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Estimation of optical diffuse properties of Fresnel lenses

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Abstract. This paper proposes a method for determining the diffuse properties of sunlight concentrators such as Fresnel lens. The decrease in Fresnel lens concentrating ability is usually associated with imperfectness in optical refractive surfaces, where some part of the direct light, which comes along the normal to the surface of the Fresnel lens and intended to be concentrated, is getting scattered and directing off a highly efficient concentrator solar cell. The diffuse light flux generated propagates inside the volume of the combined photovoltaic module. This flux undergoes multiple reflections from the structural elements, partially absorbed and ultimately reaches the photoconverters of the planar circuit.

Keywords: Fresnel lens, photoconverters, diffuse light

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Определение диффузных свойств линз Френеля

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Аннотация. В данной работе предложена методика определения диффузных свойств концентраторов солнечного излучения типа линза Френеля. Снижение концентрирующей способности линз Френеля обычно связывают с несовершенством оптических преломляющих поверхностей, когда часть прямого (поступающего по нормали к поверхности линзы Френеля и подлежащего концентрированию) излучения рассеивается и не направляется на высокоэффективный концентраторный солнечный элемент. Формируемый при этом поток диффузного излучения, распространяясь внутри объема фотоэлектрического модуля, претерпевает многократные отражения от элементов конструкции, частично поглощается и в конечном итоге попадает на фотопреобразователи планарного контура.

Ключевые слова: линза Френеля, фотопреобразователь, диффузное излучение

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Introduction

Designing the photovoltaic modules with lens sunlight concentrator is a promising solution for increasing solar energy conversion efficiency. However, despite the use of highly efficient multi-junction (MJ) solar cells (SCs) in such modules, the efficiency of which exceeds 44% (at concentration ratio of 100X and more), the overall efficiency of the modules hardly reaches 40% [1—4], particularly due to “weak” optical characteristics of Fresnel lenses.

The main reason for decrease concentrating power ability and optical efficiency of Fresnel lenses (FLs) is chromatic aberration, which leads to spectral and spatial redistribution (smearing) of the focused radiation over the MJ SC. Additional optical losses are associated with absorption of radiation in the material and its reflection on the front surface of the FL and losses on the refractive faces. Since a FL concentrates only direct light (coming normally to its surface), the imperfection of the optical surfaces leads to its diffuse scattering and/or reflection [5-8].

Up-to-date combine modules designed in terms of both concentrator photovoltaic circuit and planar one [9—13] provides energy conversion of both direct solar light by concentrator MJ SCs and scattered (diffuse) solar light by planar photoconverters. The diffuse light flux coming from FL is converted photoelectrically by a planar cell. The proportion of the direct light transformed by FL into the diffuse one is determined by the quality of the optical surfaces and the parameters of the refractive profile, namely, the technological rounding of the profile teeth’s peaks and valleys, local geometric errors in working faces and diffuse characteristics of the optical material [7, 8]. It is obvious that when fabricating an FL by copying methods, the quality of optical surfaces varies depending on the type of matrix used: weather it is the primary master matrix or its working copy [14]. Accordingly, when controlling FL quality, in addition to its concentrating ability estimation, it is also necessary to evaluate the fraction of the light being diffused. Such quantification is an experimental problem, which is both important and nontrivial.

This paper presents the percentage component estimating results for diffuse light using a simulation model for calculating the optical-energy characteristics (OPC) of Fresnel lenses based on the method of tracing the direct path of light rays coming from the source through the FL to the SC (Fig. 1). The direct light flux is simulated by a large number of conical beams with a spatial angle corresponding to the angular size of the radiation source. The proportion of diffuse light is estimated from the level of energy reduction in a concentrated flux when modeling errors in the shape of the FL profile. When experimentally detecting the proportion of the diffuse component in the total flux transmitted through the FL, the developed dual-level optical-photovoltaic system is used. Here the concentrated light is directed into an aperture formed in a full-size planar photoconverter (the first level receiver) and then, while passing through the aperture, it is captured by a receiver fixed in the certain distance below (the second level receiver). The diffuse component is recorded by the planar photoconverter itself. Thus, in the experimental installation, the conditions for the propagation and PV conversion of the diffuse flux formed by the FL turn out to be almost identical to the conditions of the combined module.

A comparison was made for the “silicone-on-glass” FLs that had been fabricated: *a*) by direct copying from a negative nickel master matrix (precision diamond micro-turning method); *b*) by the procedure of double copying to obtain a working negative matrix of polyurethane [14]. An increase (by ~ 4% abs.) in the level of scattered FL radiation for the FL sample with a profile formed from the working matrix has been found, which indicates sufficient sensitivity of the proposed method for estimating the diffuse properties of FL.

Theoretical part

When designing the Fresnel profile and calculating OPC of FLs that performs the function of sunlight concentrating, the method based on tracing the great number of rays coming from the light source through the concentrating system to the solar cell is used. The concentrating system is represented as a set of flat or curved refractive surfaces of a given size and optical

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media separating them. The model enables taking into account the influence of the set of factors (accurately described in [6, 7]) on the concentrating ability and optical efficiency of lens.

In mathematical description of ray passage from one surface of a concentrating system to another through optical media with certain refractive indices, the approaches of geometric optics, equations of analytical geometry, and vector algebra are used. Accounting for local geometric inaccuracies of the lens profile is carried out by introducing corrections to the components of the normal vector to the working faces of the teeth. When the ray hits the non-working faces, the rounding of the profile teeth tops and valleys, the ray is considered "lost", and its further tracing to the focus of the lens discontinues. Thus, the energy of diffusely scattered radiation is considered lost for the process of photovoltaic conversion of concentrated radiation.

It should be assumed that these "lost" rays form a diffuse radiation flux from the lens propagating inside the volume of the photovoltaic module. By varying in the model the effective width of zones associated with the peaks and valleys of the teeth, it is possible to estimate the proportion of diffuse radiation in the total light flux that has passed through the Fresnel lens. Thus, the calculation model makes it possible to predict FL "efficiency" in terms of converting the direct radiation flux into diffuse-scattered (Fig. 1, *b*).

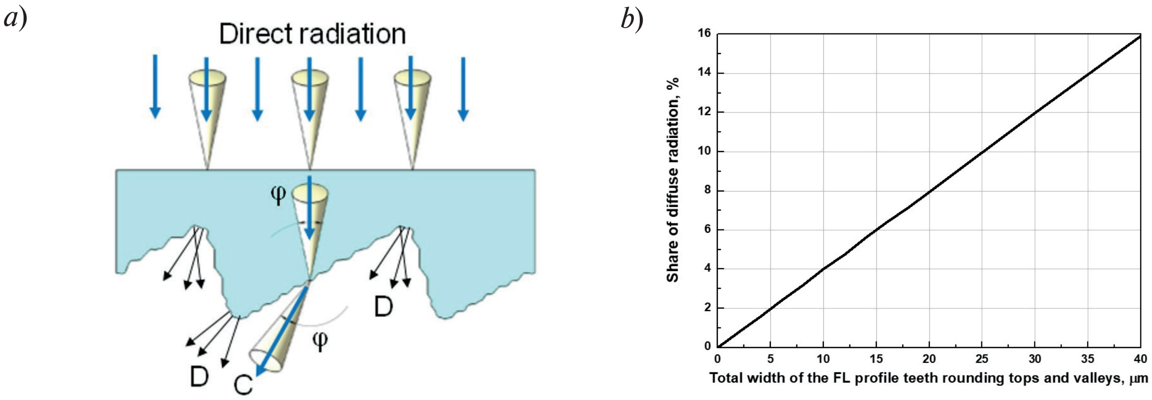

Fig. 1. Transformation of the direct (normal incident) radiation at the passage through the FL refractive surfaces with the formation of spilled direct (scattered, diffuse D) light and of the flux being concentrating in lens focus (C) (*a*). Share of diffuse radiation in the total light flux passing through the FL, depending on the width of the non-working zones (peaks and valleys) of the FL refractive teeth (*b*)

The results of mathematical modeling of the characteristics of circular Fresnel lenses with flat working surfaces show that in order to increase their energy efficiency, it is necessary to reduce the pitch of the profile teeth, and hence increase their number for a given lens size [7, 8]. In this case, a positive effect is achieved due to a more accurate approximation of the surface of the original plano-convex lens by a large number of sections of the conical surfaces of the working faces (the generatrixes of the faces are straight lines). However, an increase in the number of profile teeth leads to an increase in optical losses in the non-working (dead) zones of the teeth (technological rounding of their tops and valleys).

Experimental estimations of diffuse light productivity by Fresnel lenses

FLs comparison in terms of direct radiation "conversion efficiency" into diffuse radiation was carried out using a specially designed device, the optical scheme and general view of which are shown in Fig. 2. The collimated beam flux (1) from the pulse simulator [17, 18] is directed perpendicular to FL input aperture (2). The main portion the flux that has passed through the FL is concentrated in the focal spot (F) at a given focal length from the lens, while the rest is scattered forming a diffuse flux (D). A full-size silicon SC (photosensor "A") was mounted in the plane of the focal spot with a hole in the center for transmitting radiation concentrated in the focal spot F. By means of XYZ adjustments for the FL, such a position was chosen in which the focused light completely passes through the hole and hits the photosensor "B", which is completely similar to the photosensor "A" in terms of the structure and design of the contact grid. In this configuration, the photocurrent of the photosensor "B" made it possible to estimate (in relative units) the

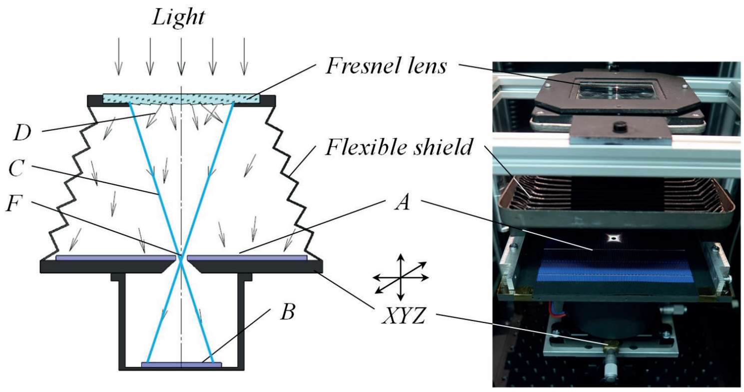

Fig. 2. The optical scheme (left) and general view (right) of the device for examination of FL in terms of scattered light productivity. On the right image, the “accordion-like” light-shield is half-lifted to show the silicon photosensor “A” with a hole (around the hole a light halo of radiation is visible, since in the photo the photosensor “A” is placed a little closer to the lens compared to the its exact focal distance)

power of the concentrated flux through FL, and the photosensor “A” – scattered (diffuse) flux propagating downward (it should be taken into account that diffuse flux is isotropic and in the presented device cannot be completely intercepted by a photosensor “A”).

To eliminate the influence of radiation reflected from the surrounding infrastructure on the current signal of the photosensor “A”, a light-shield housing of the “accordion-like” type was used, the flexibility of which ensured the unhindered movement of the receiver within ± 10 mm in the XY plane and ± 20 mm along the vertical axis Z. The inner matte (absorbing) surface of the protective housing excluded uncontrolled re-reflection of diffuse light.

The reference value when comparing FLs produced by different technological methods was the photocurrent of the photosensor “A”, which was recorded when the lens was placed directly on its surface. The value of the photocurrent obtained in this way reflects the total radiation flux passing through the lens. For all the lenses studied in the work, this value differed by no more than 0.5%, which means the equality of the integral values for the optical transmission of the studied FLs.

The procedure for adjusting the FL position was to find such a position, at which the photosensors “A” and “B” would show the minimum and maximum possible values of photocurrents, respectively. Upon completion of the necessary tuning actions for each experimental sample of the FL, the ratio of the concentrated and diffusely scattered energy of solar radiation is defined. Obviously, when changing the configuration of the refractive faces, due to technological factors in FL manufacturing, the balance of concentrated and diffused fluxes will change, and for the most part in favor of the latter one. Registration of photocurrents of the photosensors 3 and 4 is carried out during the flat part of the light flash (variation of the irradiation level within ±1.5% with duration of 1.2 ms, [15, 16]).

Comparison of experimental Fresnel lenses

A comparison has been made for the “silicone-on-glass” FLs that had been fabricated: *a*) by direct copying from a negative nickel master matrix (precision diamond micro-turning method); *b*) by the procedure of double-stage copying with obtaining an “intermidient” negative matrix of polyurethane. The FL design parameters are: aperture 60 mm × 60 mm, focal length 105 mm, profile step 0.25 mm. We also studied the FL made of poly(methyl methacrylate) with an aperture of 63 mm × 63 mm, a focal length of 125 mm, and a profile step of 0.125 mm.

For the photosensors “A” and “B”, their photocurrent absolute values measurement results are presented in Table 1. As was expected, a lens made by the direct copying method scatters radiation less. For radiation passed through the optical elements of the FL (glass, refractive profile), only 6% is diffusely scattered, while when using double copying technology, this figure reaches 10%. Accordingly, the optical efficiency of the FL, as a radiation concentrator, is higher by 4% for the FL made by direct copying. The FL made of PMMA has the highest diffuseness coefficient – almost 21% of the radiation transmitted through the lens is diffuse. It should be noted that all the samples under study are close to each other in terms of the total transmission coefficient of radiation (within 0.2% rel.), which indicates comparable losses in the reflection of radiation from the front and surface and from the refractive elements of the profile (data were recorded when FL is positioned directly over the photosensor “A”, see column 2 of Table 1).

The summation of the values of the photocurrents of the photosensors “A” and “B” (column 5) makes it possible to estimate (qualitatively) the fraction of diffuse radiation absorbed by the elements of the installation structure. It is clearly seen that the smaller the fraction of scattered radiation, the smaller the difference between the obtained data and the photocurrent of the photosensor “A” operating in the mode of total optical transmission record (column 2).

Table 1

Photocurrent absolute values measurement results

	Photosensor current, mA				
1	2	3	4	5	6
FL type	“A” (Total radiation)	“B” (Direct radiation)	“A”(Diffuse radiation)	Direct+Diffuse radiation	% of Diffused radiation
SOG Direct copy	957.8	901.6	57.5	959.1	5.9
SOG Double copy	957.4	861.9	86.5	948.4	10.0
PMMA	954.6	753.8	179.4	933.2	20.9

Conclusion

A method for determining the diffuse properties of solar radiation concentrators such as Fresnel lens was proposed. A comparison was made for the “silicone-on-glass” FLs that had been fabricated: a) by direct copying from a negative nickel master matrix (precision diamond micro-turning method); b) by the procedure of double-stage copying with obtaining a negative matrix of polyurethane. An increase (by ~ 4% abs.) in the level of scattered FL radiation for the FL sample with a profile formed from a polyurethane matrix was defined, which indicates sufficient sensitivity of the proposed method for estimating the FL diffuse properties.

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