Technical Physics Letters, 2024, Vol. 50, No. 12

Secondary optics for the „micro-CPV"system

© S.A. Levina, D.A. Malevskiy, M.A. Nakhimovich, A.A. Soluyanov, M.Z. Shvarts

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

Received May 3, 2024
Revised July 10, 2024
Accepted October 30, 2024

This work is devoted to the study of the optical-energy characteristics of optical part of micro-concentrator module and the search for the optimal design according to the criterion "the maximum average concentration of sunlight in the focal spot of the minimum radius". The results of lens optimization showed that the optimal solution for the micro-CPV module is an optical system made of a biconvex lens, which has twice the concentrating power at a shorter focal length compared to 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.

DOI: 10.61011/TPL.2024.12.60358.6584k

The technology of micro-concentrator photovoltaic („micro-CPV") modules is based on the use of solar cells (SCs) of submillimeter sizes in combination with short-focus optics [1,2]. The principal task in design of an optical system for a micro-CPV module is to obtain a high concentration ratio of radiation in a focal spot less than 1 mm in diameter with a radiation interception coefficient above 90%. Concentration systems satisfying this requirement are normally constructed on the basis of primary optical elements in the form of spherical lenses or small-sized Fresnel lenses and secondary optical elements of a spherical („ball") or hemispherical shape or their close substitutes (glass focons, LED lenses, etc.).

In the present study, we consider a micro-CPV module formed on the basis of three-junction SCs in combination with primary and secondary optical systems. The used GaInP/GaInAs/Ge SCs with a photosensitive surface diameter of 1 mm (photovoltaic part of the module) provided a photocurrent density generation level of 13.2 mA/cm^2 (AM1.5D, 1000 W/m^2) at $\sim 10\%$ shading of the photoreceiving surface by the contact grid.

The primary optical elements (POEs) were single plano-convex (PCL) and bi-convex (BCL) lenses with a square 10×10 mm aperture and a curvature radius of 26 mm made of quartz glass. As was demonstrated earlier [3], such lenses are optimal for submillimeter SCs, since they provide a higher average concentration ratio in a smaller spot area at a shorter focal length than similarly sized refractive/reflective or combined-type concentrators [4]. Two configurations of secondary optical elements (SOEs) were examined: (1) a ball lens (BL) 2 mm in diameter secured by a clamping system; 2) a half ball lens (HBL) 1 mm in diameter that is glued directly to the photosensitive SC surface with an optical compound. The object under study is a single cell of a POE−SOE−SC micro-CPV-module secured on micrometric translators and a goniometer (Fig. 1) for precise control over its motion in three planes and over the deviation from the normal to incident radiation (misalignment angle θ).

A laboratory solar radiation simulator, which forms a collimated light flux with an AM1.5D spectrum and an irradiance of 750 W/m^2 in the plane of concentrating elements of the micro-CPV module, was used in experiments. The illumination level was slightly lower than the standard (1000 W/m^2) due to the use of light filters that ensured high-quality (class A) reproduction of the spectral composition of radiation by the simulator; however, this did not affect the comparative assessment of radiation concentration systems. The photocurrent density values normalized to an irradiance of 1000 W/m^2 are presented in Figs. 2, 3 and the table. The optimum mounting plane for the optical components of the module was determined experimentally by adjusting the POE–SC distance (l) with different SOEs installed directly above the surface of the radiation receiver (see Fig. 2 and the table). The misalignment characteristics of the micro-CPV module were monitored at the same time. Thus, the established optimum distance l for the POE−SOE−SC system corresponds to the minimum size of the light spot on the photosensitive SC surface with the maximum average ratio of solar energy concentration in it. The micro-CPV module fitted with a POE only was also tested under the same experimental conditions.

A comparison of photocurrent densities J (their values in Fig. 2 and the table are normalized to the POE aperture area, which is 1 cm^2) obtained for all optical system designs examined here reveals the advantage of an HBL-type SOE: higher recorded photocurrent densities, which exceed those obtained for a BL-type SOE by 10 and 20% in the case of PCL and BCL POEs, respectively. It should be noted that the indicated advantage stems from lower optical losses at the HBL−SC interface, which are reduced due to the fact that the indicated elements are in direct contact. Additional losses arise at the glass−air interface in the BL−SC system, since the radiation-focusing sphere is simply mounted on the

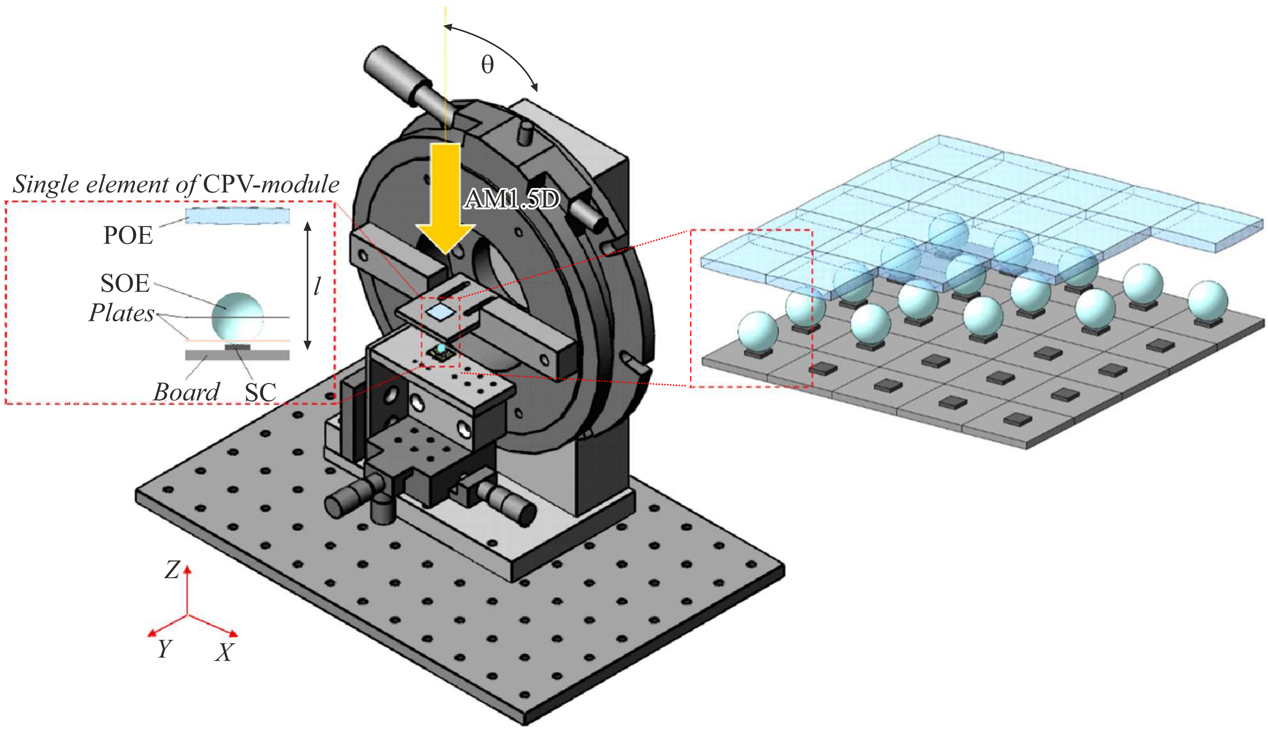

Figure 1. Image of a single POE–SOE–SC module element (left) secured on translators and a goniometer. l — distance between the POE surface and the SC; θ — angle of misalignment of a single module element relative to the normal to the incident parallel light flux (AM1.5D spectrum). The schematic diagram of one of the micro-CPV module designs is shown on the right.

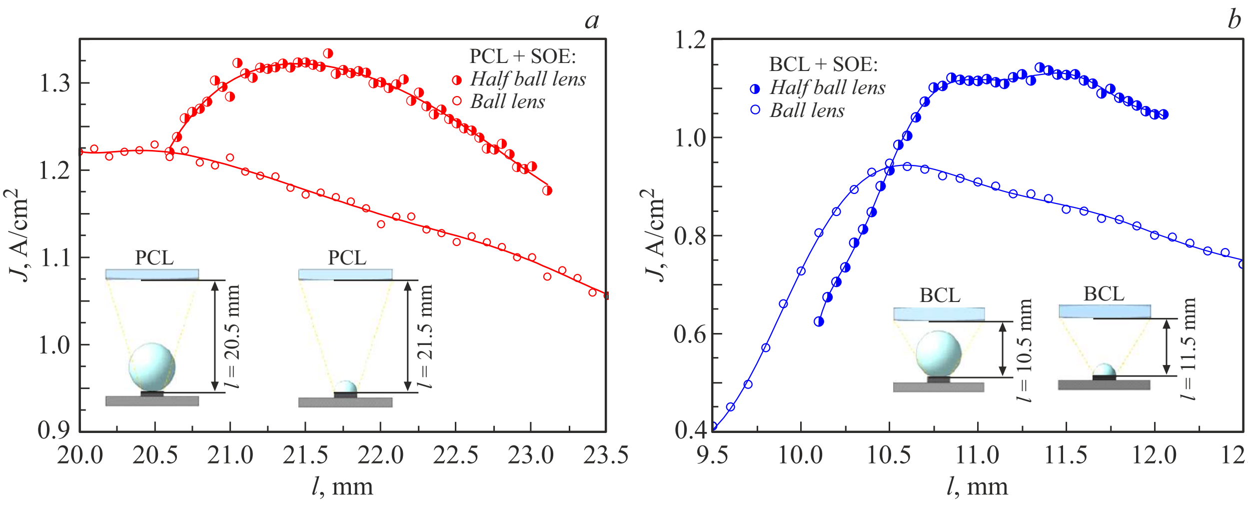

Figure 2. Dependence of the SC photocurrent density on the distance between the POE surface and the SC in the case of PCL (a) and BCL (b) and different SOEs. The optimum distances between the module elements are shown in the insets.

SC (without an additional intermediate layer of, e.g., optical glue). The module with a BL-type SOE has an advantage in a reduced structural height (see the table).

The misalignment characteristics of the micro-CPV module with a SOE and without it under identical experimental conditions are presented in Fig. 3. The estimates of „permissible" misalignment angle θ for various module configurations are given in the table. The addition of a SOE made it possible to expand the range of deviation from the normal to incident radiation to $\pm 1.5^\circ$ (in the BCL+BL optical system design), suggesting a significant increase in power generated by the module in active tracking modes under natural Sun. Comparative estimates (see the table) revealed that the optical system with a ball lens is the optimum one in terms of geometric concentration ratio and efficiency.

Parameters of the optical system of micro-CPV modules and permissible misalignment angles

Optical system configuration	Distance l, mm	Photocurrent density J, A/cm^2	Permissible misalignment angle θ, deg
PCL	21.5	1.41	0.3
PCL+HBL	21.5	1.32	0.5
PCL+BL	20.5	1.22	0.9
BCL	11.5	1.39	0.35
BCL+HBL	11.5	1.14	0.7
BCL+BL	10.5	0.94	1.5

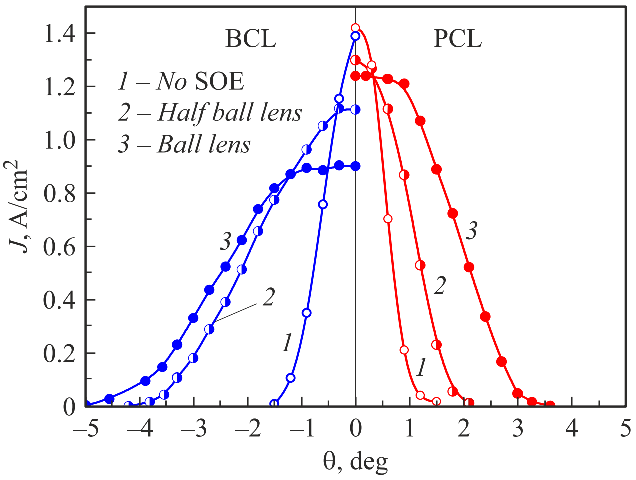

Figure 3. Dependence of the SC photocurrent density on the angle of inclination of the module relative to the normal to incident radiation for different combinations of optical elements.

Thus, although additional optical elements complicate significantly the module assembly process and require precision accuracy in mounting of microlenses on the SC surface, the use of secondary optics is justified, since it allows for a significant relaxation of requirements as to misalignment of the module relative to the direction to the Sun while maintaining a high radiation concentration ratio. Additional laboratory and field experiments will be performed in future to determine conclusively the optimum design options for micro-CPV modules with PCLs and BCLs and secondary hemispherical and spherical elements.

Funding

This study was supported by the Russian Science Foundation, grant № 23-29-00499 (https://rscf.ru/project/23-29-00499/).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] C. Domínguez, N. Jost, S. Askins, M. Victoria, I. Anton, AIP Conf. Proc., **1881**, 080003 (2017). DOI: 10.1063/1.5001441
[2] A. Ritou, P. Voarino, O. Raccurt, Solar Energy, **173**, 789 (2018). DOI: 10.1016/j.solener.2018.07.074
[3] S.A. Levina, A.A. Soluyanov, M.Z. Shvarts, Tech. Phys. Lett., **49** (12), 42 (2023). DOI: 10.61011/TPL.2023.12.57581.94A.
[4] K. Shanks, S. Senthilarasu, T.K. Mallick, Renew. Sust. Energy Rev., **60**, 394 (2016). DOI: 10.1016/j.rser.2016.01.089

Translated by D.Safin