Technical Physics Letters, 2023, Vol. 49, No. 12

Linear Fresnel lenses with reduced chromatic aberration for space solar batteries

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Received May 19, 2023
Revised July 31, 2023
Accepted October, 30, 2023

A combined linear Fresnel lens has been proposed for using in space-application concentrator modules. In the combined Fresnel lens, the size and focal distance of each microprism were selected individually taking into account the proposed criteria, which made it possible to significantly reduce the solar radiation spectral non-uniformity within the focal spot on the surface of the InGaP/InGaAs/Ge multijunction solar cell.

Keywords: linear Fresnel lens, multijunction solar cell, solar radiation concentrators, space solar batteries.

DOI: 10.61011/TPL.2023.12.57585.173A

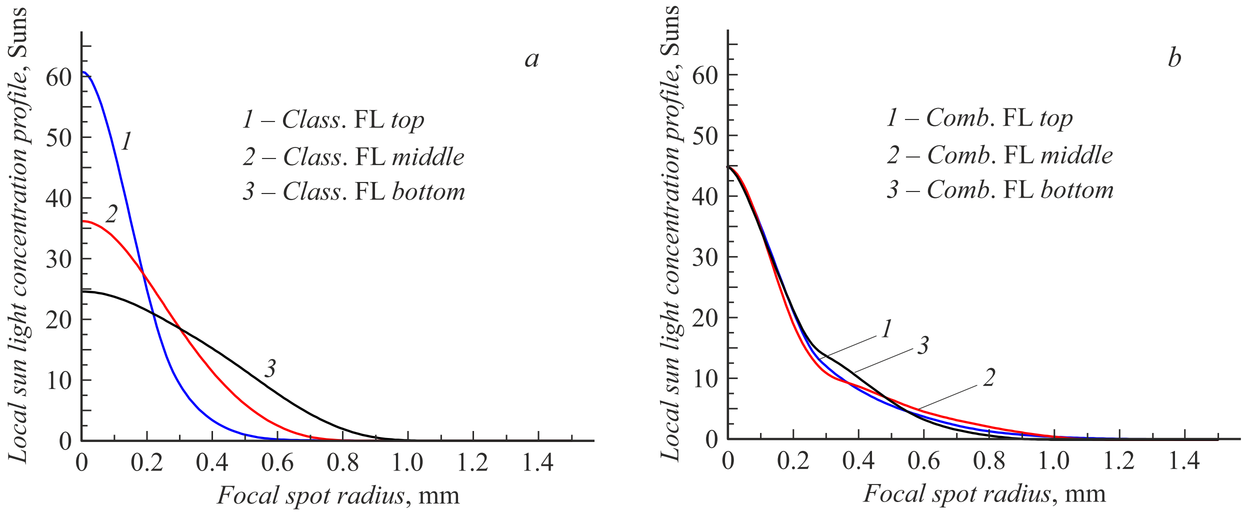
The solar radiation concentration systems based on linear Fresnel lenses (FLs) used jointly with multijunction solar cells (MJSCs) are realy promising for application in spacecraft solar batteries. The use of concentrator solar modules allow reducing the consumption of highly efficient but expensive MJSCs proportionally to the sunlight concentration ratio [1–3]. In addition, the sunlight concentration increases the solar panel efficiency and resistance to radiation. This makes it possible to use solar energy concentrators not only in low-Earth orbits but also in long-distance space missions characterized by high levels of radiation and low sunlight intensity, which lead to a decrease in the specific power output per unit area of solar panels in case concentrator-free solar panels are used. The mainstream scientific laboratories have carried out a number of research projects with concentrators based on Fresnel lenses [3–7], including those tested in a successful deep-space flight.

The classic linear FL is an array of many refractive microprisms made of silicone compound by polymerization on a glass base. The linear FL transverse size is 25 mm, the design focal distance is 32 mm. The Fresnel profile pitch is 0.25 mm. The geometric concentration of such FL is 5–8 units depending on the MJSC size (transverse size of 3–5 mm). In designing concentrators of this type, the issue was to concentrate the solar radiation in the MJSC central part into a narrow band so as to achieve the preset accuracy of the space battery orientation and reduce the required precision of mounting solar cells on the heat-removing base within the solar battery [1–3] .

The main factor reducing the efficiency of Fresnel lenses comprised in the concentrator systems at low solar radiation concentration ratios is chromatic aberration. In MJCS, photosensitive $p-n$-junctions are connected in series. Therefore, spectral non-uniformity in the solar radiation distribution profile on the MJSC surface in subranges corresponding to the spectral photosensitivity of each $p-n$-junction within the InGaP/InGaAs/Ge MJSC results in limitation of the total photocurrent and efficiency of the modules. For instance, when the previously studied linear Fresnel lenses [1,3] with a constant pitch of 0.25 mm in the focal spot center are used, the difference between the maximum and minimum solar radiation intensities for three AM0 solar spectrum subranges ($1367\,\mathrm{W/m^2}$) is tens of percent [3]. The same proportional difference is observed in the photocurrent density distribution for individual MJSC $p-n$-junctions. Being minimal, especially in the focal spot center, the solar radiation magnitude restricts the MJSC total photocurrent, since in this case the MJSC central part receives the major part of the focused solar radiation (see the Figure, *a*). A number of studies have proposed to solve this problem by creating a Fresnel lens of a more complicated configuration, for instance, by forming a Fresnel profile made of a silicone compound on a dome-shaped transparent base [4,7]. Paper [5] proposed a design of a composite solar radiation concentrator consisting of a diffraction grating and linear Fresnel lens; such a design allows for the spectral and spatial separation of solar radiation into subranges corresponding to photosensitivities of the Ge and GaAs $p-n$-junctions. In both cases, the design of the concentrator module becomes much more complex.

This study proposed to solve this problem by creating a linear Fresnel lens profile so that parameters of each microprism are selected separately, and both the Fresnel focal distance and profile pitch are being varied. The final profile of solar energy distribution on the MJSC surface was also modeled. The solar radiation distribution profile in the Fresnel lens focus was calculated by the ray tracing method. This method is based on tracing the path of multiple rays from the radiation source through the concentrating system to the receiver (MJSC). The model allows tracing the path of all the rays incident from the solar disk surface to the surface of the solar cell at the angular size of 32 arcmin.

Along with this, the following criteria were proposed for the calculation: the focal spot transverse size corresponding to the spillover efficiency of 95%, and the minimal difference between the solar radiation concentration ratios



Distribution profile of local solar energy concentration on the MJSC surface for a classic linear FL with the pitch of 0.25 mm (*a*) and combined linear FL with the pitch of 0.25 mm in the FL center and 0.15 mm at the FL edge (*b*).

The difference between the maximum and minimum values of the solar radiation local concentration in three spectral ranges in the MJSC center for two FL types, and the mass of a double linear FL 100 × 50 mm in size with the classic and combined Fresnel profiles

Parameter	Fresnel profile pitch for a classic FL and central microprism size for combined FL, mm			
	0.25	0.5	0.8	1.0
Difference in illuminances in the MJSC center for a classic FL, ratio	36.22	21.09	11.65	8.15
Difference in illuminances in the MJSC center for a combined FL, ratio	0.051	0.103	0.799	0.845
Classic FL mass (100 × 50 mm), g	2.020	2.380	2.810	3.120
Combined FL mass (100 × 50 mm), g	2.007	2.310	2.670	2.900

in three spectral subranges (top, middle, and bottom ones). Individual selection of parameters for each microprism according to the above-mentioned criteria ensured significantly higher spectral and spatial uniformity of the radiation formed by FL on the entire MJSC surface. For instance, when the central microprism widths are 0.25 mm and outer ones are 0.15 mm, the peak solar radiation concentrations in three spectral subranges are about 45 units with the maximum difference of 0.05 units in the focal spot center; this demonstrates a good solar radiation spectral uniformity in three subranges corresponding to spectral photosensitivities of three MJSC p–n-junctions (see Fig. *b* and Table).

By calculation, profiles of classic and combined linear FLs were created for a wide set of microprism transverse sizes. The microprism sizes varied from 1 to 0.25 mm. One can see that the combined linear FL ensures a significantly better spectral uniformity of solar radiation over the entire MJSC surface than the classic FL (see the Table).

Linear Fresnel lenses used in spacecraft employ high-cost ultra-pure silicone elastomers, e. g. Dow Corning DC 93-500 [5]. This is necessary because of the need to avoid degassing and deposition of any polymeric materials on the MJSC surface. Therefore, for linear Fresnel lenses important is such a parameter as the lens panel weight depending primarily on the microprism geometric dimensions. The Table presents the weights of a double linear Fresnel lens 100 × 50 mm in size with Fresnel profiles of two types; the lens load-bearing base is quartz glass 0.1 mm thick. Masses of the combined and classic LFs with the 0.25 mm pitch are significantly lower than those of the combined and classic FLs with a larger microprism transverse size; this proves to be a significant advantage in the case of space solar batteries and allows reducing their prime cost. However, solar radiation spectral non-uniformity for a combined FL with any microprism size is several times lower than that for a classic FL (see the Table).

The proposed concept of a combined Fresnel lens with individually varying transverse size and focus of each microprism allowed significant reduction in the influence of chromatic aberrations on the formation of the distribution profile of the solar radiation local concentration on the

MJSC surface. Mass of the lens panel with the combined FL profile is also less than that in the case of the classic profile. In further research concerning this problem, it will be necessary to model the formation of the photocurrent density distribution profile on the MJSC surface, including determination of the mechanism of photocurrent losses at different levels of spectral and spatial non-uniformity of the incident solar radiation.

Funding

The study was supported by the Russian Scientific Foundation (project № 22-29-20190 of 23.03.2022) and grant of the Saint-Petersburg Scientific Foundation (project № 30/2022 of 14.04.2022).

Conflict of interests

The authors declare that they have no conflict of interests.

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