides glued to the lower surface are shown.

4 MEASUREMENT PROCEDURE AND RESULTS

As the first step of investigations of the modules, the optimum distance between the primary lens and the secondary structure was found for each configuration of the optical elements in this structure. The maximum magnitude of the off-orientation curve width at the 0.9 level of the photocurrent drop ($\Omega_{0.9}$) measured by a solar tester was the optimization criterion. It is known that the cell efficiency may increase due to better light collection at better light focusing on the cell surface. Also, it can decrease due to too high local light concentration and, hence, the decrease in FF of the I-V curves. The results of the corresponding measurements for one of the concentrating system with LG length of 3 mm are shown in Figure 3. The optimum distance from the primary lens has been defined to be 71 mm in this case.

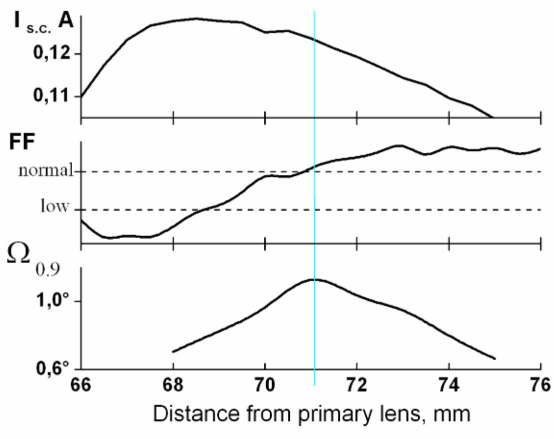

Figure 3: Results on short circuit current ($I_{s.c.}$), I-V curve fill factor (FF), and off-orientation curve width ($\Omega_{0.9}$) measurements in varying the distance between the primary lens and the secondary optical system in concentrator module with an InGaP/GaAs/Ge solar cell: LG length was 3 mm; optimum distance has been defined as 71 mm.

The local light concentration was measured by scanning the focal spots along cell diameters in several directions. To eliminate effect of the chromatic aberrations, a one-junction AlGaAs/GaAs solar cell with 0.1 mm in diameter screening hole was used for scanning. In Figure 4, illumination intensity distributions taking place at operation of the concentrator InGaP/GaAs/Ge solar cells are shown.

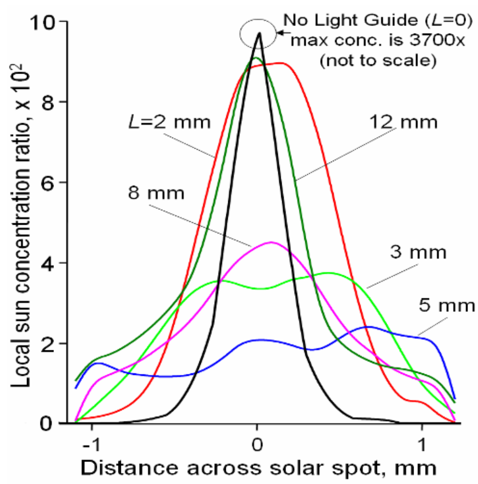

Figure 4: Illumination intensity distributions across small-in-area concentrator InGaP/GaAs/Ge solar cell recorded for the case of a combined secondary optical system: a plane-convex lens together with light guides of different lengths *L*, as indicated in the graphs.

The curves have been recorded for the case of absence of the LG, and at presence of the combined secondary optical systems with light guides of different lengths *L* (mm) (as it is indicated in the graphs). It is seen from the graphs that introduction of the LGs results in significant reduction in local intensities of the concentrated light in comparison with the case of absence of the LGs (which corresponds to the case of L=0). On the other hand, the graduate increase in LG's length makes lower local concentrations at L from 2 to 5 mm, but after this local concentration in the cell center becomes higher again at *L* value of 8 and 12 mm. This effect is due to peculiarities of light propagation through the LG of cylindrical type, when inclined beams can have a possibility to be "focused" again in the center after total internal reflections from the guide walls.

Cumulative results on short circuit current ($I_{s.c.}$), I-V curve fill factor (FF), and off-orientation curve width ($\Omega_{0.9}$) for concentrator modules with InGaP/GaAs/Ge solar cells and secondary optical systems of different configuration are shown in Figure 5. An insignificant loss in the short circuit current is mainly due to absence of an optical contact between the output edge of the LG and the solar cell surface, what was necessary for performing the comprehensive measurements involving one and the same cell sample for experiments.

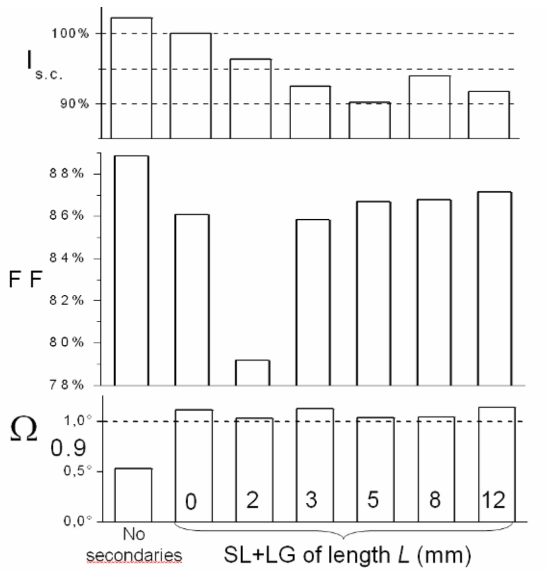

Figure 5: Cumulative results on the short circuit current ($I_{s.c.}$), I-V curve fill factor (FF), and off-orientation curve width ($\Omega_{0.9}$) for concentrator modules with InGaP/GaAs/Ge solar cells: recorded with only a primary Fresnel lens (no secondaries); recorded at presence of the combined secondary optical elements (SL+LG), when LG length *L* is varied from 0 to 12 mm, as indicated in the graphs.

5 CONCLUSION

It was found that insertion of 3÷5 mm in length light guides after the plain-convex lens leads to effective distribution of light along the cell surface, whereas shorter and longer guides produce stronger illumination in the cell center.

In concentrator modules with combined secondary optical elements (SL+LG), the off-orientation curve is kept about two times wider in comparison with the case of absence of any secondaries, if LG length *L* lies within 0–12 mm interval. Light passing through an LG of a reasonable length results in reduction in the local sun concentration ratio (less than 1000x) almost without losses in the short circuit current.

5 ACKNOWLEDGEMENTS

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