Search for the optimal solution for the optical system of the „micro-CPV"-module

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This work is devoted to studying optical-energy characteristics of the micro-concentrator module optical part and searching for the design optimal according to criterion „the maximum average sunlight concentration in the minimum-radius focal spot ". The results of optimizing the lenses showed that the optimal solution for the micro-CPV module is an optical system made of a biconvex lens having twice the concentrating power at a focal length shorter than that of a plano-convex lens of the same dimensions.

Keywords: photovoltaics, micro-concentrating module, multi-junction solar cell, optical-energy characteristics of optical systems, plano-convex and biconvex lenses.

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Recent trends in modern concentrator photovoltaics are associated with a gradual transition to increasingly compact modules which will be created on the basis of small-size short-focus microconcentrators and submillimeter-size solar cell (SC) photoconverters [1–3]. Besides decreasing the module dimensions, the approach referred to as „micro-CPV"can significantly reduce the thermal load in each cell of the module with maintaining a high average concentration of solar radiation. A more uniform heat distribution on a single heat-sink panel reduces the effect of mechanical stresses caused by the mismatch in thermal expansion coefficients of the semiconductor and heat-sink materials; as a result, the module reliability increases [2,3]. In addition, the effect of lateral currents on the current-voltage characteristics [4] caused by non-uniformity of the solar cell illumination may be suppressed. Reduction in resistive losses from lateral currents opens the way to using alternative lower-cost electrical contacts, for instance, transparent conductive layers. The negative impact of the „peripherals", which is characteristic of conventional modules, also turns out to be weaker in the case of the micro-CPV conceptual solutions.

Notice that mere miniaturization of conventional concentrator modules optimized for three-junction SCs with the photosensitive surface area equal to tens of square millimeters is not always an acceptable solution for implementing micro-CPV [6]. Reduction of sizes of the module components imposes significantly more restrictions and requirements: fabricating precision micro-optics, manipulating multiple interconnected elements in the module, and integrating microchips over large areas, positioning and optical matching of various elements with the micrometric precision, since even small deviations can significantly affect the module output characteristics. Therefore, the goal of the study was to find the optimal optical system to be used as a solar radiation concentrator as part of the micro-CPV module.

In this work we consider for the micro-CPV module optical systems based on single square-aperture plano-convex or biconvex lenses (PCL and BCL, respectively). In the calculation model, the main initial data for the task of searching for the curvature radius of refractive surfaces was preset in the form of the spectral dependence of the optical material (silicone Wacker 604) refractive index, solar radiation spectrum in the range of 300–1800 nm (that is, the spectral sensitivity range of a multijunction solar cell), aperture (Ap) of a lens 20×20, 15×15, 12×12, 10×10, 8×8, or 5×5 mm in size, and the lens–SC distance. In the case of BCL, radii of the inlet and outlet refractive surfaces (r) were assumed to be equal to each other. Local geometric deviations of the lens refractive surfaces from the ideal spherical profile were ignored.

The simulation was performed based on the method of tracing the light rays during their passing through the optical system. Radiation and angular dimensions of the source are defined by the flow of rays directed to the concentrator inlet aperture. The concentrator is represented as a set of planar and curved refractive surfaces of the given size and optical media separating them. The optical-energy characteristics of the system are to be calculated by summing the light ray energy contributions to the cells of the receiverś radial-ring grid with accounting for optical losses of all types, including spherical and chromatic aberration. The presence of aberrations prevents the rays passing through the lens against focusing at a single point but makes them intersecting a somewhat extended segment of the optical axis. Under these conditions, the calculated focus position (f) in most cases cannot serve as a reference for obtaining the receiver coordinates ensuring the optimal optical-energy characteristics of the concentrating system. Therefore, modeling was performed in the paraxial approximation

Lens optical-energy characteristics at $k = 0.95$

Lens size, mm	Focal distance, mm		Maximum mean concentration, vol.%		Spot diameter in focus, mm	
	BCL	PCL	BCL	PCL	BCL	PCL
20 × 20	40	60	229	129.8	1.42	1.88
15 × 15	30	45	232	129.9	1.06	1.4
12 × 12	24	36	235	129.7	0.84	1.12
10 × 10	20	30	237	129.5	0.70	0.94
8 × 8	16	24	240	129.9	0.56	0.74
5 × 5	10	15	251	129.5	0.34	0.46

when the optical system parameters are related through the thin lens formula. In this approach, the PCL curvature radius can significantly affect the occurrence of Fresnel losses near the lens peripheral areas, up to the total internal reflection. Thus, in the case of PCL, the transmittance factor at the extreme angular point of the lens was estimated depending on r and f (see Fig. 1 and Table). The results showed that the effect of total internal reflection at the PCL edges (transmittance > 95%, the gray area in Fig. 1) may be eliminated if the minimum lens curvature radius is restricted to $0.85Ap$. Thereat, the PCL focal length appears to be 30% greater than that of BCL with a similar aperture. Thus, by choosing BCL with a shorter focal length we can significantly reduce the design height of the micro-CPV module.

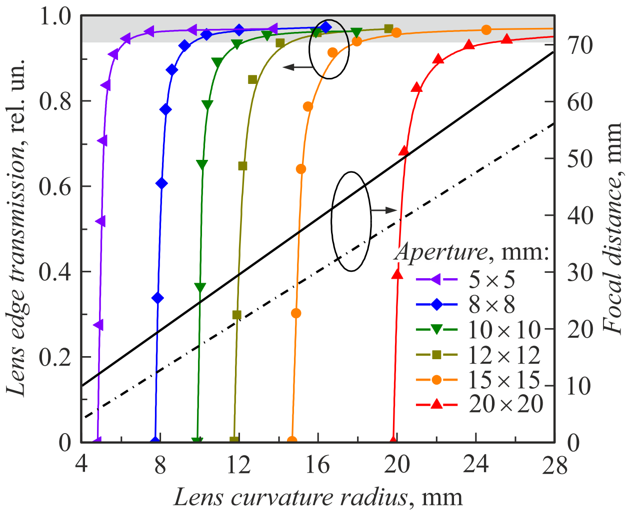

Figure 1. Dependences of transmittance in the PCL corner part on the refractive surface curvature radius for different apertures, and dependences of focal lengths of PCL (solid line) and BCL (dash-and-dot line) on the lens curvature radius.

Calculation of the optical system begins with fixing the preset distance between the top of the lens outlet surface and receiver; after that, the first approximation of the lens radius is to be calculated via the thin lens formula. In further optimization, the refractive surface radius is to be varied until the minimum-size criterion for the focused spot on SC is met provided the average radiation concentration factor within it is maximal. In the framework of the micro-CPV concept, this approach allows avoiding imposing severe restrictions or requirements concerning the minimum module height. Fig. 2 presents the

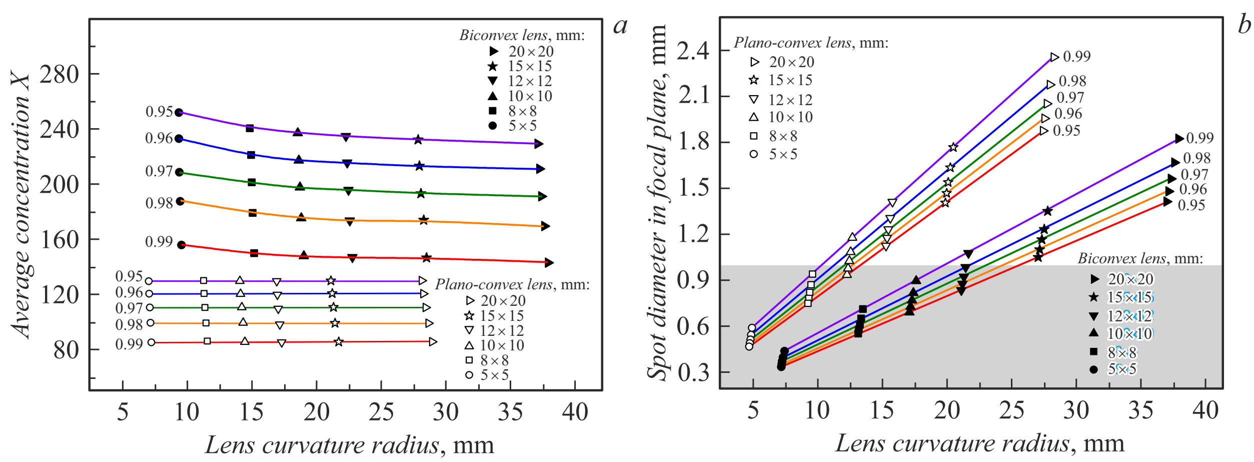

Figure 2. Dependences of the average concentration factor in the spot (*a*) and focused spot diameter (*b*) for BCL and PCL of different sizes on the surface radius at concentrated-radiation interception factors $k = 0.95-0.99$.

results of the accomplished optimization of the lenses at different interception factors k of the concentrated radiation. The results show that, at optimal values of the refractive surface radii, the average energy concentration in the spot appears to be almost the same for all the lenses. The same may be said about the optical efficiency which is $\sim 94\%$ for lenses of both types (BCL and PCL). This is because the ratio of the lens size to focal length remains fixed in the course of optimization. Nevertheless, when k and overall dimensions of the lenses are identical (Fig. 2, a), the average PCL concentration is about 1.75 times lower, while the focal spot is proportionally larger than in the case of BCL. As for the focal length at which the minimal light spot gets formed, it is 1.5 times less in the case of BCL.

The BCL system appeared to be most optimal also from the viewpoint of the focused spot diameter (Fig. 2, b). Comparative estimates showed that lenses less than 15 mm in aperture (the gray area in Fig. 2, b) should be chosen for submillimeter-sized SCs.

Thus, the study has shown that optical systems with BCL have the best potential for the micro-CPV concept, since they form a concentrated radiation spot of a smaller area at a shorter focal length compared to similar PCL-type concentrators.

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Conflict of interests

The authors declare that they have no conflict of interests.

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