Analysis of spectral irradiance blurring by Fresnel lens sunlight concentrators

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Abstract. Solar spectral irradiance blurring in the focal plane of the Fresnel lens arising from the chromatic aberration (CA) inherent to a lens was studied. The experimental complex for recording both irradiance distribution and spectral irradiance redistribution for the radiation concentrated by a small-sized energy concentrator based on a solar simulator with the possibility of modeling the spectral composition of light is presented. The methodology for scanning the irradiance spectral redistribution by a fiber spectrometer is described.

1. Introduction
The steady increase in the conversion efficiency of concentrated solar radiation due to the development of technologies and structures of multi-junction solar cells (MJ SC) predetermines interest in the wider use of this method of obtaining “green” energy [1]. Systems with lens concentrators, more specifically with Fresnel lenses (FL) [2], are the most widely used due to their high operational and economic characteristics (low price, ease of production, potentially high optical efficiency, and light weight).

However, the achievement of high levels of concentrating ability and optical efficiency for the Fresnel lenses is hampered by the chromatic aberration (CA) inherent to all types of refractive systems. It is the CA with a wide spectral radiation range and a finite angular size of the Sun that leads to a spatial and spectral irradiance redistribution at the focus of the lens and rather strongly influences the concentration ratio of solar radiation [3]. The solution of the problem of reducing the influence of chromatic aberration on the concentrating ability of a Fresnel lens lies in the plane of creating profiles of various types [2], including achromatic ones [4]. There is an obvious interest in the study of the irradiance blurring in the focal spot and the search for ways to control the irradiance spatial distribution taking into account the spectral “deformations” determined by CA. For the experimental determination of the irradiance spatial distribution and the construction of the optical-energy characteristics of concentrators (dependences of the concentration ratio and optical efficiency on the size of the focal spot), various methods and complexes were used [7]. The irradiance distribution profile is detected by the CCD arrays [4] or with the use of the systems for precision scanning by small-sized semiconductor photo sensors. At the same time, the spectral resolution of these approaches is insufficient to determine the level of practical effect of CA on the optical-energy characteristics of the refractive concentrators.

The spectrometer (a device with high spectral resolution and calibrated for sensitivity to the spectral density of the solar irradiance) is used as a scanning sensor to evaluating the color irradiance redistribution in the focal spot. The method for studying and processing the results of evaluating the optical characteristics of Fresnel lenses is presented in this paper.
2. Experimental setup

The setup diagram for recording the irradiance spatial distribution and the construction of optical-energy characteristics of concentrators is shown in figure 1. The light flux of the primary xenon emitter (1) is focused by an ellipsoidal reflector at the input of the integrating sphere (3). In order to adjust the emission spectrum, optical filters are installed between the lamp and the sphere. Thus, the integrating sphere serves for color mixing of the radiation and forms a stream with a spectrum close to AM1.5D. From the output port of the sphere, radiation is directed to a collimating spherical mirror (5), which provides a parallel flow in the direction of the tested object (6). The diameter of the output port of the sphere and the distance from the sphere to the collimator was selected to ensure the radiation divergence of 32 min. of arc. The object of study was installed on the XYZ-αβ platform and was oriented perpendicular to the light flux. The focal spot area was scanned by a fiber with an aperture of 100 microns, the second end of which was attached to the spectrometer (7). The position of the fiber was set by the precision XYZ automated coordinate device, which has made possible to detect the irradiance distribution profile with high spatial resolution.

![Figure 1](image)

**Figure 1.** (a) – optical scheme of the installation: (1) – initial emitter based on a xenon lamp; (2) – optical filters; (3) – integrating sphere; (4) – optical chopper; (5) – collimating mirror; (6) – Fresnel lens under test; (7) – small-size detector. (b) – simulator spectral irradiance.

The use of an integrating sphere as an emitter allows to achieve solar irradiance on the FL surface less than one solar constant, which, however, was not necessary to obtain data on the concentration ratio of irradiance in the focal spot. In addition, the reduced irradiance in the focal spot provides an opportunity to use sensitive instrument with high resolution such as AvaSpec 2048 fiber optic spectrometers.

3. Measurement methodology

Some methodological and functional approaches of installation were checked at the Fresnel lens measurements (Silicon-on-glass type, 60mm x 60mm in size [5]-[6]). The designed focal length of the concentrator was 105 mm (figure 2), and the diameter of the focused radiation was about 2 mm.
The study of the spectral “deformations” determined by chromatic aberration was carried out for the receiving aperture (100 μm) for two types of movement (in two directions):

1) along the diameter of the focal spot when the possible symmetry breaking of the solar irradiance distribution and of the spectral density of the spectral irradiance was registered;
2) along the optical axis to determine the effective focal distances for the selected radiation wavelengths.

When scanning along a focal spot diameter at the designed focal distance from the lens (figure 3), spectral irradiance was recorded at each point in the wavelength range of 350-1100 nm, which was caused by the sensitivity range of the spectrometer. The scanning starts at the center of the lens (point 0), which was determined according to the method presented in [7]. As the detector shifts from the center to the periphery (from point 0 to point (a), figure 3), the local irradiance level decreases point “a” corresponds to the irradiance distribution profile, which is similar to the Gaussian. However, any significant changes in the spectral composition of the radiation focused by the lens under study were not observed. In the opposite direction (from the center point to the point (b), figure 3), not only the change in the irradiance level, but also the spectral modification in the light flux were clearly observed: at the point “b” the fraction of short-wave radiation was much smaller rather than the long-wavelength one. The obvious conclusion is that the lens under test has some shape deviations that lead to a departure from symmetry for the spectral components in a focused light flux.

To assess the degree of asymmetry for the integrated irradiance profile, each spectrum recorded during the scanning process was integrated within the selected wavelength ranges (for the presented case, the selected spectral intervals corresponded to the sensitivity ranges of the subcells of the triple-junction SC). The resulting “color” energy patterns (figure 4) have shown that in the FL under study, in one region of the focal spot, the “blue” light prevails in the concentrated radiation, while on the opposite the red” light does. Clearly this type of “color” asymmetry leads to some lateral currents in the layers of the semiconductor structure of a multi-junction SC and reduce its effectiveness [8].

Spectral deviations measured along the X-axis are caused by the combination of two factors. First, is the deviation of the lens profile occurred during the manufacture. Secondly, are the adjustment methods [7], i.e. minor inaccuracies in the location of the FL and/or a scanning sensor.

At the type 2 (Z axis), the measuring fiber was placed at the center point in the XY plane. The registration of spectral distributions began at the design focus point (105 mm), with a displacement of ± 10 mm (95-115 mm) and a step of 1 mm. As in the previous case, each registered spectrum was divided into ranges. Dependencies presented in figure 5 are essentially nothing more than the experimentally recorded spectral effect of chromatic aberration, showing the real distances at which maximum focusing of the radiation is provided for the selected solar radiation energy ranges.

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**Figure 2.** The FL optical monitoring setup

**Figure 3.** Spectral irradiance: (a) corresponds to the distance of 500 μm, (b) - 500 μm.
4. Conclusions
In this paper, the methodology and equipment for the studying the spatial and spectral parameters of irradiance were described, and the results of the analysis of the optical-energy characteristics of lens solar concentrators were presented. The measurement procedure based on the precision scanning of the focal spot by a fiber spectrometer with an entrance aperture diameter of 100 μm. For each point of the focal spot, the full spectrum (350-1100 nm) of radiation was recorded. The subsequent differentiation according to the selected spectral intervals has allowed forming “color” energy patterns for the ranges corresponding to the sensitivity of the p–n junctions of the multi-junction solar cell. The functional of the experimental complex has made possible the scanning the irradiance profile at different distances from the hub, and the procedure used to process the recorded signals has provided a collection of data sufficient for calculating and estimating the photoelectric parameters of solar cells and predicting the energy characteristics of the “lens-solar cell” pair.

According to [3], the correct choice of the lens design parameters reduces the negative effect of chromatic aberration by a factor of 1.5–2. In [2] the authors demonstrated that proper design and manufacture of FL enable to achieve the average ratio of the concentration of sunlight of 730X with an optical efficiency of more than 82%. Also, the reduction of chromatic aberration can lead to the power gain of photovoltaic converters approximately of about 6.5% [9].

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