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From sphere to hemisphere: secondary optics for micro-CPV modules

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The paper considers secondary concentrating elements of the full sphere (glass ball)−truncated sphere−hemisphere form factor for the micro-CPV module system with primary focusing optics of the biconvex short-focus lens type. It is shown that the maximum average radiation concentration factor in the focal spot is achieved using a truncated sphere with a minimum diameter, but at a relatively large distance from the primary concentrator to the radiation receiver. Increasing the sphere diameter while simultaneously decreasing the average radiation concentration factor in the focal spot allows reducing the specified distance, i.e. the overall height of the micro-CPV module.

Keywords: micro-CPV module, biconvex lens, secondary radiation concentrator, solar cell, average concentration factor, focal spot.

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The main basic concept for microconcentrator („micro-CPV") modules is the use of short-focus optics formed based on primary (Primary Optical Element, POE) and secondary optical elements (Secondary Optical Element, SOE) that direct the solar radiation to the receiver (Solar Cell, SC) of submillimeter size [1,2].

In this paper, the parameters of full-body SOEs with the shape of „glass ball" (Full Ball Lens, FBL), Truncated Balls Lens, TBL, Half Balls Lens, HBL) and search for the optimal combination of distances POE −SOE−SC, at which a light spot of minimum size with a fraction of energy 90−95 % of the one passed through the primary concentrator will be formed in the plane of rational installation of the radiation receiver. If this condition is met, the maximum values of the average concentration coefficient in the spot will be provided, and therefore the conditions for minimizing the size of the photosensitive surface SC should be formed.

The model is based on tracking of light rays passing through the optical system. The source radiation and its angular dimensions are given by the ray flux directed to the input aperture of the concentrator. The concentrator is represented as a set of flat and curvilinear refracting surfaces of a given size and optical media separating them. The optical-energy characteristics of the system are calculated by summing the energy contributions of light rays to the cells of the radial-ring grid of the receiver, taking into account all types of optical losses, including spherical and chromatic aberration. In [3] it is shown that one of the effective (optimal) solutions for micro-CPV-module is an optical system based on an array of double-convex lenses, which form a spot of concentrated radiation of smaller area at a shorter focal length compared to flat-convex lenses of comparable aperture.

Therefore, in this paper, it is the BCL (aperture 10×10 mm, radii of curvature of refractive surfaces 26 mm) that is considered in the modeling as POE. The SOE is represented as different versions of a full sphere, hemisphere, and sphere with a flat edge at the SC junction at radii of curvature of the refractive surface 0.5, 1, 1.5, 2 mm (hereafter referred to as $D = 1$, 2, 3 and 4 mm diameters, respectively). A schematic of SOE placement in the output beam of the BCL is shown in Fig. 1, where by varying the distance from the top of the BCL output surface to the center of the secondary sphere, the following important positions can be indicated: $F_{\min}$ and $F_{\max}$ — the near and far boundaries of the working zone, within which full interception of SOE radiation is ensured and there is no transit (radiation passes by the sphere and is not refracted by it) optical loss; Z_1, Z_2 — the distances at which the outermost rays exiting the BCL touch the sphere surface in the converging and diverging beam, respectively. Optical losses on the refracting surfaces of the secondary sphere for the outermost rays coming out of the BCL do not exceed 5 %.

In all of the above cases of secondary optics placement, the radiation receiver is located in direct contact with the surface of a sphere, with its output flat facet or with a hemisphere (Fig. 2). Depending on the type of secondary optics considered, the following variants of values are possible for the value δ, which will denote the distance from the top of the output surface of the sphere in the direction of the ray path from POE (in other words, δ is essentially the height of the segment cut off from the sphere): a — full-body full sphere ($\delta = \delta_{\mathrm{FBL}} = 0$); b — hemisphere ($\delta = \delta_{\mathrm{HBL}} = -D/2$); c — truncated sphere ($\delta_{\mathrm{TBL}} < 0$). The sections δ_{HBL} and δ_{FBL} pass through the center and vertex of the output surface of the sphere, respectively. The truncated form of the SOE corresponds to the negative values δ

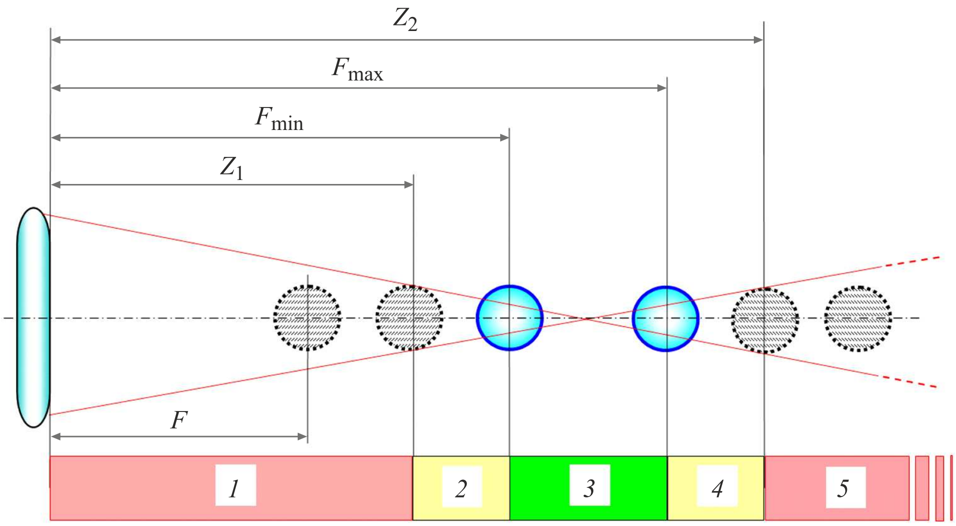

Figure 1. Classification of secondary sphere placement zones. *1* — zone of transit losses in the converging beam; *2, 4* — zones of increased optical losses of the extreme rays of the beam on the sphere surfaces; *3* — working zone; *5* — zone of transit losses in the diverging beam. A color version of the figure is provided in the online version of the paper.

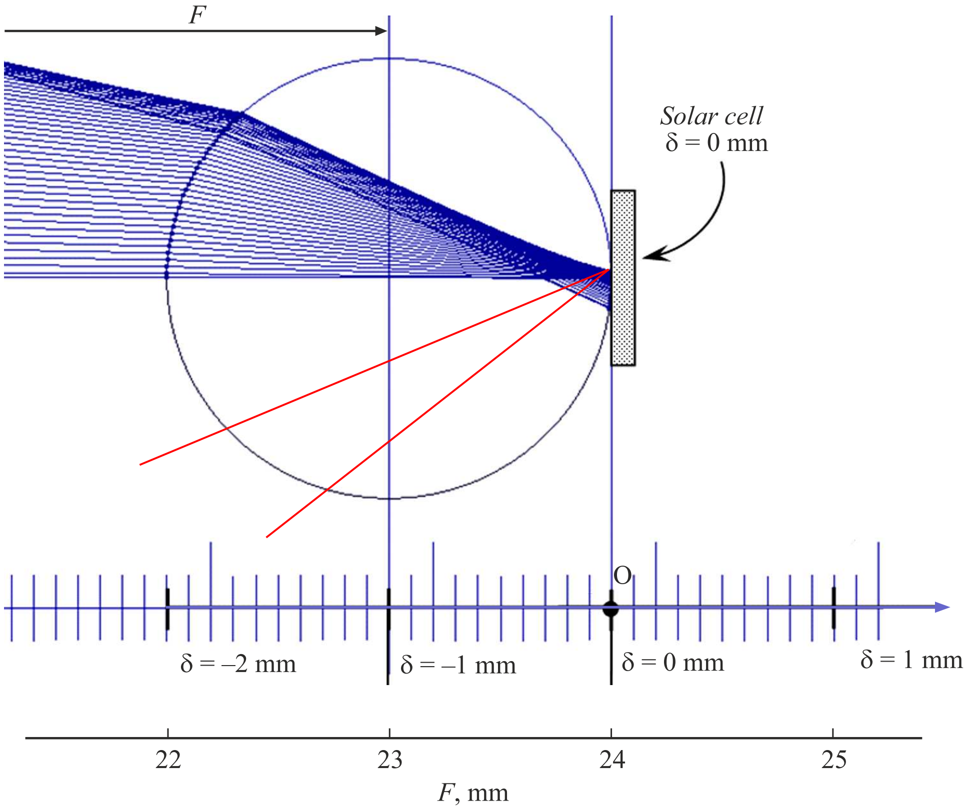

Figure 2. The path of the rays through the secondary optical element. δ — distance from the top of the FBL output surface in the direction of ray path from POE, F — the focal distance of the lens. Rays experiencing total internal reflection at the sphere output surface are marked in red.

and the gap that occurs between the FBL and the receiver corresponds to the positive ones.

For convenience of consideration, only half of the rays through the upper part of the BCL are plotted in Fig. 2. The rays through the lower part of the BCL are mirror reflections. The rays that experienced total internal reflection at the exit surface of the sphere (red lines in Fig. 2) were not tracked after the reflection, and their possible subsequent refraction at the sphere boundary was not considered.

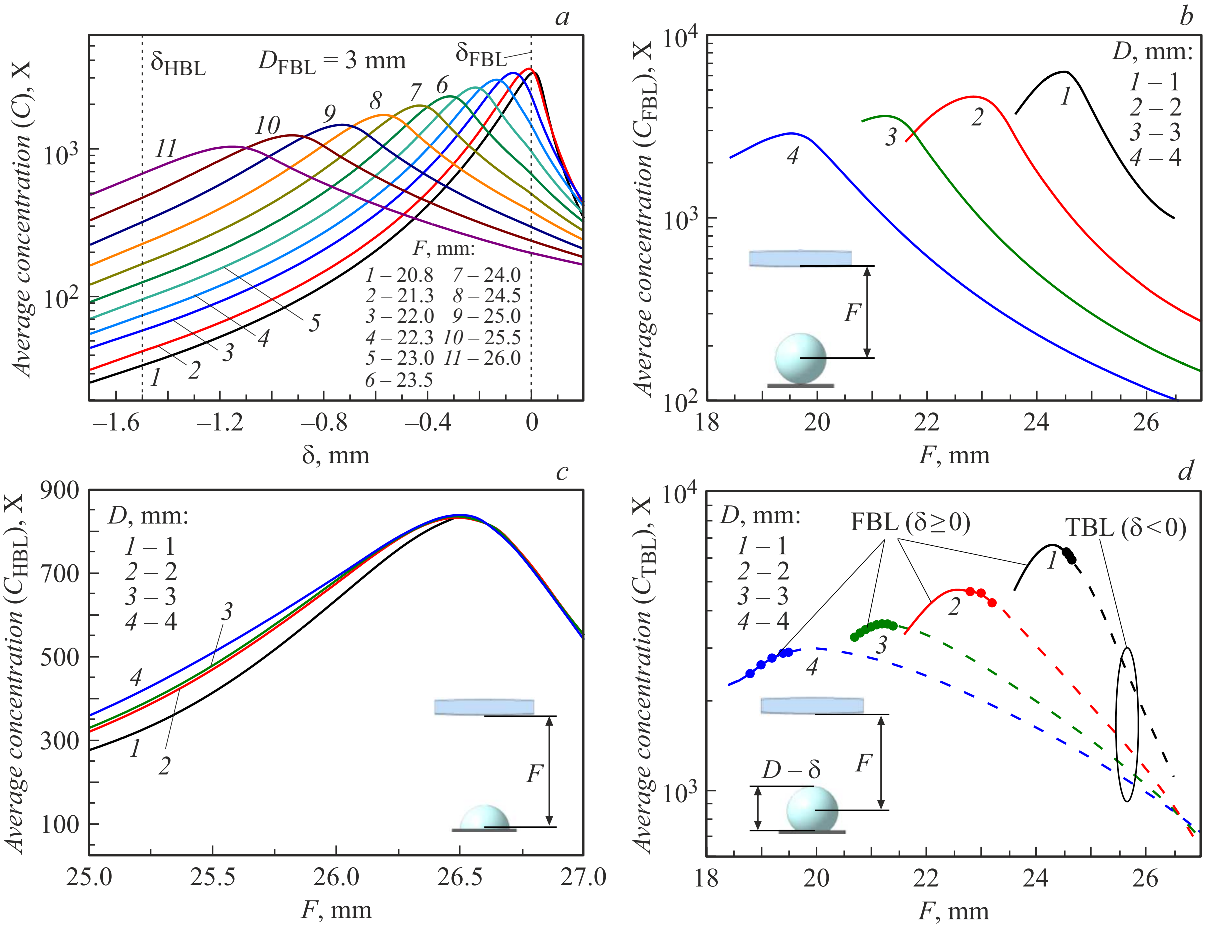

Figure 3. The average concentration factor in the focal spot as a function of the section plane position δ for the FBL-type SOE with $D = 3$ mm (*a*) and from the distance F for different D at $\delta_{\mathrm{FBL}} = 0$ (*b*), $\delta_{\mathrm{HBL}} = -D/2$ (*c*). *d* — dependence of the mean concentration ratio at the focal spot on distance F at $\delta > 0$ (solid lines), $\delta = 0$ (dots) for FBL and at $\delta < 0$ for TBL (dashed lines). The insets (*b*–*d*) show optical circuits consisting of primary and secondary concentrators.

Table 1. Parameters of the rational plane of SOE installation

Diameter spheres D, mm	Z_1, mm	$F_{\min}$, mm	$F_{\max}$, mm	Z_2, mm
1	24.40	–	–	26.35
2	22.90	23.34	25.13	26.40
3	20.34	21.94	26.12	28.11
4	18.40	20.74	27.19	29.83

Based on the results of the calculations, the boundaries of the zones with increased optical losses for the extreme rays on the surfaces of the SOE (zones *2* and *4* in Fig. 1), as well as the near and far boundaries of the working zone (zones *1* and *5* in Fig. 1, Table 1) were determined. The values of $F_{\min}$ and $F_{\max}$ for FBL with $D = 1$ mm could not be calculated. It was found that at such a diameter there are no regions within which the optical losses on the refractive surfaces of the secondary sphere for the outermost rays coming out of the BBL would not exceed 5 %. For all other cases ($D = 2,\ 3,\ 4$ mm) the FBL can theoretically be located at any distance from the BCL in the working zone with a range of distances $[F_{\min}; F_{\max}]$, within which the energy losses in the system are minimal and the efficiency of such SOE is thereby maximized. At the same time, it should be noted that the increased optical losses in *2* and *4* (Fig. 1) refer only to the peripheral beams, while most of the remaining beams pass through the secondary concentrator with sufficiently high efficiency. Therefore, it was reasonable to extend the search range of the optimal sphere position to the boundary values $[Z_1; Z_2]$.

The dependences of the average concentration factor in the spot containing 95 % of the concentrated radiation at different values of F in the range $[Z_1; Z_2]$ were obtained (Fig. 3, *a*). In this case, the values of the average concentration coefficient were tracked in the following planes along the ray path: the top of the sphere (corresponding to the $\delta = \delta_{\mathrm{FBL}} = 0$ mm), plane), the center of the sphere $\delta_{\mathrm{HBL}} = -D/2$) plane), and the location of the truncation (transect) plane of the sphere (δ_{TBL}).

Table 2. The average concentration factor C (multiples) and distance F (mm) for rational installation plane of SC

Diameter of the sphere D, mm	$\delta_{\text{FBL}} = 0$		$\delta_{\text{HBL}} = -D/2$		δ_{TBL}		Coordinate and plane δ, mm
	C_{FBL}	F	C_{HBL}	F	C_{TBL}	F	
1	6288	24.55	836	26.5	6625*	24.35	0.010
2	4621	22.8	835	26.5	4710*	22.6	0.025
3	3603	21.2	838	26.5	3603*	21.2	0.000
4	2894	19.5	839	26.5	3005	20.0	−0.050

* At $\delta \geq 0$ FBL is considered for SOE.

Figure 3, *a* shows an example for the case of $D = 3$ mm (similar dependencies were obtained for $D = 1$, 2 and 4 mm). For each of the selected planes, the corresponding average spot concentration coefficients C_{FBL}, C_{HBL}, C_{TBL} were determined at different SOE diameters (Fig. 3, *b–d*). The results of calculations of the maximum values of concentration factors ($C^{\max}$) for various configurations of secondary optics are presented in Table 2. It was found that for FBL-type SOEs with $D = 1$, 2 mm $C^{\max}_{\text{FBL}}$ values are observed when the sphere does not touch the radiation receiver and there is an air gap between them $\delta_{\text{FBL}} = 0.01$ or 0.025 mm, respectively. Obviously, configurations with such a small optical gap between SOE and SC are difficult to implement in practice. Therefore, variants with SOE−SC optical contact should be considered as priority and more technologically advanced for the experimental design of micro-CPV-module. Despite the maxima for the values of the average concentration factor of systems with FBL ($D = 1$, 2 mm), the distances F, at which such values are achieved, are outside the range of rational SOE installation (Table 1). And this means a significant increase in transit losses: part of the radiation, passing by FBL, will create scattered light inside the module and, falling on the electric generating board, heat it.

Calculations show that for the considered BCL with $R = 26$ mm and the SOE variant of the full-sphere type, the coordinates of the section plane with $C^{\max}_{\text{FBL}}$ coincide with those of the receiver plane at $D = 3$ mm, whereas at $D = 4$ mm such a plane is located inside the SOE at a distance of $\delta = -0.05$ mm. Accordingly, in the variant of SOE of TBL type with $\delta_{\text{TBL}} = -0.05$ mm there will be provided a decrease in the light spot with simultaneous growth of the average multiplicity of radiation concentration in it in comparison with the case of FBL of the same diameter with a SC sphere ($\delta = \delta_{\text{FBL}} = 0$ mm) located on the surface of the sphere. However, the observed increase in the value of the average multiplicity of radiation concentration using SOEs of the TBL type does not exceed 3−5 %, which makes its application inexpedient due to the difficulties in manufacturing optics with the „truncated-sphere“ shape. From the technological point of view, the coordination of optical and electrical parts when mounting a micro-CPV-module turns out to be many times simpler and cheaper with the use of SOEs with a larger diameter.

It should be concluded that SOE of the full sphere type with a diameter of 3 mm is the most optimal variant for the micro-CPV-module system with a primary concentrator based on a quartz double-convex lens with an aperture of 10×10 mm, because it allows maintaining sufficiently high values of the maximum average radiation concentration factor in the focal spot (compared to the FBL variant with $D = 1$ mm). At the same time, the module height is reduced by 10−15 % with virtually no transit losses of radiation. The proposed approaches to finding an effective solution for the optical system of a micro-CPV-module are obviously applicable to other design parameters POE (with another radius of curvature of refractive surfaces) with saving the principles of searching for the optimal diameter of the full sphere for SOE.

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Conflict of interest

The authors declare that they have no conflict of interest.

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