Technical Physics Letters, 2024, Vol. 50, No. 4

07.2;07.3

Trade-offs in designing modules with Fresnel lens sunlight concentrators

© M.Z. Shvarts, V.M. Emelyanov, S.A. Levina, M.V. Nakhimovich, A.A. Soluyanov

Ioffe Institute, St. Petersburg, Russia
E-mail: shvarts@scell.ioffe.ru

Received November 30, 2023
Revised December 13, 2023
Accepted Devember 13, 2023

The paper discusses options for the design of concentrator photovoltaic modules with reduced structural heights; those options are based on trade-offs between reducing the Fresnel lens optical efficiency, changing the profile of the light power distribution in the focal spot, and ensuring the required (permissible) misorientation angles at the pre-specified average geometric concentration in the lens−solar cell pair.

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

DOI: 10.61011/PJTF.2024.07.57461.19823

The discussion about construction of optimal (balanced in terms of efficiency, performance characteristics and cost) concentrator photovoltaic modules (PVMs) continues to be relevant both for designers and operators of the photovoltaic systems and embraces an increasing number of significant (major) and secondary (minor) parameters. It is obvious that the competitiveness of the concentrator photovoltaic concept and its popularity in the energy market will be determined, first of all, by minimizing the cost per unit of installed or generated electric power (cost of kW/h). When expensive, highly efficient multijunction solar cells (SCs) are used, the success lies in the field of searching for simple (with the smallest number of elements), efficient and low-cost optical designs allowing for maximal engineering tolerances and minimal material consumption.

In a classical lens-based PVM of the SMALFOC or FLATCON type [1,2], the mentioned interrelated parameters will affect each other in the following way.

1. The power output (efficiency) of the module is determined by the Fresnel lens (FL) optical efficiency (η_{opt}) and efficiency of SC itself operating in the mode of converting the concentrated sunlight with the specifiable profile of FL illumination distribution. In view of finding an efficient solution for FL, provision of the highest PVM output power needs simultaneous fulfillment of two conditions: on the one hand, collection of the maximum portion of optical power on SC, and, on the other hand, ensuring the maximum average concentration of sunlight power ($C_{av}^{\max}$) in the minimum-size ($d^{\min}$) focal spot.

As shown in [3], there exists only one combination of design parameters, size (aperture)/profile pitch/focal length ($a/t/F$), at which $C_{av}^{\max}$ and $d^{\min}$ are simultaneously achieved at optimal focal length F_{optim}. Deviation of F from optimal length F_{optim}, as well as an increase in profile pitch t, entails an increase in the focal spot size $d^{\min}$ and decrease in average radiation concentration C_{av}. Manufacturing errors of the Fresnel profile, which arise in diamond cutting the master matrices and molding the refractive facets (roundings of peaks and troughs, roughness, etc.), have a greater impact on optical efficiency η_{opt} of FLs with small profile pitches t. For instance, as the number of teeth increases, the portion of radiation scattered from roughness and local shape inaccuracies of the working facets (roundings, angular profile errors) increases, thus reducing η_{opt}. Hence, optical efficiency η_{opt} at preset profile pitch t will be higher for long-focal FLs (Fig. 1). However, the larger is focal length F, the greater are the module structural height, material consumption and cost.

2. The functionality should be associated with the requirement for the accuracy of pointing the module at the Sun and maintaining tracking parameters at the selected ratio between the concentrator and SC sizes, i. e. with geometric concentration C_{geo}. The permissible misorientation angle (α) is assumed to be an angle at which the modulés output power or photocurrent is 90% of that in the exactly oriented position. Higher requirements for the orientation accuracy lead to an increase in the complexity and material consumption of the module tracking system necessary to ensure the specified orientation modes.

It was proposed [1] to define the compromise between geometric concentration C_{geo} and misorientation angle α as follows:

$$\mathrm{CAP} = \sqrt{C_{geo}}\sin\alpha, \qquad (1)$$

(CAP is the concentration acceptance product).

However, in the case of simple PVMs (without of secondary optics), expression (1) does not account for such FL characteristics as the above-mentioned optical efficiency η_{opt} and profile of the sunlight distribution in the focal spot, which also depend on F and α.

3. The PVM prime cost depends on the size of SC based on high-cost III−V heterostructures, i. e. on the geometric concentration C_{geo}, number of optical and power-generating elements, and material consumption of PVM depending on its height and governed by the lens focal length.

In this work, the authors discuss possible trade-offs for the FL−SC pair, which is expected to enable a reduction in the lens focal length and, hence, in the PVM design height and material consumption with retaining high values of C_{geo} and α. For the tracking system, this will mean a reduction

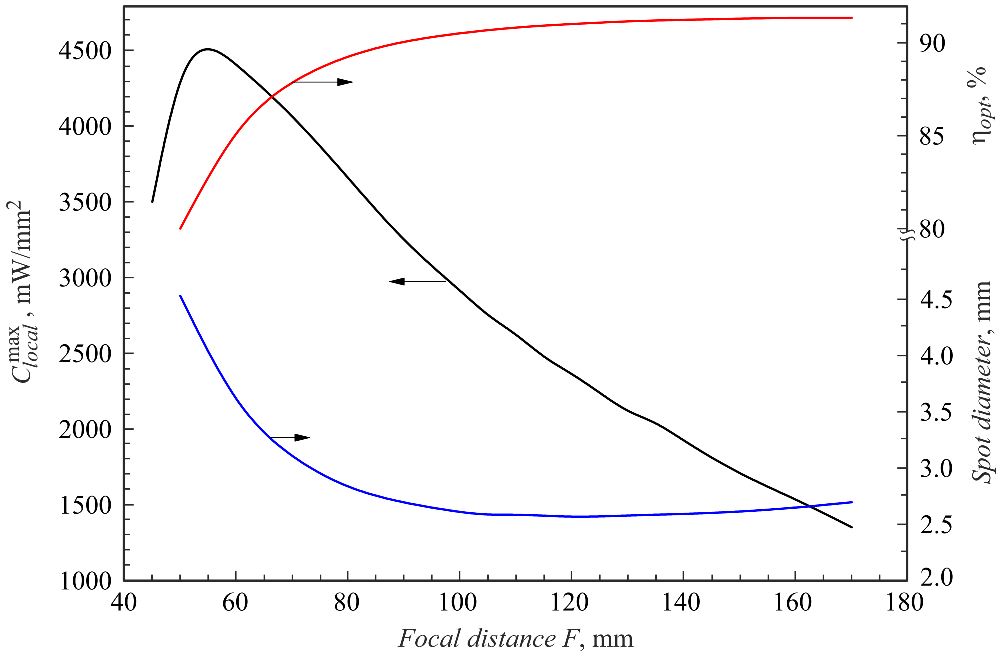

Figure 1. Local concentration factor $C^{\max}_{local}$, size $d^{\min}$ of the focal spot containing 95% of the concentrated sunlight power, and FL optical efficiency η_{opt} versus design focal length F. The refractive facet profile pitch is $t = 0.35$ mm. The estimates are given for an „ideal“ FL (ignoring the energy losses on roundings of the tooth peaks and troughs and those due to refractive facet shape errors, roughness of optical surfaces, etc. [4,5]).

in the weight of the structure itself as well as weakening the requirements for rigidity, which will result in a reduction in the operating costs for tracking.

In searching for compromise solutions for the FL design parameters, there was used a mathematical model for sunlight concentration based on direct ray tracing [4,5]. This approach makes it possible to solve problems of designing FLs and comparing their optical-power characteristics (with accounting for the constraints imposed by the applied manufacturing methods and FL shape errors that are deviations in the shape of refractive facets, surface roughness, etc.). Besides the profiles of sunlight power distribution in the FL focus at different misorientation angles, the set of characteristics includes the dependences of optical efficiency η_{opt} on focal spot size d for the design focal length F, and the misorientation dependence for the FL$-$SC pair.

In [6,7] there were considered modules based on „silicone-on-glass“ FLs with the aperture of 60×60 mm ($a = 60$ mm) and focal length of 105 mm, while the optimal focal length estimated by the authors of this work by the method described in [3] was for such an FL $F_{optim} = 125$ mm (the size of a focal spot containing 95% of the concentrated sunlight energy, $d^{\min} \approx 2.6$ mm). The choice of a reduced focal length F was not clearly justified in [6,7] but can be explained by extremely weak dependence of $d^{\min}$ and η_{opt} on design F in the range of 125 ± 20 mm (Fig. 1). Efficiency of FL with shape inaccuracies at $F = 105$ mm is being estimated based on the level of $\eta_{opt} \approx 88\%$ (versus 88.5% at $F = 125$ mm) with permissible $\alpha \approx \pm 0.95^\circ$ for SCs 6×6 mm in size ($C_{geo} = 100$X). More opportunities for ensuring a high geometric concentration and retaining relatively large misorientation angles can be revealed by using the secondary concentrating optics [8,9].

Focal spot size $d^{\min}$ will increase with increasing design focal length, while the FL optical efficiency η_{opt} LF will decrease (Fig. 1); this means a decrease in the FL optical power on the SC surface, as well as in SC photocurrent. However, local concentration value $C^{\max}_{local}$ should be monitored as well. For instance, reducing F to 85 mm and sacrificing about 1.5 to 2% of optical efficiency ($\eta_{opt} \approx 87\%$), an increase in $C^{\max}_{local}$ from 2200X to 3230X could be monitored, (i. e. by more than 45%) (Fig. 1, 2). Hence, the level of local current generation will also increase proportionally, thus raising the share of resistive power losses in SC [1]; in the case of certain SC design solutions, this may negatively affect the PVM efficiency, i.e. its power output.

Under real operating conditions (tracking the Sun by the system), the FL optical efficiency will depend on misorientation angle α. The profile of the sunlight power distribution in the FL focal spot will vary with increasing α with a characteristic increase in both the spot size (blurring) and level of peak local irradiance (Fig. 2). Minor deviations from the exact position ($\alpha = 0{-}0.4^\circ$) make the FL optical efficiency decrease monotonically at all F (Fig. 3). At the same time, already at $\alpha \geqslant 0.5^\circ$, the $\eta_{opt}(F)$ dependences begin exhibiting a maximum which shifts to shorter focal lengths with increasing misorientation angle. Simultaneously, the exit of a portion of radiation beyond the SC surface begins to be observed. For a lens having $F = 85$ mm at $\alpha = 1.1^\circ$ (to be considered as a limiting angle), optical

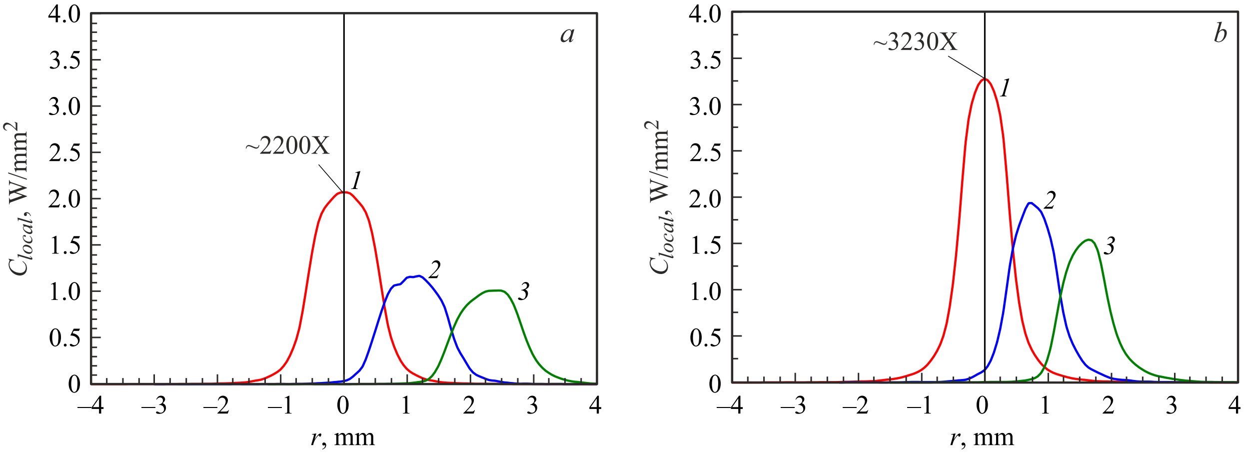

Figure 2. Dynamics of variations in the irradiance distribution profile in the focal spot of the optimal ($F_{optim} = 125$ mm) (a) and short-focus ($F = 85$ mm) (b) FL and of spot motion over the SC surface depending on the angle of the FL–SC pair misorientation from the direction to the Sun. *1* — $\alpha = 0°$ (exact orientation), *2* — $\alpha \approx 0.5°$, *3* — $\alpha \approx 1.1°$ (maximum permissible misorientation angle).

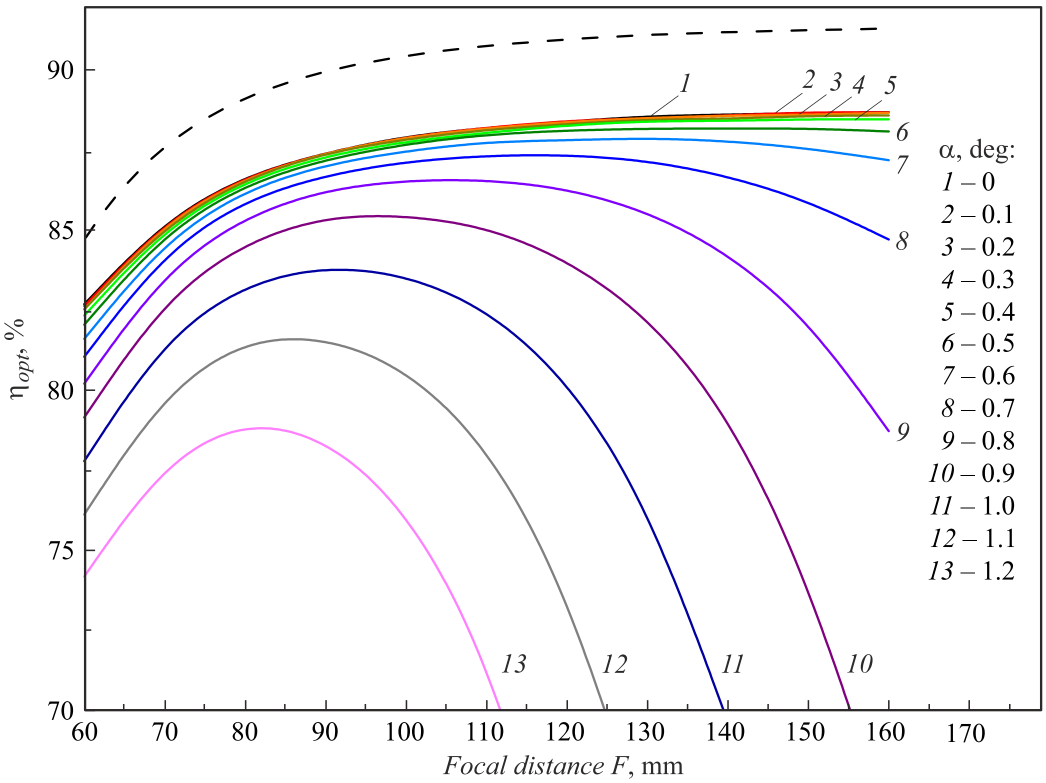

Figure 3. Optical efficiency of the Fresnel lens versus design focal length F and angle α of the FL–SC pair misorientation from the direction to the Sun. Estimates were made for FLs with shape errors (size of 60×60 mm, refractive facet profile pitch $t = 0.35$ mm). The estimates are given for FL having roundings of tooth peaks and troughs (at the rounding zone width of $5\,\mu$m), deviations in refractive facet shapes (at the standard deviation of the LF tooth inclination angle of ± 5 arcmin), and roughness of optical surfaces (no more than $0.1\,\mu$m) [4,5]. The dashed line represents the dependence for the „ideal“ FL.

efficiency η_{opt} will be slightly higher than 81% (0.93 of the initial level) at the predicted (acceptable) level of shape errors of the refractive facets [4,5], i.e. the expected drop in the SC photocurrent will not exceed 10% of the value for an optimal FL ($F_{optim} = 125$ mm), which is within the range of levels discussed in literature [1]. Thus, the found solution (Fig. 3) that is, $F = 85$ mm for the „silicone-on-glass“ FL with the 60×60 mm aperture, should be considered the best both in view of the module functionality (the permissible misorientation angle is $\alpha = 1.1°$ when the FL optical efficiency or solar photocurrent drops to 10% of the maximum value detected at the exact orientation) and in view of the modules material consumption and weight (the module weight will be reduced by $\sim 5\%$ due to reduction in the module construction height by $\sim 32\%$ and the aluminum consumption for PVM frame will be diminished on $\sim 30\%$).

Further reduction in the lens focal length and module height is unreasonable because of a significant decrease in the FL optical efficiency both in the $\alpha = 0^\circ$ position (exact orientation) and at the maximum permissible misorientation angles. In this case, an increase in the level of local sunlight concentration ratio in the focal spot center (Fig. 1) and relevant increase in the SC ohmic losses will take place; this may result in a decrease in the elements' service life due to light-induced degradation of antireflective coatings and contacts under ultra-high irradiances.

An obvious and often considered solution for expanding the PVM misorientation angular capabilities with simultaneous increase in the average (geometric) radiation concentration is integration of secondary optics elements; this requires additional research with taking into account the above-mentioned compromise solutions.

Thus, this paper presents key aspects of searching for trade-offs for concentrator PVM designs ensuring a reduction in their structural height, material consumption and weight. For the concentrator of the „Fresnel lens“ type, here is proposed an option implying reducing the module structural height with retaining the main optical-power characteristics. A justification was made for a feasible option ensuring a reduction in the structural height of the module based on FL with the aperture of 60×60 mm by $\sim 32\%$ (from 125 to 85 mm) with retaining the FL optical efficiency at the level of more than 83% and providing average (geometric) radiation concentration ratio on SC of more than 100X at permissible misorientation angles of up to 1.1°.

Funding

The study was supported by the Russian Science Foundation (project No 22-19-00158 (https://rscf.ru/project/22-19-00158/).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] *Handbook on concentrator photovoltaic technology*, ed. by C. Algora, I. Rey-Stolle (John Wiley & Sons, N.Y., 2016), p. 59–244, 339–432, 589, 684. DOI: 10.1002/9781118755655

[2] M. Wiesenfarth, I. Anton, A.W. Bett, Appl. Phys. Rev., **5**, 041601 (2018). DOI: 10.1063/1.5046752

[3] M.Z. Shvarts, V.M. Emelyanov, M.V. Nakhimovich, A.A. Soluyanov, V.M. Andreev, AIP Conf. Proc., **2149**, 070011 (2019). DOI: 10.1063/1.5124210

[4] M.Z. Shvarts, V.M. Andreev, V.S. Gorohov, V.A. Grilikhes, A.E. Petrenko, A.A. Soluyanov, N.H. Timoshina, E.V. Vlasova, E.M. Zaharevich, in *Proc. of the 33rd IEEE Photovoltaic Specialists Conf.* (IEEE, 2008), p. 1–6. DOI: 10.1109/PVSC.2008.4922751

[5] M.Z. Shvarts, A.A. Soluyanov, Adv. Sci. Technol., **74**, 188 (2010). DOI: 10.4028/www.scientific.net/AST.74.188

[6] E.A. Ionova, N.Yu. Davidyuk, N.A. Sadchikov, A.V. Andreeva, Tech. Phys., **66**, 1208 (2021). DOI: 10.1134/S1063784221090073.

[7] A.V. Chekalin, A.V. Andreeva, N.Yu. Davidyuk, N.S. Potapovich, N.A. Sadchikov, V.M. Andreev, D.A. Malevskii, Tech. Phys., **66**, 857 (2021). DOI: 10.1134/S1063784221060050.

[8] N.A. Sadchikov, N.S. Potapovich, D.A. Malevsky, N.Yu. Davidyk, A.V. Andreeva, A.V. Chekalin, Tech. Phys., **68**, 751 (2023). DOI: 10.21883/TP.2023.06.56529.239-22.

[9] N.S. Potapovich, N.Y. Davidyuk, V.R. Larionov, V.P. Khvostikov, Tech. Phys., **65**, 2026 (2020). DOI: 10.1134/S1063784220120221.

Translated by EgoTranslating