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Temperature effect on spectral irradiance blurring of solar radiation by Fresnel lens sunlight concentrators

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Abstract. This work is devoted to the study of the effect of temperature on the spectral irradiance blurring (concentrated in the focal plane of a Fresnel lens) arising due to the inherent chromatic aberration (CA) of the lens. This paper presents equipment for recording both irradiance distribution and spectral irradiance redistribution for the radiation concentrated by a small-sized energy concentrator adapted to temperature measurements, as well as the results of a study of Fresnel lenses.

Keywords: Fresnel lens, chromatic aberration, solar simulator, photovoltaic concentrator

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Материалы конференции
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Влияние температуры на спектральную «деформацию» солнечного излучения в фокусе линзы Френеля

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Аннотация. В данной работе описывается методика и оборудование для регистрации пространственно-спектрального распределения сконцентрированного линзой Френеля излучения при различных температурах. Функционал экспериментального комплекса позволяет сканировать профиль освещенности на различном расстоянии от концентратора, а используемая процедура обработки регистрируемых сигналов обеспечивает получение совокупности данных, достаточных для расчета и оценки фотоэлектрических параметров линзовых концентраторов и прогнозирования энергетических характеристик пары «линза-солнечный элемент».

Ключевые слова: линза Френеля, хроматическая аберрация, имитатор солнечного излучения, фотоэлектрический концентратор

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Introduction

In state-of-the-art high performance photovoltaic modules for concentrating solar radiation, the use of Fresnel lenses (FL) has already become a standard. To date, FL with two configurations are usually used: monolithic, made of polymethyl methacrylate (PMMA) by hot pressing [1]; and composite, made of a pair of different materials glued together ("silicone on glass", SiOG) [2]. The second type of FL is preferable. It has a number of advantages (high profile accuracy, high accuracy in reproducing the teeth angles, a decrease in the inactive area between the faces, as well as increased lens rigidity and profile protection due to glass). However, the characteristics of SiOG lenses are more susceptible to change under the temperature influence. There are two main reasons for this. First, the coefficient of linear thermal expansion (CLTE) of glass and silicone can differ by an order of magnitude (depending on the chosen brand of glass and silicone). Secondly, the refractive index of silicone changes significantly [3] with temperature (Fig. 1). The change in the refractive index shifts the focal length of the lens. A difference in CLTE causes the lens teeth deformation and increase in the tilt angle error. As a result, the refracted rays will be displaced [4–6]. Eventually, in the solar cell plane, the concentrated spot enhances. The spatial and spectral distributions of the radiation energy in the spot are also changed.

Depending on the region and the time of a year, photovoltaic modules are forced to operate in highly variable temperature conditions. The ambient temperature can be below zero in winter and exceed 40 °C in summer (the temperature of photovoltaic modules can rise even higher). The influence of temperature on the solar cells efficiency is well studied, while the influence on the FL optical characteristics requires further exploration. The first issue to be determined is the effect of temperature on the light flux spatial and spectral distribution in the focus. As a consequence, one can establish the temperature dependence of the FL efficiency.

The paper presents an approach to register the spatial-spectral distribution of concentrated radiation energy using a method developed in the Ioffe Institute PV laboratory. Experimental setup [7] was adapted for temperature measurements of small-sized concentrators. The measurement technique proposed in the paper is based on precision three-dimensional scanning of the "focal space" (the region between the FL and the double focus) with a fiber-optic spectrometer with an entrance aperture diameter of 100 μm. At each scanned point, the spectrum (350–1100 nm) is recorded with subsequent splitting into spectral sensitivity ranges of subcells of a multijunction solar cell (MJ SC). Further, by integrating and combining data, it is possible to obtain the spectral-spatial distribution (in a 3D image) of energy at a certain distance from the concentrator.

The lens under study was placed in an optical thermal chamber, which provides precise control of the FL temperature conditions. The resulting "spectral patterns" allow to trace the dynamics of changes in illumination profiles in strictly defined spectral ranges corresponding to the subcells sensitivity ranges.

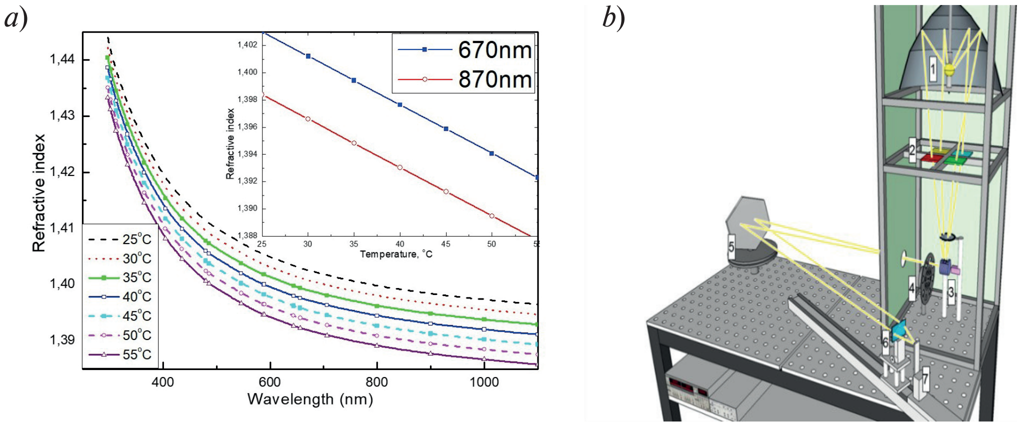

Fig. 1. Refractive index of silicone profile of Fresnel lenses (*a*). Optical scheme of experimental setup (*b*)

Experimental setup

The optical scheme of the measuring part of the setup for recording the spatial distribution of illumination is shown in Figure 2. Collimated light flux with a radiation divergence of 32 arcsec. min (which corresponds to the angular divergence of solar radiation) is directed to the studied FL. The lens is mounted on the *XYZ*-αβ platform and oriented perpendicular to the light flux. The lens with the platform is placed in the thermal chamber. Several thermistors inside the chamber directly measure the current temperature of the FL during optical measurements and work as a feedback to maintain the set conditions. The chamber can maintain temperatures up to 60 degrees for a long time measurement. An optical fiber with an aperture of 100 μm plays the role of a receiver that scans the focal spot area. The second end of the fiber is connected to AvaSpec 2048 spectrometer. The position of the receiver is set by a precision *XYZ* automated coordinate device (controlled from a computer), which makes it possible to detect a radiation distribution profile with a high spatial resolution.

Measurement methodology

The measurement process begins with the determination of the light spot center focused by the lens in the design focus (105 mm) according to the developed technique [7]. Next, a scanning of the field along the *XY* axes (the size is determined by the spot diameter) of the focused radiation by the fiber receiver is performed. Spectral irradiance is recorded at each point in the wavelength range of 350–1100 nm, due to the sensitivity range of the spectrometer. Then the measuring fiber with the selected pitch (1 mm) is shifted along the optical axis (*Z* axis) relative to the design focus. In the new position, the field (slice) is also scanned along the *XY* axes. The operation is repeated for all selected points on the optical axis (approximately ± 10 mm relative to the design focus). Thus, we obtain a 3D representation of the radiation concentrated by the FL. The data enable to get complete analysis of the spatial-spectral distribution of the radiation above and below the focal plane relative to the design focus. Then the next temperature is set in the thermal chamber and after the lens temperature is stabilized, the registration of the "focal volume" is repeated.

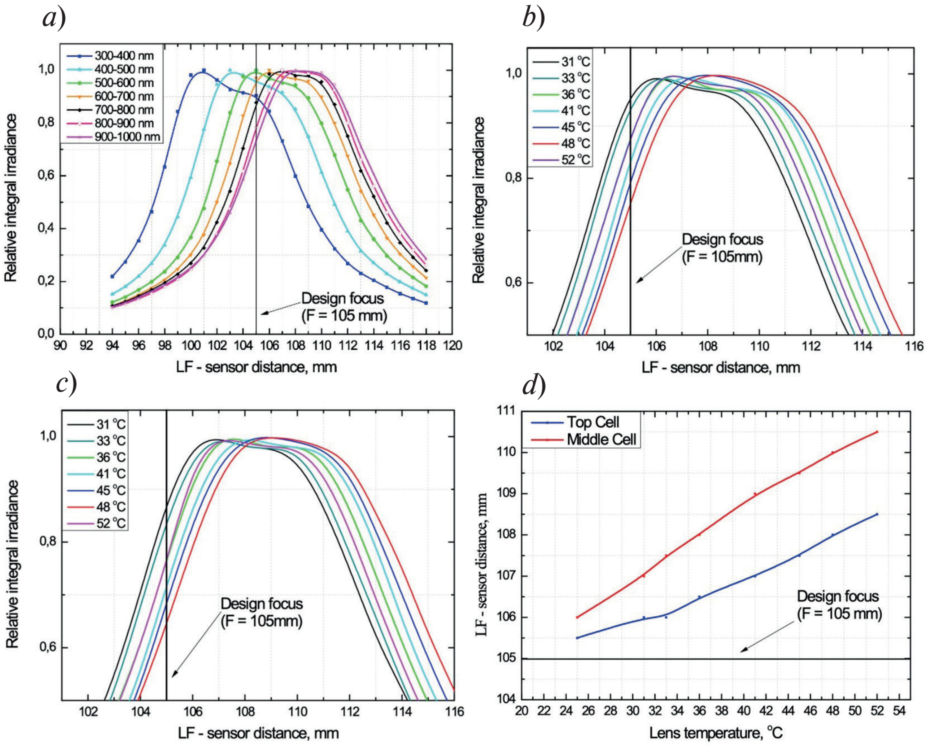

Fig. 2. The dependence of relative integral irradiance on the focal length for different spectral ranges. The temperature dependence of relative integral irradiance for spectral ranges corresponds to top GaInP (*a*) and middle GaAs (*b*) subcells sensitivities (*c*). The temperature dependence of focus distance for top (blue line) and middle (red line) subcells (*d*)

The measurement at each temperature turns out to be quite lengthy (approx. 10 000 points, each of which contains a spectrum in the range of 350–1100 nm). In order to facilitate data analysis, the spectral composition distribution recorded during the scanning process was integrated in several wavelength ranges (integration step is determined by the scanning task). Such a procedure makes it possible to form “color” energy patterns for the corresponding wavelength ranges typical for subcells of MJ SC.

The dependence of relative integral irradiance on the focal length (Fig. 3, *a*) for different spectral ranges (integration step 100 nm, registration point $X = 0$, $Y = 0$) occurs due to the effect of spectral blurring of light energy in the focal spot arising from chromatic aberrations. Experimentally recorded light energy blurring shows the real distances at which the maximum light focusing is provided for the selected energy ranges of solar radiation.

To make graphics readable, we take the ranges of the subcells maximum spectral sensitivity (top junction GaInP — 670 nm, middle junction GaAs — 870 nm). It can be seen from Fig. 3, *b* (GaInP) and Fig. 3, *c* (GaAs) that the main effect with increasing temperature is the displacement of the focal plane from the concentrating surface. It could be assumed that this happens because of the change in the refractive index (from Fig. 1, *b* it can be seen that the refractive index of silicone changes linearly and the rate of change is constant for the selected wavelengths). However, Fig. 3, *d* clearly shows that for the measured FL the linearity is preserved, but the rate of the focal length shift is higher for the longer wavelength spectrum (red line Fig. 3, *d*). It can be concluded that the second factor, CLTE, is involved in the focal length shifting. The change in the geometry of the refractive profile amplifies with the temperature rise and results in the displacement enhancing of the focal length from the surface of the concentrator.

Conclusion

The paper has presented the technique and equipment for recording the spatial-spectral radiation distribution of concentrated FL at various temperatures. The functionality of the experimental setup allows scanning the illumination profile at different distances from the concentrator. The procedure used for processing the recorded signals has provided a set of data sufficient to calculate and evaluate the photoelectric parameters of lens concentrators and predict the energy characteristics of the lens-solar cell pair.

It is known that temperature affects the characteristics of FL due to two main mechanisms: changes in the refractive index and deformation of the profile caused by CLTE. An increase in temperature has been shown to cause approximately linear shift of FL focal lengths for each wavelength. However, the temperature dependence of focal length shift for shorter wavelengths is slower than for longer ones. For a concentrated module, different rates of the focal length shifts depending on the wavelengths that cause an increase in focal spot size. As a result, optical efficiency will be reduced due to light scattering outside the active region of the solar cell. Therefore, when designing SiOG concentrators, it is necessary to take into account the operating temperature of the module and optimize parameters of the lens and the secondary optics, as well as, the photoconverter.

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