Development of Lens Concentration Systems with Secondary Optical Elements

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Abstract: In the work, results of comparative investigation of the optical efficiency and power characteristics of concentrating systems with primary Fresnel lenses and secondary optical elements (SOE) are presented. The following types of the secondary optics are under consideration: an open truncated tetrahedral equilateral pyramid with specular walls and a kaleidoscope with a flat or convex top surface, which ensure achieving the high optical efficiency of a two-element optical system, lowering its sensitivity to the Sun tracking inaccuracy and increasing uniformity of concentrated radiation distribution on a solar cell. As a result of the investigations carried out, the optimum parameters of the secondary optics have been determined, and the best optimal versions are recommended for practical usage in concentrator modules.

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INTRODUCTION

To reduce the cost of photovoltaic power installations with lens sunlight concentration, it is necessary to decrease dimensions of a solar cell (SC), in fabricating which expensive semiconductor materials and technologies are used. The “smearing out” the lens focal spot due to the chromatic aberration and the requirements to maintain the response to sunlight in the wide range of acceptance angles hinders the substantial decrease of SC dimensions and, hence, of the average sunlight concentration on the SC. The problem solution is in application of secondary optical mirror or lens elements of different types (or their combination) or filters as a part of the concentration systems.

In a number of cases, the SOE are responsible for:

- uniformity of SC surface irradiation or formation of a predetermined illumination profile on it [1,2];
- compensation of the initial lens thermoaberrations arising due to variation of its operating temperature [3];
- spectral splitting of the concentrated radiation flux with the aim to achieve the maximum efficiency of its conversion by solar cells of different types [4];
- compensation of the scatter on the focal distance and of the nonparallelism of the optical axes of the initial lenses at their integration into a lens panel and also compensation of inaccuracies in positioning the SCs on a heat-spreading plane [2].

The criterion for selecting the optimum version of the SOE may be, predominantly, formulated in the following way: the concentrating system should ensure the maximum average sunlight concentration and optical efficiency and, also, high uniformity in distribution of the concentrated radiation on a SC in a prescribed range of sun tracking angles.

In this work, the following versions of secondary optical elements (SOE) have being considered:

- open equilateral pyramid with specular walls (further – specular pyramid or SP);
- kaleidoscope (equilateral truncated glass pyramid with a flat or convex spherical top surface).

The comparative investigation of optical-power characteristics of concentrating systems with a Fresnel lens concentrator and SOE of different types are presented.

PRIMARY FRESNEL LENS

A comparison of optical materials suitable for manufacturing a primary Fresnel lenses (FLs) has shown that the refraction index increase in combination with less difference in refractive index values for short (UV) and long (IR) wavelengths affects positively the lens concentrating capability [5]. Based on this, the FL profile was designed of urethane polymer. The optimal FL has side dimension of 40 mm, focal distance f = 70 mm and pitch step of 0.25 mm [5]. It has been found that, in going to the material with the greater refraction index, at accurate system orientation to the Sun and absence of the secondary optics, the average concentration ratio on a SC reaches 700 X and the system optical efficiency approaches 86 %. In this case, 95% of the power is concentrated on a SC with 1.4 mm x 1.4 mm designated illumination area. The values mentioned above are obtained with accounting for the mean-statistical value of the FL tooth tilt angle deviation equal to 6 min. of arc and with accounting for radiation losses on the profile tooth top and valley roundings (were taken constant and equal to 5 μm) [3] and served as the references in comparing optical systems having the secondary optics of different types both between each other and with a system without the secondary optics.

SECONDARY OPTICAL ELEMENTS

The mathematical models and algorithms based on ray tracing have been elaborated for calculating the optical-power characteristics (OPC) of the "FL-SOE" system [6]. For each type of a SOE, calculations of dependencies of the average concentration ratio C_{av} for a SC and of the system optical efficiency η_{opt} on the acceptance angle ν have been carried out.

To describe the set of the parameters being optimized (pyramid height h, inclination angle of its walls θ and radius of curvature of the covering input surface R_s.) in Fig. 1, as an example, a SP and a kaleidoscope with a spherical top surface are presented.

The preliminary calculations carried out have shown that, practically for all versions of the SOE, the obtained optimum values of secondary element geometrical parameters do not coincide for the conditions of accurate and inaccurate orientations.

To resolve this contradiction, the criterion of their choice was formulated with use of the concession principle. This principle implies that the system optimization is carried out independently over all criteria available, and the choice of optimal parameters is done according to one of them, which is accepted as main one. For the rest of the criteria such concession values are taken that determine the acceptable level in reducing the system efficiency by these criteria. Thereby optimization of SOEs of different types was carried out twice: by the maximum η_{opt} criterion at accurate orientation and by that at a typical value of the acceptance angle ν=1°. As the main criterion, the optical efficiency maximum at ν=1° was chosen, and the concession value was taken equal to 10%.

Beside capability of the secondary optics to raise the average concentration ratio and optical efficiency, its important property is a possibility to change the flux density distribution character and to create uniform irradiance of the SC surface with the aim to compensate the negative effect of the radiation redistribution on the multijunction SC characteristics. For this reason, to choose the optimal "FL – SOE" system, it is necessary to compare the optical-power characteristics (OPC) of these system with the aim to choose a version ensuring the most uniform irradiance distribution on a SC.

In the given case, of great interest is the analysis of OPCs obtained in a system with a kaleidoscope at different orientation conditions, since possibilities to change the irradiance character by a specular pyramid appear to be insignificant compared with distribution produced by a primary lens.

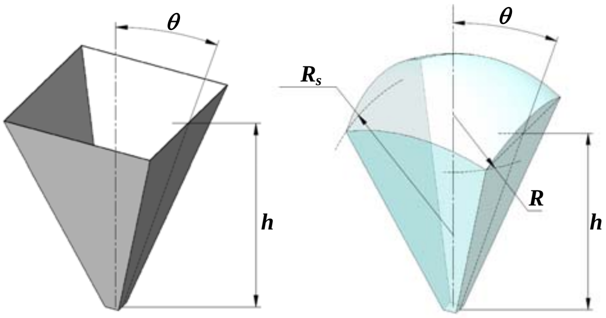

Figure 1. SOE of two types: specular pyramid (left) and kaleidoscope (right).

RESULTS OF SOE OPTIMIZATION

Kaleidoscopes with flat and convex top surfaces

To arrange an optimization process in a more convenient way the dimensionless parameter $\overline{R}$ (relative radius) was introduced. $\overline{R}$ is the ratio of R_s to the radius of a circle circumscribed about the pyramid top base R: $\overline{R} = R_s/R$. So, at $\overline{R}=1$, the covering lens is a semisphere, at $\overline{R} \to \infty$ - the top surface becomes flat and the kaleidoscope is shaped in a form of a truncated tetrahedral equilateral pyramid. For intermediate cases at $\overline{R}>1$ a covering lens is segment of sphere, height of which decreases with $\overline{R}$. Thus, the optimized parameters for specular pyramid are the pyramid height h and the inclination angle of walls θ, and those for the kaleidoscope - h, θ and $\overline{R}$, correspondingly.

The process of optimizing the kaleidoscope with convex top surface parameters by the pull-down method has been organized in the form of three home loops: by the specular pyramid height h (outer loop), by the angle of inclination of its walls θ and by the curvature relative radius of the input surface $\overline{R}$ (inner loop). Iterations by variable parameters inside each cycle were performed up to achievement of the local maximum of the chosen system efficiency. The optimum values of the secondary concentrator parameters correspond to the largest value of the system efficiency among obtained local maxima.

Fig. 2 presents dependencies of η_{opt} on the inclination angle of the kaleidoscope walls θ for its heights h from 2 to 10 mm at four values of the curvature relative radius of the input surface $\overline{R}$ and at the acceptance angles $\nu = 0°$ and $\nu = 1°$. It follows from the analysis of the presented dependencies that, to achieve maximum values of the optical efficiency and, correspondingly, maximum values of the average concentration ratio in the misorientation conditions, the curvature relative radius $\overline{R}$ of the kaleidoscope top surface must be within 1.5 - 2 at the inclination angle of walls of 22 - 28° and the height of 4 - 8 mm.

The effect of the angle of inclination of the kaleidoscope walls θ on its efficiency is associated with contradicting effect of this parameter on the primary lens intercepted radiation flow value and on the value of losses at reflection from the “glass -air” demarcation line. At a small kaleidoscope height, a large part of rays is reflected once (i.e. without losses) and the reflectance coefficient is practically independent on the angle θ in a wide range of its variation.

With increasing the kaleidoscope height, the number of reflections from its walls rises, in most cases only the first reflection being total (due to the total internal reflection effect), and all following ones being accompanied by an increase of the energy losses. The drastic rise of these losses is associated with the second and following reflections, at which the angle of the beam incidence on the “glass-air” demarcation line becomes, as a rule, smaller than the limiting one, and more and more rising part of its energy passes into the refracted beam, and, due to this, is lost.

Flux density distribution on a SC

Data on the optimum values of the secondary concentrator parameters obtained by simulation are presented in Table 1. It should be taken into account that the optimum secondary concentrator parameters correspond to the criterion of the maximum η_{opt} at the acceptance angle $\nu = 1°$ for a system with preassigned parameters of the primary lens and SC dimensions.

Comparison of OPCs show that the uniform irradiance distribution can be achieved at the following kaleidoscope parameters: $h = 6$ mm, $\theta = 22°$, $\overline{R} = 1.1$ (Fig. 3). However, in this case, the optical losses at misorientation become significant, which result in the efficiency drop down to ~79% (Table I). The optical losses can be decreased to some extent, if the version with $h = 10$ mm, $\theta = 20°$, $\overline{R} = 4$ (Table I and Fig. 3) is accepted, the illumination distribution nonuniformity rising.

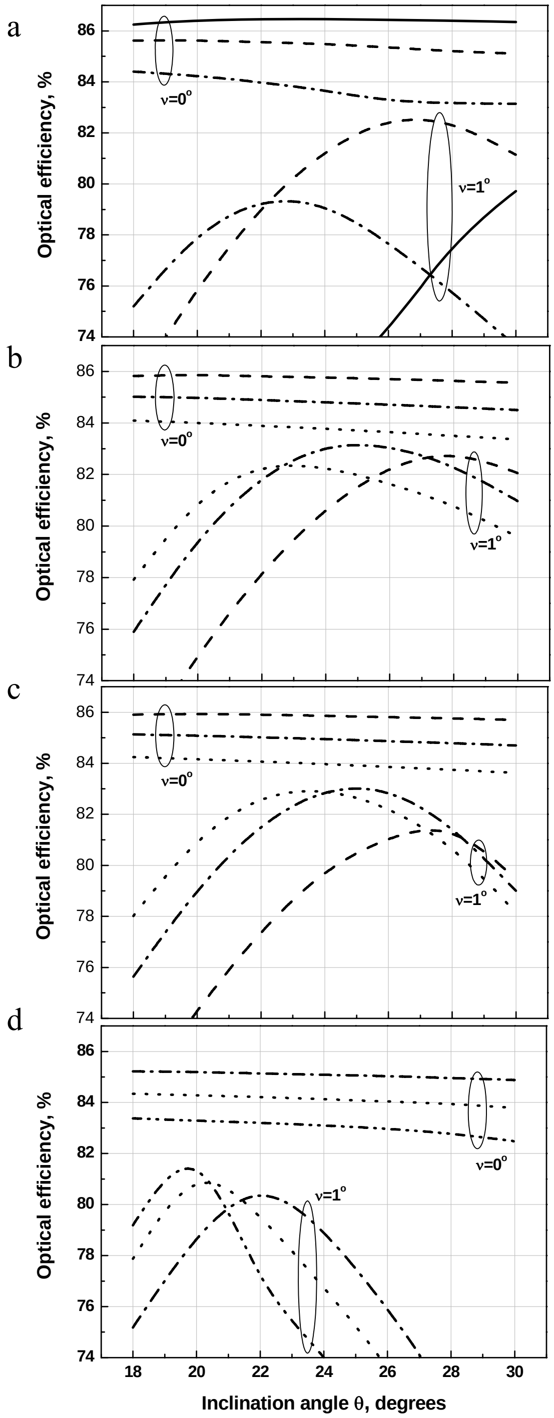

Figure 2. Rated dependencies of the optical efficiency on the height (h) and the inclination angle of walls (θ) of a kaleidoscope with the convex top surface at the acceptance angles $\nu=0°$ and $\nu=1°$. The relative radius $\overline{R}$ is equal to: a – 1.1 , b –1.5 , c – 2 , d – 4 . Kaleidoscope height h is indicated in following lines: solid – 2 mm, dash – 4 mm, dash dot – 6 mm, dot – 8 mm, dash dot dot – 10 mm.

Maximum optical efficiencies are achieved in the system with $\overline{R} \approx 1.5$ - 2 (see Table I), but in these cases it is impossible to compensate the pronounced nonuniformity of the irradiance distribution at any combination of h and θ parameters. The most acceptable version with the maximum optical efficiency at the level of 85.8% at precise orientation, that comparable with optical efficiency for a system without the secondary optics, is achieved at the kaleidoscope parameters $h = 4$ mm, $\theta = 28^{\circ}$, $\overline{R} = 2$ (the local concentration in the center is 3450X). Going to a position with $v = 1^{\circ}$ for the mentioned kaleidoscope configuration leads to forming the more uniform light distribution in conserving the efficiency at the level of 81.7 %.

Table I: Data for the optimum types of the secondary optics: 1-7 - kaleidoscope with convex (1-6) and flat (7) top surface, 8 - specular pyramid

Type	$\overline{R}$	R_s mm	h, mm	θ, deg.	C_{loc}, X		η_{opt} , %	
					$v = 0^{\circ}$	$v = 1^{\circ}$	$v = 0^{\circ}$	$v = 1^{\circ}$
1	1.1	3.6	4	27	5620	8230	85.3	82.5
2	1.1	4.9	6	22	870	1220	84.0	79.2
3	1.5	6.9	6	25	5560	7880	84.8	83.1
4	2	9.9	6	25	3760	3880	84.9	83.3
5	2	8.0	4	28	3450	2690	85.8	81.7
6	4	25	10	20	1500	1660	83.3	81.3
7	∞	∞	10	18	720	970	83.5	77.0
8	-	-	18	17	2340	1690	89.3	76.6

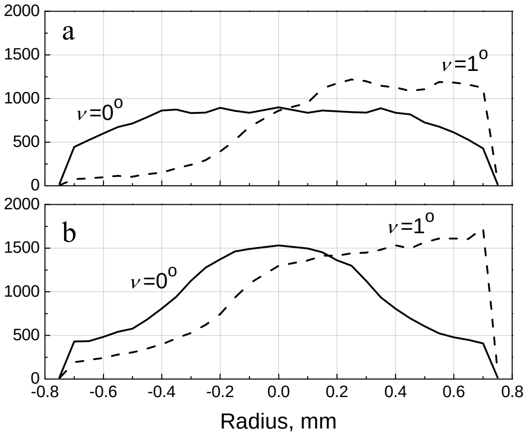

Figure 3: Distribution of the concentrated radiation over the solar cell radius for the kaleidoscope systems of following configurations (see Table I): a – 2, b – 6.

CONCLUSION

The following conclusions are obtained from the simulations. For any considered primary Fresnel lens with preassigned design–geometrical parameters, there exist versions of manufacturing the SOE of the kaleidoscope type, at which a uniform irradiance distribution on the SC surface takes place at precise orientation to the Sun and the optical efficiency exceeds 83.4 %. In the misorientation conditions, an insignificant difference in illumination over the SC surface arises at conserving the optical efficiency at the level higher than 80% at angles 0.7° and 0.5° (Table I, kaleidoscope version 2 and 7, correspondingly). It is obvious that the "FL - kaleidoscope" optical system version of 2 and 6 types (see Table I and Fig. 3) creating a more uniform irradiance distribution are, by the sum total of effects, preferential at their matching with multijunction SCs, even in spite of an insignificant (at the level of 2%) drop of the optical efficiency compared with maximally achievable rated values.

In going to the systems with higher values of the optical efficiency at $v = 1^{\circ}$, it should be searched for a compromise between 2 and 4% reduction of optical losses and a possible negative effect of significant differences in illumination of the cell surface on the operation of a multijunction SC.

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