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Optimization solutions for photovoltaic modules with Fresnel lenses and 3-5-junction solar cells

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The paper discusses the advantages of using five junction solar cells (compared with three-junction cells with similar efficiency values) in concentrator photovoltaic modules with Fresnel lenses. It has been shown that the five-junction solar cells applying make it possible to reduce the focal length of the Fresnel lens and the design height of the module by $\sim 15\%$, and to gain in material consumption and weight respectively. An additional advantage of short–focus lenses is the preservation of high optical efficiency at misorientation angles up to 1° with a geometric concentration of 100X preset for the „lens$-$solar cell"pair. This makes it possible to predict an increased average energy output of concentration photovoltaic modules as part of a tracking photovoltaic installation under outdoor operating conditions.

Keywords: Fresnel lens, multijunction solar cell, average geometrical sunlight concentration, misorientation angle.

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The current records of efficiency of conversion of terrestrial concentrated solar radiation are 44 and 46% for multijunction photoconverters (solar cells, SCs) based on three (3-junction, 3J) and five (5-junction, 5J) photoactive $p-n$- junctions (subcells), respectively [1]. These record-high values are typically recorded with uniform irradiation of the photoreceiving SC surface. When installed at the focus of a concentrator (e.g., a Fresnel lens, FL), SCs operate in substantially different conditions characterized by strong spatial and spectral nonuniformity of the distribution of light energy over their surface. This affects the SC efficiency and the efficiency of a concentrator photovoltaic module (CPVM) as a whole.

The issues of optimization of the design of multijunction SCs and Fresnel lenses, which is needed to improve the energy and functional characteristics of CPVMs, have been discussed numerous times in literature [2–5]. At the same time, the advantages of CPVMs with 5- and 6-junction solar cells over their counterparts based on 3-junction SCs have been examined only rarely [6–9].

In the present study, we further the discussion (see [7,10,11]) on the problem of finding such design solutions for an FL$-$SC pair that would reduce the overall height of a module and establish the optimal operating conditions for concentrator SCs in regard to their energy efficiency.

Chromatic aberration (governed by dispersion of the refraction index of the optical material used to fabricate an FL) induces a spectral redistribution of solar radiation energy in the light spot, which predetermines the formation of different photocurrent generation profiles in subcells of multijunction SCs. Depending on the FL profile [10–12], the semiconductor structure, and the design of a 3-junction GaInP/GaInAs/Ge SC, such operating conditions may arise under which the „local" current limitation mode from the Ge subcell prevails within a certain part of the photoreceiving SC area. This limitation naturally initiates the flow of current in lateral planes and causes a reduction in the fill factor of I–V curves and the efficiency of multijunction SCs.

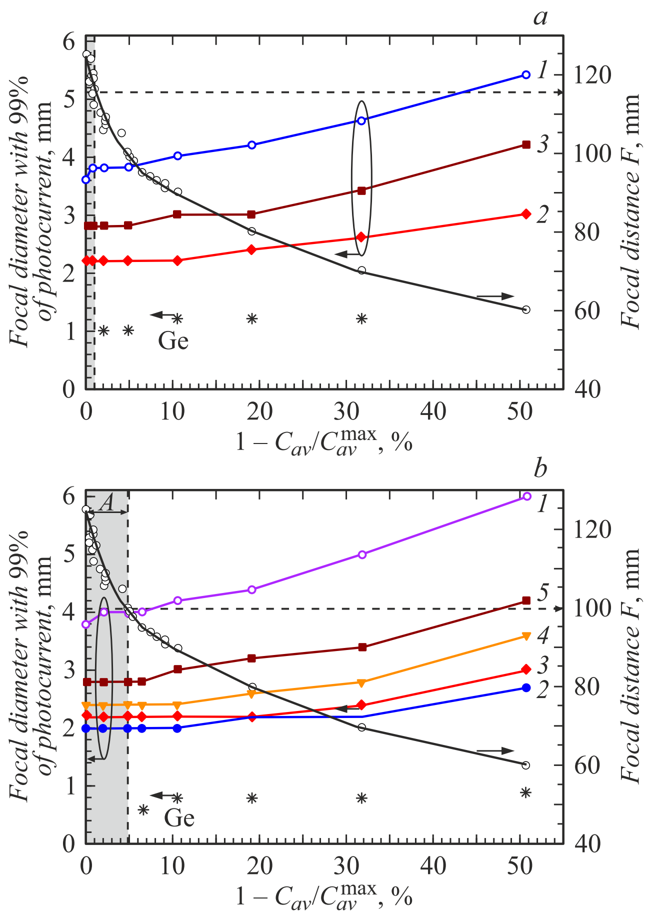
The reasons for the emergence of current limitation modes in a 3-junction GaInP/GaInAs/Ge SC and their relation to the principles and concepts of design of refracting FL teeth were discussed in [11]. It was demonstrated that local current limitation effects may be suppressed by positioning an SC at an optimal or increased (compared to the design value) distance from a concentrator. It is evident that an increase in the FL$-$SC distance entails an increase in the overall structural CPVM height, the material consumption, and the device weight. This contradicts the objectives of constructing cheap (cost-effective) and lightweight (with low energy cost of tracking the Sun) ground-based concentrator photovoltaic systems.

Just as in [11,12], a „silicone-on-glass" FL with an aperture of 60×60 mm and an optimal (determined by the method detailed in [10]) focal distance $F = 125$ mm (the diameter of the focal spot containing 99% of the energy of concentrated solar radiation is $d^{\min} \approx 3.8$ mm and the average radiation energy concentration factor is $C_{av}^{\max} \approx 600$X) is analyzed in the present study. When the FL design parameters are altered with the aim of reducing its focal distance, the parameters of light spots in three or five spectral intervals are examined. The photocurrents of subcells are determined for these intervals on the basis of standard data on the spectral sensitivity of 3-junction [13] and 5-junction [14] SCs.

As the design focal distance becomes shorter, focal spot diameter $d^{\min}$ increases, while average radiation energy concentration factor C_{av} in it decreases. This reduction is represented in the figure as $C_{av}/C_{av}^{\max}$, which is expressed as a percentage. The variation of sizes of light spots containing 99% of radiation for current generation by subcells of 3J and 5J SCs and the focal distances at which these spots are formed by a lens with the $C_{av}/C_{av}^{\max}$ value is illustrated in this figure. The diameters of light regions within which the current generation is reduced (local limitation on photocurrent) relative to the other subcells of multijunction SCs are indicated for a narrow-gap subcell based on Ge. Negative aspects of this phenomenon, which were discussed in [7,11], impose restrictions on the design of FLs with a reduced focal distance. The presented data reveal (see the figure and the table) the possibility of shortening the focal distance in an FL−3J SC pair (by altering the design parameters of the FL refracting profile) from 125 to 115 mm (i.e., by just 8%). In an FL−5J SC pair, this shortening may be much more noticeable: from 125 to 100 mm, which is a 20% change. This is accompanied by a slight increase in the size of the light spot in which concentrated radiation provides the generation of 99% of photocurrent for the corresponding subcell of multijunction SCs: this size changes from $d^{\min} \approx 3.8$ mm at $F = 115$ mm to $d^{\min} \approx 4$ mm at $F = 100$ mm for 3J and 5J SCs; i.e., the photoreceiving SC area increases by $\sim 10\%$. In both cases, the specified sizes of current generation regions are set by the upper (wide-gap) subcells and are related directly to their spectral sensitivity range. With the optimal FL with $F = 125$ mm, the sizes of these regions are 3.6 and 3.8 mm for 3J and 5J SCs, respectively. In other words, geometrical concentration factor C_{geom} for the „FL with $F = 100\,\text{mm} + 5\text{J SC}$“ design decreases to ~ 285X, while the „FL with $F = 115\,\text{mm} + 3\text{J SC}$“ structure provides a concentration factor of ~ 310X. The photocurrent losses due to the FL optical efficiency reduction, which stems from the suboptimal configuration of the refracting profile of short-focus lenses, are ~ 0.2 and $\sim 0.5\%$ in these cases (compared to the optimal FL design with $F = 125$ mm). A comparable reduction in the overall efficiency of a CPVM with a short-focus FL is to be expected.

An important advantage of the transition to short-focus configurations of lens concentrators is their higher optical efficiency in the case of misorientation (in comparison with the optimal FL). As was demonstrated in [12], the optical efficiency of a classical FL with $F = 100$ mm at misorientation angle $\alpha \approx 1^\circ$ (the receiver size is 6×6 mm and the geometric concentration factor is 100X) almost reaches the maximum level (compared to other designs of both shorter-focus and longer-focus lenses). In the case of an FL with $F = 115$ mm, the optical efficiency decreases by ~ 2.5 abs.%.

Thus, it should be concluded that while the initial efficiencies of 3J and 5J SCs are virtually equal, the use of 5J SCs provides a number of advantages in terms of the overall CPVM design: a smaller height of the structure helps reduce the material consumption and weight of the module (at least a 20% reduction in weight should be associated with a reduction in the amount of material spent on fabrication of the module body), which will enable the design of lighter tracking systems and help cut energy costs of tracking and the overall operational expenses.



Calculated data on the dynamics of variation of size of light spots containing 99% of radiation for current generation by subcells of 3-junction (curves *1–3*) (*a*) and 5-junction (curves *1–5*) (*b*) SCs and the focal distance at which these spots are formed by a lens with the magnitude of reduction of the average radiation concentration factor ($C_{av}/C_{av}^{\max}$). The diameters of light regions within which the current generation is reduced (local limitation on photocurrent) relative to the other subcells of multijunction SCs are indicated for a narrow-gap subcell based on Ge (asterisks).

The advantages of using 5-junction SCs in the construction of CPVMs with a reduced design height over the use of modules based on 3-junction solar cells were revealed. It was demonstrated that short-focus FLs are better suited (in terms of efficiency expressed in material consumption and module weight) for modules with 5J SCs. A slight (10%) reduction in the average radiation concentration factor in the 5-junction design is compensated by a $\sim 15\%$ reduction in the CPVM height with a corresponding gain in volume and weight of the structural materials used (specifically, the module weight per 1 m^2 of its photoreceiving surface decreases by 5−7% due

Key parameters for an FL–SC pair (see the figure)

SC type	FL focal distance F, mm	$d^{\min}$, mm (at 99% of photocurrent)	$1 - C_{av}/C_{av}^{\max}$, %	C_{geom}, X
3J	115	3.8	1	310
	125	3.6	0	350
5J	100	4.0	5	285
	125	3.8	0	310

just to a reduction in the amount of material spent on fabrication of the aluminum body). Another undeniable advantage of short-focus „FL with $F = 100\,\text{mm} + 5\text{J SC}$" CPVMs over „FL with $F = 115\,\text{mm} + 3\text{J SC}$" ones is the preservation of high optical efficiency of the lens at misorientation angles up to $\alpha \approx 1^\circ$, which should translate into higher energy production of CPVMs operated as part of a tracking photovoltaic installation in actual-use conditions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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