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Improved Concentration Capabilities of Flat-plate Fresnel Lenses

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Abstract. This paper presents an experience in designing, manufacturing and testing the Fresnel lenses (FLs) for sunlight concentration in photovoltaic modules with multi-junction solar cells (SCs). A power ray tracing model is used for calculating and optimizing refractive profile parameters and obtaining optical-power characteristics (OPCs) of Fresnel lenses. In searching the optimum combination of the lens aperture, its focal distance and profile configuration, the optimization criterion was the maximum of the average sunlight concentration at high optical efficiency in the focal spot of minimum size. Analysis of characteristics of circular Fresnel lenses with conical (the facet generating lines are straight ones) and curvilinear (the facet generating lines are curved ones) refracting surfaces has been carried out. The effect material parameters on the lens optical efficiency were studied. Molds for Fresnel lens formation and experimental specimens were fabricated and a control of their profile parameters has been done. A degree of the effect of the light flux characteristics and Fresnel lens geometrical imperfections on validity of the experimental data interpretation has been examined. The correction procedure have been applied in the calculation model to establish the lens optical efficiency values at standard irradiance conditions.

Introduction

Fresnel lenses (FLs) are finding ever-widening application in modern actively developing photovoltaics becoming the main type of sunlight concentrators in different photovoltaic modules. Creation of photovoltaic modules, in which the high radiation concentration ratio is ensured (up to 500X and higher), appears to be the most justified in terms to economics [1-6]. However, in spite of the use of highly-effective multijunction SCs the efficiency of which reaching 40% [7,8], the total efficiency of the concentrator modules does not exceed even 30% [5, 6] [9.10]. One of the reasons for such an essential distinction between the efficiency values is a relatively low optical efficiency of both Fresnel lenses in themselves and the “lens-SC” system as the whole. It is obvious that the problem to search for optical materials, designs and parameters of Fresnel lenses ensuring achievement of the maximum sunlight concentration on a SC at a high value of the optical efficiency remains to be actual one. The lens chromatic aberration (CA) hinders to satisfaction of this requirement, which, at the wide sunlight spectral range and the finite Sun angular dimension, results in the essential “smearing out” the concentrated radiation in the plane of the SC location and in reduction of the irradiance level on SC due to special and spectral sunlight energy redistribution. The problem of decreasing the negative effect of the CA on the power efficiency of the “FL-SC” system may be solved by both a purposeful variation of the concentrated radiation characteristics by means of changing the profile and Fresnel lens parameters [11] and also selecting an optical material for forming the lens.

In this paper, the results of our activity on creating methods and approaches for designing circular Fresnel lenses, on selecting materials for their manufacture, in fabrication of experimental specimens and on studying the lens optical-power characteristics (OPCs) are presented.

Fresnel lens profile design and OPC calculation

In [12], a procedure for reducing the negative effect of chromatic aberrations in lens concentrators by a correct selection of the optimum combination of the lens dimensions, lens focal distance and geometric parameters determining the refracting surface profile. The criterion for optimization is the maximum of the average radiation concentration corresponding to the minimal size of the focal spot. The parameters controlling the lens profile at its preset dimensions and focal distance is the refraction index, the values of which are selected from its exactly determined dependence on wavelength for the chosen lens material. The calculations were performed with applying two models of the concentration process, based on the representations of the geometrical optics and photometry (power optics).

The photometric model of the concentration process is preferable one, since in that case one can obtain and analyze the lens OPCs, which describe the distribution of the concentrated radiation density in the focal plane. In determining the average values of the concentration ration and the optical efficiency, one may consider not the entire area of the focal spot, but the area of the circle, in which 95−98 % of the concentrated radiation power is collected (interception coefficient K_{int} =0.95-0.98) This allows obtaining a high-average concentration on the receiver without essential losses of the total power of the radiation passed through the lens.

For a lens with a profile corresponding to the selected value n_{calc}, OPCs are calculated.

A simulation mathematical model for calculating Fresnel lens optical-power characteristics is based on the ray tracing method for sunlight beams from the radiation source thought the lens toward the receiver. The incident radiation flux is simulated by the large number of conical bundles of rays with a body angle corresponding to the angular dimension of the radiation source. The conical bundle tops are located on the input surface of the protecting glass (or of the lens, if there is no glass) randomly according to the uniform distribution law. Each bundle consists of the great number of rays converging to its top, location of which within the radiation source body angle is also determined randomly according to the uniform distribution law. The considerable number of tracing rays were involved into simulation process to reduce errors in calculating the FL OPC.

The calculation procedure allows accounting for influence of the following factors on the OPCs:

-- local geometric inaccuracies of the operating facets (roof-mean square deviations of the angular profile errors σ);

- spectral dependencies of the refraction indices of the lens material and protecting glass determining the occurrence of the chromatic aberration;

- radiation power losses due to reflection from the glass top surface and from the glass-lens interface, Fresnel losses on the operating tooth facets and absorption in the glass and lens materials;

- radiation power losses on the nonoperating faces, technological top roundings and profile tooth valleys.

For mathematical description of the ray passage according to the geometrical optics laws from one concentrating system surface to another one through optical mediums with definite refraction indices, the equations of the analytical geometry and vector algebra were used. Accounting for local geometrical inaccuracies of the lens profile is done by introducing corrections for the vector components of the normal to the operating tooth facets. These corrections are calculated with using a generator of random numbers distributed by the normal law with a mean-square deviation. As a ray passes through absorbing optical mediums and their interfaces, the radiation energy transferred by it decreases. When the ray is incident on the nonoperating facets, rounding of tops and valleys of teeth of the profile, the ray is considered as "lost" one, and its further tracing is stopped.

To obtain the concentrated radiation power distribution in the receiver plane, it is divided into cells by a coordinate grid. Tracing the run of each ray in the system is ended by definition of the number of the receiver coordinate grid cell, on which it falls. The total luminance of each cell of the receiver (or a local radiation concentration ratio K_e) is determined by summarizing the energy contributions of all rays hit the given cell. Integration over all coordinate grid cells of the receiver allows obtaining the system optical efficiency η_{opt}, the average ratio of radiation concentration on the receiver K_{av} and other characteristics. η_{opt} and K_{av} are determined simultaneously in calculating for a great set of receivers from a minimal one single cell-sized to a maximal one, which accepts absolutely all rays passed through the concentrating system. Using approximation, one can obtain the $\eta_{opt}(r)$ and $K_{av}(r)$ dependencies, where r is the distance from the lens optical axis across the focal spot. Beside the enumerated characteristics, a dependence of interception coefficient of concentrated sunlight on the distance from the lens optical axis $K_{int}(r)$ was used. The value of $K_{int}(r)$ characterizes a portion of the radiation power in a spot of radius *r* with respect to the power of radiation passed through the lens $K_{int}(r)=\eta_{opt}(r)/\ \eta_{opt}(r_{max})$, where r_{max} is the receiver maximum radius.

Lenses with improved characteristics

The main requirement to the material for fabricating the Fresnel lens are its optical transparently for forming a profile with preset geometrical parameters, mechanical rigidity, availability and low cost at large-scale production. It present, the most widespread are combined “silicon-on-glass” FLs and FLs of PMMA. Also, technologies for hot-pressing the Fresnel profile of glass are being developed. Each of the approaches has its own merits and demerits.

The combined “silicon-on-glass” FLs consist of solar grade glass and a Fresnel profile formed by the method of polymerization of transparent silicone, which ensures the high optical lens efficiency at low cost of their fabrication and easy adaptation to large-scale production of lens panels by copying from negative molds [13, 14]. Significant discrepancies between values of the refraction indices of glass and silicone are considered as disadvantages, since they do not allow achieving limiting values of the lens optical efficiency due to Fresnel losses at the “glass-lens” interface. Another demerit is that the silicone refraction index depends on temperature [15].

The lenses of PMMA, at the ease and economic feasibility of fabrication, have low mechanical rigidity and stability of optical characteristics at extended operation in the conditions of the effect of the environment factors.

The merits of glass lenses are:

− higher optical efficiency compared to that of polymer FLs, which results from the absence of Fresnel losses at the “protecting glass-lens” interface;

− feasibility for depositing antireflection coatings on both input and, in contrast to polymer lenses, operating FL surface;

− long-term stability of geometric and optical lens characteristics at operation factors influence;

− high mechanical rigidity.

One of the main disadvantages of glass as a material for fabricating FLs is impossibility to form at mass production the operating profile with a small pitch, which is a necessary condition to achieve the high power efficiency of such lenses, in particular, the profile pitch of modern heliotechnical polymer FLs may be 0.3 mm and less. To ensure the feasibility of the use of the technology for mass production of glass FLs (for-example, injection molding), it is necessary that the lens profile pitch would be reasonably large – of the order of several millimeters.

The results of the mathematical simulation of characteristics of circular FLs with flat operating facets show [16] that, to rise their power efficiency, it is necessary to decrease the profile tooth pitches, and, hence, to increase their number at a preset lens size. The positive effect is achieved, in this case, due to more precise approximation of the initial plane-convex lens surface by the great number of sections of the operating facet conical surfaces (facet generating lines are straight ones). However, increasing the number of the profile teeth results in the rise of optical losses on the nonoperating tooth facets and technological roundings of their tops and valleys, and also in the rise of the cost of such lens fabrication.

One of the ways to ensure high power efficiency of FLs without shortening the profile pitch is the use of lenses, the operating facets of which are formed from segments of nonconical surfaces but other ones (facet generating lines are curved ones) allowing approximating the initial plane-convex lens more precisely.

Investigation of the effect of the profile pitch on the average concentration ratio K_{av} in the focal spot (interception coefficient K_{int}=0.95) of FLs with straight and curved generating lines of operating facets have shown that FLs with curved generating lines of operating facets conserve a relatively high concentrating capability in the whole investigated range of the profile pitch variation [16]. The comparison was carried out for combined “silicon-on-glass” FL with the side dimension of 40 mm and the focal distance of 80 mm. the technological roundings of the tooth tops and valleys were accepted as alike for the entire lens surface and were 5 µm and 10 µm, respectively. The angular profile inaccuracies were 8 ang. min, and the deviation angle of the light beam after its passing through the lens was taken to be equal to 34 ang. min [17].

It was obtained that the C_{av} values at t=0.3 mm for both lens types practically coincide (both with allowing for losses and without it). This is explained by quite insignificant difference between curved and straight generating lines at their small length. In consequence of the decrease of the profile tooth number with increasing the pitch the relative value of the optical losses on the roundings of tooth tops and valleys decreases for lenses of both types. At the pitch value higher than 1.0…1.5 mm, losses on the tooth roundings stop to play a noticeable role. So some maximum observed in the range of pitch values of 0.7-1.0 mm is explained by the passing ahead decrease of the losses on the tooth roundings compared to the decrease of C_{av} caused by the pitch increase.

The prospect to use a FL with the curved operating facet generating lines and with the increased profile pitch opens additional feasibilities for fabricating glass FLs (for-example, injection molding technique), which will result in reduction of the lens cost at simultaneous achievement of the higher power efficiency compared to those of the lenses with straight generating lines.

Optical material for FLs

For determining the dependence of the average concentration ratio in the lens focal spot on the optical material characteristics, calculations were carried out for the lenses with the operating facet straight generating lines and the profile pitch t=0.25 mm and t=1 mm, correspondingly.

In calculating, the spectral dependencies of the refraction indices of these materials in the operating spectral range 340-920 nm have been used. The lens focal distances were predominantly optimized according to the criterion of the average concentration maximum in the focal spot containing 95 % of the concentrated radiation. In optimizing, for each focal distance, the optimum lens profiles were calculated by selecting a rational (optimal) value of the refraction index n_{calc} involved in calculation to allow obtaining the maximum average concentration in the focal spot. The FL optimum focal distance corresponds to the obtained maximum average concentration ratio.

From the physical point of view, selection of the optimum value of the refraction index allows lowering down the negative effect of the dispersion and the chromatic aberration resulted from it on the FL OPCs. This effect shows up stronger, when the difference between the refraction indices of the FL material at the “near” and “far” ends of the operating spectral range is greater. This difference may be qualitatively characterized be means of the dispersion coefficient v, calculated similar to the Abbe number (value):

$$v=(n_{opt}-1)/(n_{\lambda 1}-n_{\lambda 2}) \tag{1}$$

where $n_{\lambda 1}$, $n_{\lambda 2}$ are values of the material refraction index at the “near” and “far” ends of the spectral range.

The main material characteristics used as initial data are presented in Table 1, and the calculation results − in Fig. 1.

The concentrating capability of the glass FL depends linearly on the lens material dispersion coefficient in the operating spectral range. This is associated with the decrease of the chromatic aberrations since the rays with wavelengths corresponding to the ends of this range give the smaller scatter with respect to the focus. If follows also from the plot in Fig. 1 that the most appropriate materials (from those investigated) for fabricating FLs are glasses OptiWhite, N-FK5, BSC7 and urethane polymer.

Table 1. Characteristics of the optical materials for Fresnel lenses

No	Optical material	Refraction index		Rated refraction index n_{calc}	Dispersion coefficient $\nu=(n_{calc}-1)/(n_{\lambda 1}-n_{\lambda 2})$
		λ_1=340 nm	λ_2=920nm		
1	E-F3	1.668451	1.598201	1.613690	8.735815
2	Wacker	1.432711	1.400100	1.407334	12.490711
3	NBF1	1.788668	1.729145	1.743996	12.499340
4	N-LAK9	1.728368	1.678812	1.690575	13.935220
5	N-SK4	1.643593	1.602710	1.612756	14.988007
6	N-SK5	1.617203	1.579771	1.589158	15.739408
7	OptiWhite	1.547500	1.515400	1.523625	16.312305
8	PMMA	1.513003	1.482949	1.491017	16.337906
9	LK5	1.498995	1.470711	1.477664	16.888255
10	FC5	1.507260	1.480440	1.487254	18.167693
11	Uretan	1.524939	1.498148	1.507845	18.956244

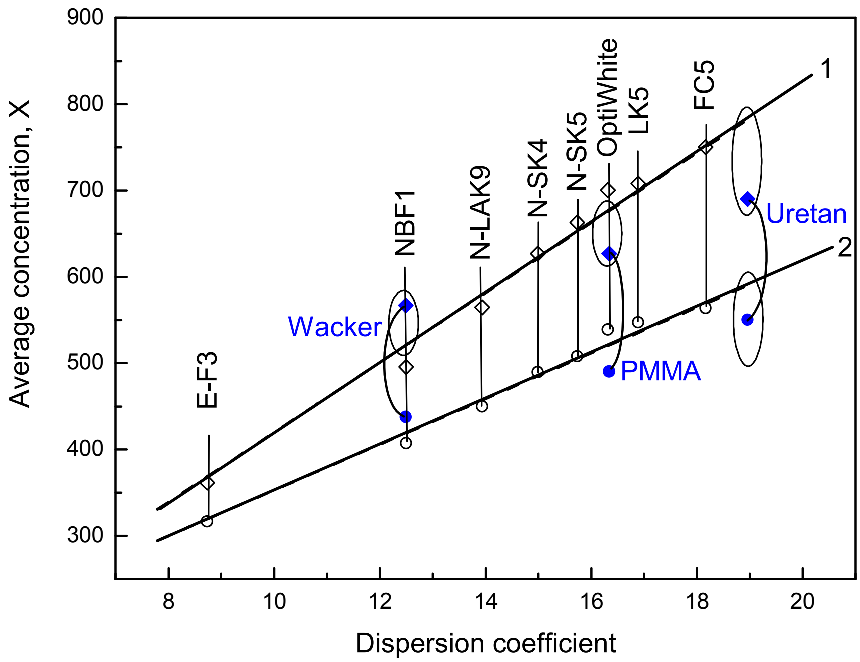

Fig. 1. Dependence of the average concentration ratio on a receiver on the dispersion coefficient of the material of a lens with straight profile facets generating lines for two profile steps (t) at a_l=40 mm, f=80 mm, K_{int}=0.95: 1 - t=0.25 mm, 2 - t=1 mm. Average concentration values were calculated with accounting the angular inaccuracies of the profile (8 ang. Min), the discrepancy angle of the light beam after its passing through the lens (34 ang. Min), the width of the rounding zones of the tooth tops (5 µm) and tooth valleys (10 µm). The no glass materials are marked by colored dots.

Lens manufacturing and testing

The verification both the proposed method for Fresnel lens profile optimization and the approach for optical material selection for profile formation was done with use of FL with straight refracted facets. To achieve the maximum average concentration level in a focal spot the urethane polymer have been chosen for profile formation.

The experimental FL specimens were manufactured by means of a direct copying the Fresnel profile from a negative mold on glass during ultraviolet polymerization of the urethane material. The control of quality of the fabricated lens refracting surfaces has shown that, the lens tooth operating surface roughness repeats the mold roughness.

For experimental determination of the fabricated lens OPCs a test bench based on a lighting device with a xenon lamp and an optical system for forming directed flux with the angular divergence of 32′ was used [11]. This test bench meets in full measure the requirements to simulating the sunlight parameters in investigating the OPCs.

To account the experimental factors influence on the accuracy of OPC determination the approach proposed in [11]. The sunlight simulator spectrum, photodetector spectral sensitivity and mean-statistical value of FL tooth tilt angle deviations (σ) were introduced into the calculation model. The effect of local geometrical inaccuracies of the shape (tooth tops and valleys roundings) and microroughnesses of the refracting surface was allowed for. When the light ray is incident on profile tooth tops and valleys roundings, the ray is considered as "lost" one. In the frames of the calculation photometric model, the effect of partial scattering of radiation at refraction was taken into account by a minor increase (from 32′ to 34′) of the incident beam discrepancy angle. It means that the spatial angle of the refracted beam could be greater than that of the incident beam in conserving the axis direction of the latter after refraction.

The allowing for all results of experimental investigations in the calculation model is necessary for obtaining a real FL OPC and optical efficiency value for standard test condition (AM1.5D LAOD, 1000 W/m^2 , 32′).

Comparison of the corrected rated OPC with the experimental one has shown a quite good agreement at φ=34′ and σ=10′ and with accounting the optical losses on the rounding zones of the tooth tops (5 μm) and tooth valleys (10 μm).

An OPC calculated for the standard spectrum with accounting for the deviations obtained in the laboratory experiments is presented in Fig. 2 (curve 5). The same figure shows the degree of the effect of the source angular dimensions and the value of the profile mean-squared errors on the Fresnel lens resulting OPC. The values of parameters used in calculations are summarized in Table 1. Fig. 3 presents the dependencies of the lens average radiation concentration and optical efficiency on the focal spot diameter. The dependencies show the proposed method for designing the profile and the selected method for the lens fabrication allows creating the Fresnel lenses ensuring the average radiation concentration of 650X at the optical efficiency of 83% at K_{int}=0.95 on a SC with the photosensitive surface diameter of 1.6 mm.

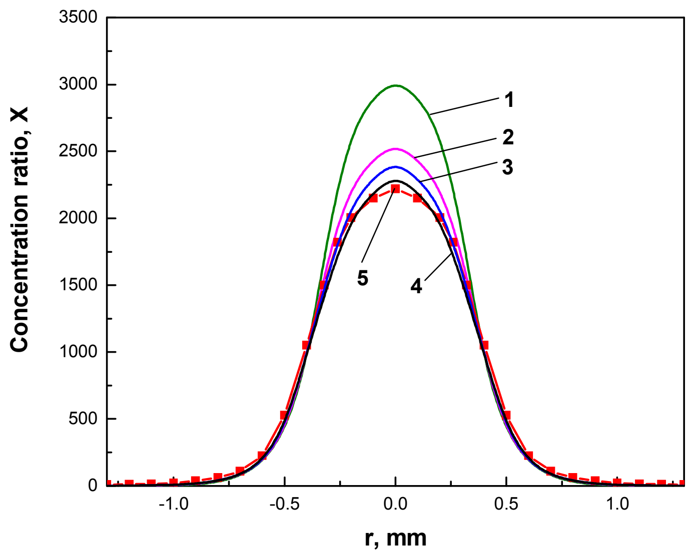

Fig. 2. Optical-power characteristics of Fresnel lens (parameters used for simulation are presented in Table 1). Experimental curve is indicated in dots (5).

Table 2. Parameters used for simulation of Fresnel lens optical-power characteristics.

Curve number	Light divergence angle, min of arc	Tooth tilt angle deviation (σ), min of arc	Accounting of losses on tooth top (5 μm) and valley (10 μm) roundings
1	32	0	no
2	34	4	yes
3	34	8	yes
4	34	10	yes

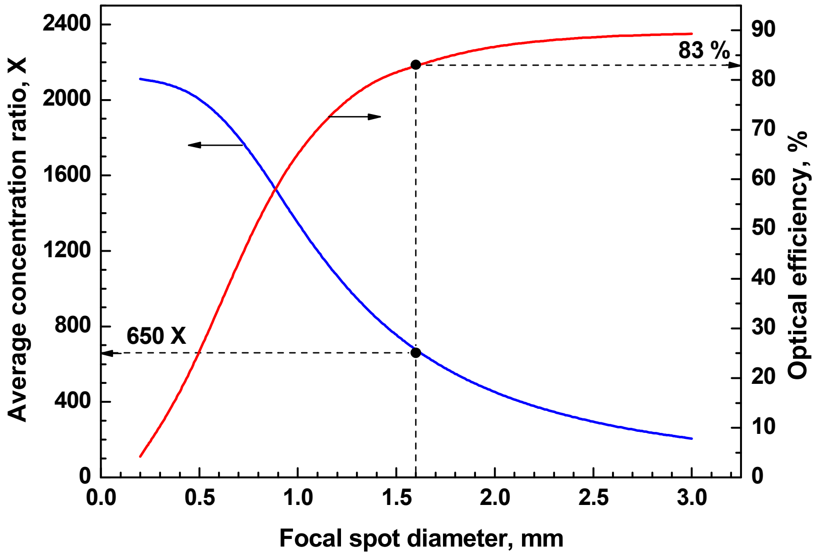

Fig. 3. Average concentration ratio and optical efficiency versus the focal spot diameter for the FL made of urethane polymer.

Summary

Authors present the experience on the development, optimization and testing of the circular flat-plate Fresnel lenses intended for sunlight concentration in photovoltaic modules. The main results of the carried out investigations are:

- mathematical model based on power ray tracing has been developed for optimizing the FL profile parameters and calculating lens optical-power characteristics with allowing for technological peculiarities of lens manufacture;
- the advantageous of lenses with curvilinear operating facets in saving higher concentrating capability in increasing of Fresnel profile step owing to the reduction of losses on the tooth tops and valleys roundings have been demonstrated in comparison with conventional Fresnel lenses with conical operating facets;
- the procedure for searching the optimal optical material for lens manufacturing have been presented;
- an experimental OPCs have been obtained indoors for developed lens specimens with use of specially designed optical bench;
- a good agreement between the measured and simulated data was obtained;on the bases of the experimental results, correction of the calculation model of the concentration process in Fresnel lenses was performed and

With the use of the corrected calculation model, an OPC for the standard solar spectrum AM1.5D LOAD has been obtained. It has been shown that the use of the procedures proposed for designing and manufacturing lenses allow producing FLs ensuring the average radiation concentration of 650X at the optical efficiency of 83% at K_{int}=0.95 on a SC with the photosensitive surface diameter of 1.6 mm.

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