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Investigation of concentrator photovoltaic modules with reflective secondary optical elements

© N.A. Sadchikov, N.S. Potapovich, D.A. Malevsky, N.Yu. Davidyk, A.V. Andreeva, A.V. Chekalin

Ioffe Institute, St. Petersburg, Russia
e-mail: N.A.Sadchikov@mail.ioffe.ru

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The characteristics of concentrator photovoltaic modules based on a 120×120 mm Fresnel lens with secondary concentrators in the form of hollow aluminum focons with internal mirror walls are studied. The optimal sizes and configurations of secondary concentrators are determined to increase the efficiency of focusing systems of concentrator modules. The maximum value of the allowable misorientation angle was obtained, equal to $\pm 0.75^\circ$, corresponding to a power drop to a level of 90% relative to the maximum power value of the concentrator photovoltaic module at normal beam incidence. For a module with the most efficient focon 40 mm high and side face slope angles of 17°, the maximum efficiency of the module under laboratory conditions was obtained, equal to 35.15%. Under natural conditions, the efficiency value reached 33.8%. The results obtained correspond to the level achieved for the best foreign analogues.

Keywords: concentrator photovoltaic modules, Fresnel lens, focon, secondary optical element, acceptance angle.

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Introduction

One of the promising directions for generating electricity using „green" energy methods is the photovoltaic conversion of solar radiation using highly efficient multijunction solar cells (SC), the efficiency of which currently exceeds 45% when converting direct solar radiation at level of ratio of solar radiation concentration of 500–1000 [1–3]

These properties of solar cells make it possible to reduce the total area of solar cells in power units in proportion to the ratio of solar radiation concentration when using inexpensive optical concentrators with high optical efficiency and providing the necessary degree of concentration [4–7]. Currently, there are two main approaches to the method of concentrating the solar radiation on the surface of solar cells in concentrator photovoltaic energetics. In the first case, light-refracting optical elements are used, such as, for example, flat Fresnel lens, in the second case, reflective spherical mirrors. Today, the use of Fresnel lens as primary concentrators of solar radiation becomes the most widespread among manufacturers of concentrator photovoltaic modules (CPMs) [4–10].

The most important parameters of CPM are the solar radiation conversion efficiency and the misorientation characteristic of the module. The analysis of the optical-energy characteristics, when Fresnel lens are used as primary lens, shows that the main obstacle to increase their energy efficiency and concentrating ability is chromatic aberration [11]. One of the ways to reduce the effect of chromatic aberration and inaccurate orientation of optical concentrators on the energy efficiency of the concentrating system, as well as to increase the average level of radiation concentration on the solar cell without reducing the optical efficiency, is the use of secondary concentrating optics (SCO) placed directly in front of the surface or on the surface of photoconverters [12,13]. SCOs not only reduce losses associated with chromatic aberration [14] and uneven distribution of radiation over the surface of solar cells [15,16], but also improve the misorientation characteristics of modules. The family of secondary optical elements used in practice is quite wide and includes reflective and refractive elements of various shapes, as well as their combinations [17–22].

The simplest way to increase the light concentration and the beam capture angle is to install an inverted truncated pyramid with internal mirror walls (focon) on the photoreceiving surface of the solar cell as an element of secondary optics of the reflecting type, the size of the outlet of the pyramid is smaller than the size of the focused light spot of the primary lens. In this case, part of the rays that do not fall on the surface of the solar cell after reflection from the side surfaces of the focon can be redirected to the solar cell. This reflector option is preferred when solar cells and square Fresnel lenses are used.

When studying characteristics of the developed concentrator photovoltaic modules the Fresnel lens with size 120×120 mm with a focal length of 225 mm were used as primary concentrators of solar radiation. Three-junction GaInP/GaAs/Ge SCs with size 6×5.6 mm with efficiency of 42.5% served as radiation receivers. Above the photoreceiving area of solar cell, the dimensions of which were 5.5×5.5 mm, the focons of different configurations and sizes were installed (Fig. 1).

The main objective of this paper is to optimize the parameters of secondary optical elements hollow inverted truncated pyramids with internal mirror walls.

1. Method of fabrication and designs of studied elements of secondary optics

To determine the optimal parameters of secondary optical elements, a number of focons of different configurations were fabricated.

Anodized aluminum sheet 0.4 mm thick was used as the material for the focons, it has an additional multilayer coating, which makes it possible to significantly increase the reflection from the surface of the material and protect it from degradation during long-term use in CPM. The reflection coefficient of the inner mirror surface of the focons was 96–98%.

Focon samples were manufactured by obtaining flat blanks of the desired profile using laser cutting, followed by the formation of volumetric reflectors with internal mirror walls by bending on pyramidal templates.

The main changing parameters of the focons are their height (h) and the faces slope angle (α) (Fig. 1). A set of focons was made, the height of which varied from 5 to 50 mm, the faces slope angle — from 15 to 25°. The output aperture size (m) of the focons varied from 3.5×3.5 to 5×5 mm.

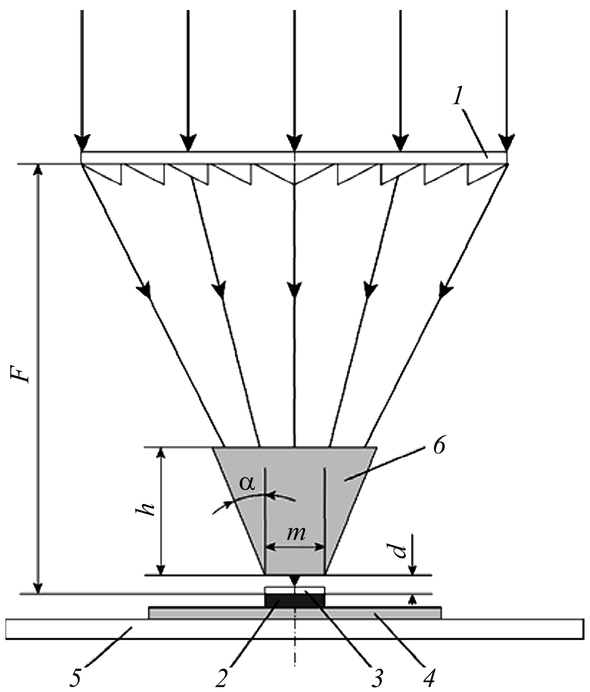

Figure 1. Scheme of CPM with secondary concentrator in the form of focon: *1* — Fresnel lens, *2* — colar cell, *3* — protective glass (if available), *4* — heat-conducting electrical insulating board, *5* — aluminum heat-removing base, *6* — focon. F — focal length of Fresnel lens, h — focon height, m — focon output aperture size, d — gap foconIFx3xsolar cell, α — slope angle of focon faces.

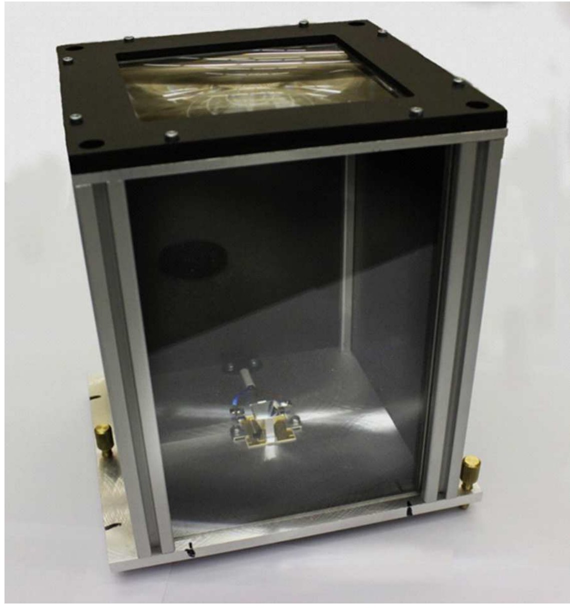

Figure 2. External view of CPM with Fresnel lens and focon installed above the photoreceiving area of solar cell.

To study the characteristics of concentrator photovoltaic modules with secondary optical elements in the focusing system, an experimental sample of the module was made. The solar cell with dimensions 5.5×5.5 mm was fixed on the photoreceiving panel, solar cell was soldered onto a heat-conducting electrically insulating board made on the basis of alumina technology with dimensions $30 \times 30 \times 3$ mm. Above the photoreceiving area of the solar cell with size 5.5×5.5 mm, placed in the focal spot of the Fresnel lens, the studied focon was installed. The lens and photoreceiving panels were connected by side walls. The appearance of the module is shown in Fig. 2.

2. Measurement procedure

To measure the parameters of concentrator photovoltaic modules a laboratory pulse measuring complex was used, which includes a pulsed light source (xenon lamp), a collimator, a positioning system for optical elements and the module as a whole, and a radiation registration system [23]. The optical system of the measuring system ensured the formation of a light flux with a radiation density of 1000 W/cm^2, a spectral composition corresponding to AM1.5D, and an angular divergence identical to the divergence of the light flux coming from the solar disk (32 arcmin). The positioning system of the complex ensured precise movements in the light flux of each of the elements of the studied concentrator systems in three coordinates and the rotation of the entire installed structure relative to the optical axis of the incident radiation. The steps of linear displacements and angles of rotation were set using a computer program of the recording system, which also

The results of measurements of the electrical characteristics of the modules, obtained when irradiated with light flux of the pulsed simulator of solar radiation and by direct solar radiation

Conditions Tests	Focon	Sun insolation, W/m^2	I_{sc}, A	U_{xx}, V	I_{opt}, A	U_{opt}, V	P, W	FF, %	Eff, %
Laboratory	No	1000	1.856	3.103	1.739	2.706	4.707	81.7	32.69
Laboratory	Yes	1000	1.982	3.103	1.873	2.702	5.061	82.3	35.15
Field	No	824	1.681	3.006	1.513	2.466	3.734	74.7	31.46
Field	Yes	824	1.731	3.001	1.629	2.463	4.014	77.3	33.8

Note I_{sc} — Short circuit current, U_{xx} — Idle voltage, I_{opt} — current in optimal load point, U_{opt} — voltage in optimal load point, P — power, FF — CVC filling factor, Eff — efficiency.

provided the radiation control of a flash lamp, recording the load current-voltage characteristic (CVC) of the solar cell during a single light pulse and calculating such CVC parameters as short-circuit current (I_{sc}), output electric power at the point of optimal load (P_{max}), CVC filling factor (FF) and the efficiency of photovoltaic conversion of radiation incident on the surface of the Fresnel lens.

When determining the effect of focons of different configurations on the efficiency of the studied module, the Fresnel lens and the solar cell with the studied focon were fixed in holders ensuring their mutual coaxial location in the focal plane of the Fresnel lens, and the optical axis of the focusing system was set parallel to the optical axis of the collimator. When the Fresnel lens was irradiated with collimated radiation from the flash lamp, the recording system recorded CVC of solar cell, and the efficiency of the modules with the selected focon was calculated. Comparison of the obtained results with the efficiency of modules with focusing system without focon made it possible to evaluate the effect of focons on the characteristics of the studied concentrator modules.

The positioning system made it possible to carry out precise movements of the solar cell with the installed focon in directions parallel or perpendicular to the optical axis of the Fresnel lens. This made it possible to determine the optimal values of the focal length of the concentrating systems with focons and the limiting values of errors during optical elements installation in CPM.

To study the misorientation characteristics, the focusing system with focon or single module was mounted on a turntable with axis of rotation perpendicular to the optical axis of the collimator. During the measurements, discrete rotations of the table were carried out by fixed values of the angle of rotation, and during irradiation with light pulses, the CVCs were recorded in each position, and the values of the short-circuit current were determined. According to the CVC results a misorientation curve of the module was plotted, i.e., short-circuit current vs. angle of deviation of optical axis of the module relative to the optical axis of the collimator. Since the magnitude of the short-circuit current is proportional to the number of quanta of radiation incident on the photoreceiving area of the solar cell, the plotted misorientation curve characterizes the parameters of the focusing system of the module only. The allowable range of deflection angles ($\pm W_{0.9}$) was estimated from the half-width of this curve at a level of 0.9 of value I_{sc} at normal incidence of rays on the primary lens.

3. Laboratory study results

At the first stage of studying the characteristics of the fabricated focon samples, square-shaped Fresnel lens with dimension 120×120 mm was installed perpendicular to the direction of the light flux of the measuring complex. A three-stage solar cell with the size of the photoreceiving area 5.5×5.5 mm was installed at focal length of 225 mm coaxially with the Fresnel lens. The radiation conversion efficiency in modules without focons was 32.5%. The focon under study was fixed in a holder and placed on the surface of the photoreceiving area in such a way that the sides of the focon output window were set parallel to the side faces of the solar cell and symmetrically relative to the center of the photoreceiving area. During this series of studies all focons had an output aperture size of 4.5×4.5 mm.

Fig. 3 shows the measured efficiency values of modules using groups of focons of different heights as secondary concentrators depending on the side faces slope angle.

Fig. 4 shows an increase in the efficiency of radiation conversion in modules with an increase in the height of focons having different side face slope angles.

As can be seen from the measurement results shown in Fig. 3, in all groups of focons of the same height the ranges of optimal values of the side face slope angles are observed, at them the values of the radiation conversion efficiency are maximum. For focons with a height of 5 to 15 mm the values of the optimal slope angles are in the range $21-23^\circ$. For focons with height of 20 to 30 mm — in the range $17-19^\circ$. The decrease in the efficiency of focons at side face slope angles less than optimal is explained by decrease in the angle of capture of scattered radiation from the Fresnel lens with decrease in the entrance aperture of the focons, and decrease in the efficiency curves at slope angles greater than optimal — increase in optical losses with increase in the number of light re-reflections from the side faces.

The results shown in Fig. 4 show that when using focons of all configurations, the increase in the efficiency

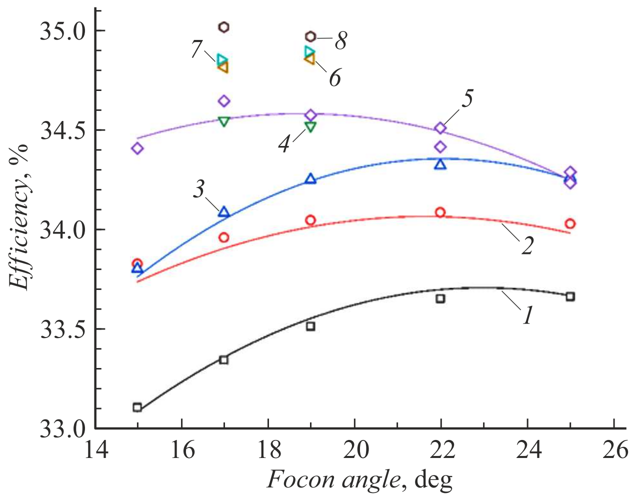

Figure 3. Efficiency of radiation conversion in modules with focons of different heights vs. angle of inclination of side faces of focons. Focon height: *1* — 5, *2* — 10, *3* — 15, *4* — 20, *5* — 25, *6* — 30, *7* — 40, *8* — 50 mm.

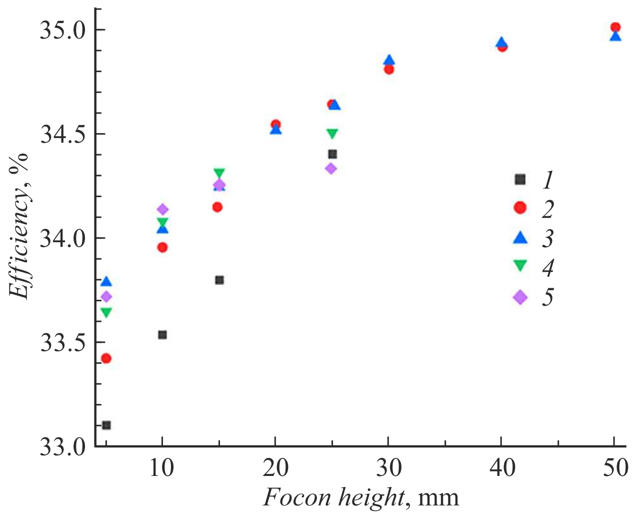

Figure 4. Efficiency of radiation conversion in modules with focons with different side face slope angles vs. focon heights. Slope angle: *1* — 15, *2* — 17, *3* — 19, *4* — 22, *5* — 25°.

of radiation conversion with focon height increasing is observed. This effect is explained by the increase in the angle of capture of scattered radiation from the Fresnel lens with the increase in the input aperture of the focons with height increasing and the input focon window approach to the Fresnel lens. However, note that at height of focons above 30 mm, the increase in the light conversion efficiency is insignificant. Considering the significant additional consumption of materials during the high focons manufacturing and the difficulties arising when fixing high focons on the surfaces of solar cells in photovoltaic modules, the focons with height of about 25ṁm seem to be optimal at side face slope angles 17–19°.

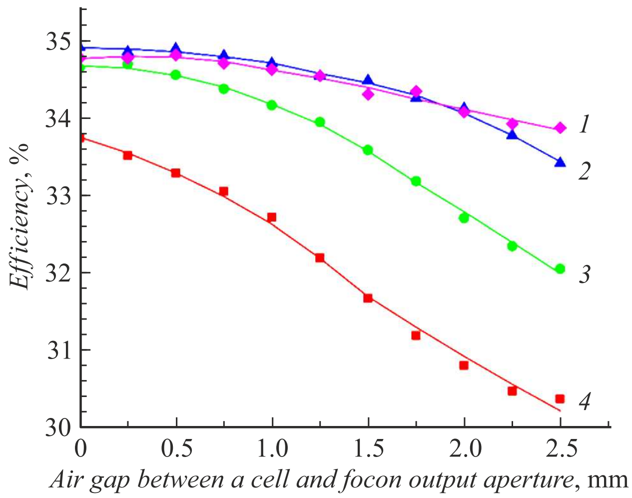

Figure 5. Efficiency of radiation conversion in modules with focons with different output aperture sizes vs. size of gap between faces of focon output window and surface of photoreceiving area of solar cell. Output aperture size: *1* — 5 × 5, *2* — 4.5 × 4.5, *3* — 4 × 4, *4* — 3.5 × 3.5 mm.

Note that the installation of the edges of the output window of the focons directly on the photoreceiving areas of the solar cells can cause damage to the photoreceiving surfaces and the contact grid, which leads to decrease in the efficiency of radiation conversion and decrease in the service life of photovoltaic modules. Therefore, when assembling concentrator photovoltaic modules with secondary optical elements, it is advisable to place focons above the surface of photoreceiving areas with a gap.

The effect of the size of the gap between the faces of the output window of the focons and the surface of the photoreceiving area of solar cell on the efficiency of radiation focusing was studied. During measurements we used focons of the same height of 25ṁm with different output aperture sizes. To preserve the values of the focused light fluxes, all focons were made with the same entrance aperture, size 21.7×21.7 mm, and different slopes of the side faces.

Fig 5 shows the change of efficiency of radiation conversion in modules with focons with different output aperture sizes vs. size of gap between faces of focon output window and surface of photoreceiving area of solar cell.

Comparison of the behavior of the curves shown in Fig. 5 allows us to conclude that in focons with output aperture sizes of 4.5 ×4.5 and 5 × 5 mm, the increase in the gap between the faces of the output window of the focons and the surface of the photoreceiving area to 0.7 –0.8 mm does not leads to significant change in the conversion efficiency. Such a behavior of the curves is explained by the fact that the size of the light spot focused by the lens on the solar cell surface is smaller than the size of the output aperture of the focon, and the addition to the efficiency of the focusing system occurs due to the focusing of the scattered radiation

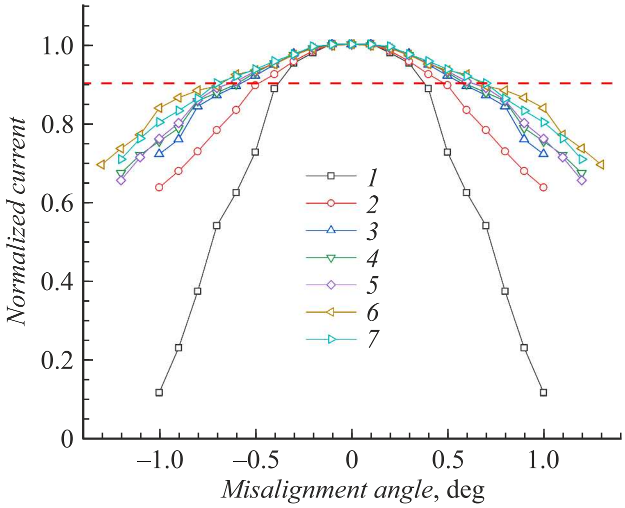

Figure 6. Misorientation characteristics of CPM without focon (*1*) and with installed focons with the corresponding face slope angles and heights: *2* — 19 and 10; *3* — 19 and 15; *4* — 17 and 25; *5* — 19 and 25; *6* — 17 and 40; *7* — 19° and 40 mm. The red dashed line (in the online version) indicates the level above which the concentration of radiation focused on the photoreceiving surface of the solar cell decreases by maximum 10% of the maximum value.

of the Fresnel lens by the side faces of the focons. With increase in the gap of more than 0.7–0.8 mm, a part of the focused rays hits the side faces of the focons near the outlet and is reflected outside the photoreceiving area of the solar cell. In focons with the output aperture size 4×4 mm, which is close to the sizes of the focused light spot, such an effect is observed when the gap is larger than 0.2 mm. In the case when the size of the focused spot is larger than the output aperture of the focon (3.5×3.5 mm), the part of the focused rays from the lens are re-reflected by the focon faces outside the photoreceiving area of the solar cell when the focon is placed on the solar cell surface, and the fraction of these rays increases with gap increasing.

The possibility of placing focons with output aperture sizes4.5×4.5 and 5×5 mm above the surface of photoreceiving areas of the solar cell with gap of up to 0.7 mm without reducing the efficiency of radiation conversion makes it possible to install structural elements on photoreceiving surfaces that protect surfaces from mechanical and environmental effects.

In the course of the experiments, it was demonstrated that sticking 0.2 mm thick optical glass plates on the solar cell surface with optical silicone, followed by installation of focons of various configurations with output aperture sizes4.5×4.5 mm on the glass surface, resulted in decrease in the radiation conversion efficiency by 4% compared with the option of placing these focons directly on the photoreceiving surfaces of the solar cell. This decrease in efficiency is explained by reflection losses at the glass-air interface and can be reduced by coating the glass surface.

The effect of focons of different configurations on the misorientation characteristics of photovoltaic modules is shown in Fig. 6.

Measurements were made of the disorientation characteristics of modules containing focons with height of 10 to 40 mm and face slope angles of 17 and 19°. For comparison, Fig. 6 shows the misorientation characteristic of the module without the focon. As expected, the greatest broadening of misorientation curves is observed in modules with focons 40 mm high. The decrease in the slope of the misorientation curves with increase in the focon height is explained by decrease in the distance between the center of the Fresnel lens and the plane of the entrance window of the focons, which leads to smaller linear displacements of the entrance aperture of higher focons at the same misorientation angles of the focusing system of modules relative to the direction of incidence of solar radiation. Changing the side face slope angles of focons 17–19° does not lead to significant changes in the course of the curves.

From the course of the curves shown in Fig. 6, it is possible to calculate the allowable misorientation angles $W_{0.9}$, determined at the level of 90% of the maximum value of the curve, for the focusing system of modules formed by Fresnel lens with sizes 120×120 mm with focus of 225 mm and solar cell, and size of the photoreceiving area 5.5×5.5 mm with focons of various configurations. Without focons $W_{0.9}$ is $\pm 0.4°$. Installation of focon 40 mm high above the solar cell surface increases the admissible misorientation angle $W_{0.9}$ to the value $\pm 0.75°$.

To determine the focon effect on the radiation conversion efficiency of concentrator modules with focusing system

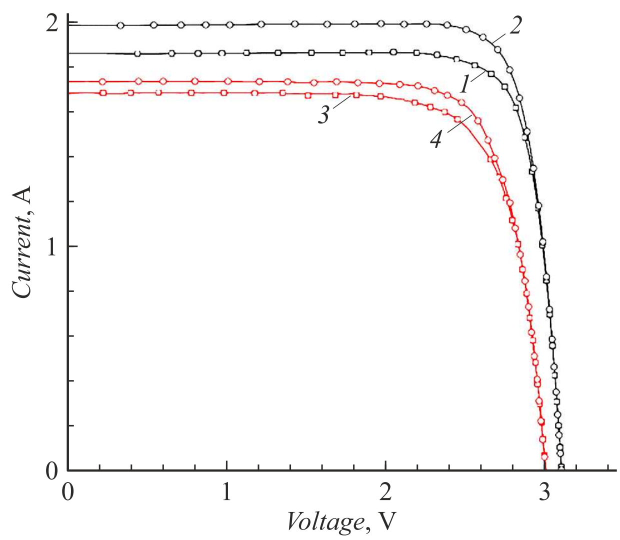

Figure 7. CVC of CPM with Fresnel lens with sizes 120×120 mm and three-stage GaInP/GaAs/Ge solar cell with sizes 5.5×5.5 mm, recorded under irradiation with pulsed simulator: module without focon (*1*), module with installed focon 40 mm (*2*) high and recorded when exposed to direct solar radiation: module without focon (*3*), module with installed focon 40 mm high (*4*).

based on Fresnel lens of size 120×120 mm and secondary concentrators in the form of hollow aluminum focons 40 mm high the modules shown in Fig. 2 were used. During measurements focons 40 mm high with faces slope angles of 17 were installed in the modules. The parameters of the modules under study were measured under laboratory conditions under irradiation with pulsed solar radiation simulator providing energy illumination of $1000\,W/m^2$ with AM1.5D spectrum, at ambient temperature $T = 24 \pm 1^\circ C$, as well as under natural conditions when irradiated with direct solar radiation with power of $824\,W/m^2$ and ambient temperature $T = 22^\circ C$. Fig. 7 shows CVCs of concentrator modules with and without installed focons, and the Table shows the results of the electrical characteristics measurements of the modules.

When irradiated with pulsed solar radiation simulator (at energy illumination of $1000\,W/m^2$), the maximum light conversion efficiency in the module with installed focon 40 mm high was 35.1%. The maximum light conversion efficiency in the module with the installed focon under direct solar radiation with power of $824\,W/m^{\ 2}$ was 33.8%.

The decrease in the efficiency of light conversion by modules when irradiated with direct solar radiation in natural conditions is associated with the increase in the operating temperature of the solar cell under conditions of continuous illumination. The second reason for the decrease in the efficiency of the modules is the change in the spectral distribution of solar radiation at the latitude of St. Petersburg at power levels $824\,W/m^2$ in comparison with the reference spectrum AM1.5D, for which the spectral distribution of the layers sensitivity of the three-cascade solar cell was calculated.

The obtained values of the radiation conversion efficiency of the designed concentrator photovoltaic modules with secondary optical elements in the form of focons correspond to the values of the best foreign analogues [4,24].

Conclusion

The characteristics of CPMs, the focusing system of which included Fresnel lens with size 120×120 mm, and secondary concentrators in the form of hollow aluminum focons of various sizes and configurations with internal mirror walls, were studied. The three-stage solar cells with the photoreceiving area size 5.5×5.5 mm were used as radiation receivers. For the experiments, focons with height of 5 to 50 mm, the side face slope angles of 15 to 25°, and output aperture sizes of3.5×3.5 to 5×5 mm were made.

It was identified that when using focons of all configurations, the increase in the efficiency of radiation conversion with focon height increasing is observed. When CPM was irradiated with light flux of the pulsed simulator of solar radiation, the values of the radiation conversion efficiency in modules with focons 5 mm high increased to 33.8%, compared with 32.5% in modules without focons, and up to 35% in modules with focons 50 mm high. It was determined that for focons with a height of 5 to 15 mm, the optimal side face slope angles are in the range$21-23^\circ$, for focons with a height of 20 to 30 mm — in the range of $17-19^\circ$.

Measurements were made of the disorientation characteristics of modules containing focons with height of 10 to 40 mm and side face slope angles of 17 and 19°. In modules with focons 40 mm high and face slope angles of 17, the maximum admissible misorientation angle $W_{0.9} = \pm 0.75^\circ$ was obtained, which is almost by two times higher than the values of $W_{0.9} = \pm 0.4^\circ$ for similar modules without focons.

For modules without secondary optics and containing focon 40 mm high with face slope angles17°, the values of direct solar radiation conversion efficiency in natural conditions were determined. At the power of the incident solar radiation $824\,W/m^{\ 2}$ and ambient temperature $= 22^\circ C$ in the module without secondary optics, the maximum value of the electric power at the optimal load point $P_{max} = 3.73$ W and the radiation conversion efficiency Eff $= 31.46\%$ were obtained. For the module which as the secondary optical element used the focon 40 mm high with side face slope angles 17°, the values of these values were respectively $P_{max} = 4.01$ W and Eff $= 33.8\%$, which correspond to the values of the best foreign analogues.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Fraunhofer ISE Develops the World's Most Efficient Solar Cell with 47.6 Percent Efficiency. [Online] Last accessed: 24.12.2022. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/ press-releases/2022/1322_PR_ISE_World_Record_47,6Percent-SolarCell.pdf

[2] J.F. Geisz, R.M. France, K.L. Schulte, M.A. Steiner, A.G. Norman, H.L. Guthrey, M.R. Young, T. Song, T. Moriarty. Nature Energy, **5**, 326 (2020). DOI: 10.1038/s41560-020-0598-5

[3] CPV Solar Cells. PV Solar Cells. [Online] Last accessed: 24.12.2022. https://www.azurspace.com/index.php/en/products/products-cpv/cpv-solar-cells

[4] CPVMod — CPV Module in Modular Design. [Online] Last accessed: 24.12.2022. https://www.ise.fraunhofer.de/en/research-projects/cpvmod.html

[5] New World Record for Concentrator Photovoltaics — 36.7 Percent for New Solar Module Using Highly Efficient Multi-Junction Solar Cells. [Online] https://www.ise.fraunhofer.de/en/press-media/press-releases/2014/new-world-record-for-concentrator-photovoltaics.html

[6] Zh.I. Alferov, V.M. Andreev, M.Z. Shvarts. In: *High-Efficient Low-Cost Photovoltaics. Recent Developments*, ed. by V. Petrova-Koch, R. Hezel, A. Goetzberger (Springer International Publishing, 2020), p. 133. DOI: 10.1007/978-3-030-22864-4
[7] M. Green, E. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, A. Ho-Baillie. Prog. Photovolt: Res. Appl. **28** (1), 3 (2019). DOI: 10.1002/pip.3228
[8] Zh.I. Alferov, V.M. Andreev, V.D. Rumyantsev. *III–V Heterostructures in Photovoltaics. Concentrator Photovoltaics*. Eds. A. Luque Lopez, V.M. Andreev. *Springer Ser. in Optical Sciences* (Berlin-Heidelberg, Springer-Verlag, 2007), v. 130, p. 25–50.
[9] V.D. Rumyantsev. Springer Series in Optical Sciences, **130**, 151 (2007).
[10] V.A. Grilikhes, M.Z. Shvarts, A.A. Soluyanov, E.V. Vlasova, V.M. Andreev. *The new Approach to Design of Fresnel Lens Sunlight Concentrator. Proc. of the 4th Int. Conf. on Solar Concentrators for the Generation of Electricity or Hydrogen* (El Escorial, Spain, 2007)
[11] S. Kurtz, M.J. O'Neill. *Estimating and Controlling Chromatic Aberration Losses for Two-Junction, Twoterminal Devices in Fefractive Concentrator Systems.* 25th PVSC, 361 (1996).
[12] G. Peharz, J. Jaus, P. Nitz, T. Schmidt, T. Schult, A.W. Bett. *Development of Refractive Secondary Optics for FLATCON Modules.* Proceeding 23rd EPVSEC (2008).
[13] I. Garca, C. Algora, I. Rey-Stolle, B. Galiana. *Study of Non-Uniform Light Profiles on High Concentration III-V Solar Cells Using Guasi-3D Distributed Models, Proceeding 33rd IEEE Photovoltaic Specialist Conf.* (2008).
[14] C. Domınguez, I. Anton, G. Sala, S. Askins. Photovoltaics, **21** (7), 1478 (2013).
[15] R. Herrero, M. Victoria, C. Domınguez, S. Askins, I. Anton, G. Sala. AIP Conf. Proc., 1679, 050006 (2015);
[16] M. Victoria, R. Herrero, C. Domınguez, I. Anton, S. Askins, G. Sala. Prog. Photovoltaics, **21** (3), 308 (2013).
[17] P.A. Davies. Pure Appl. Opt., 2, 315 (1993).
[18] M. Victoria, C. Dominguez, I. Anton, G. Sala. Opt. Express, 17, 6487 (2009).
[19] R. Winston, J. Miano, P. Bentez. *Nonimaging Optics* (2005)
[20] P. Benitez, J.C. Minano, P. Zamora, R. Mohedano, A. Cvetkovic, M. Buljan, J. Chaves, M. Hernandez. Opt. Express, 18, 25 (2010).
[21] J. Jaus, P. Nitz, G. Peharz, G. Siefer, T. Schult, O. Wolf, M. Passig, T. Gandy, A.W. Bett. *Second Stage Reflective Andrefractive Optics for Concentrator Photovoltaics. 33rd IEEE Photovoltaic Specialists Conf.* (San Diego, USA, 2008), p. 1–5.
[22] V.M. Andreev, V.D. Rumyantsev, N.Yu. Davidyuk, E.A. Ionova, V.R. Larionov, D.A. Malevskiy, A.O. Monastyrenko, P.V. Pokrovsky, N.A. Sadchikov. *Concentrator PV installations based on modules with Fresnel minilens parquets, Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion*, (Valencia, Spain, 6–10 September 2010), p. 102–107, ISBN 3-936338-26-4
[23] V.D. Rumyantsev, V.R. Larionov, D.A. Malevskiy, P.V. Pokrovskiy, N.A. Sadchikov. *Solar Simulator For Characterization Of The Large-Area HCPV Modules, Proceedings of the 7th International Conference on Concentrating Photovoltaics* (CPV-7) (Las Vegas, USA, AIP Conf. Proc., April 4–6, 2011), v. 1407, p. 212–215.
[24] E. Gerster, T. Gerstmaier, A. Gombert, R. Krause, S. Riesena, S. Wanka, T. Zech. AIP Conf. Proc., **1679**, 040006 (2015). DOI: 10.1063/1.4931517

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