Sunlight simulation in investigating characteristics of small-size sunlight concentrators and multijunction solar cells

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Abstract. Presented are technical solutions on constructing optical systems for experimental simulating the sunlight parameters. Designs of two types of solar simulators are proposed. In the first one, the spectrum and the radiation angular divergence are simulated on the basis of a continuous light source, what corresponds to the principle “necessity and sufficiency” of simulated parameters of the light flux in investigating optical and power characteristics of small-size sunlight concentrators (Fresnel lenses). In the second type simulator, based on a pulsed radiation source, the emphasis has been placed on high-quality simulation of irradiance and spectrum for satisfying requirements in recording current-voltage characteristics of multijunction solar cells and in determining their efficiency.

1. Introduction
Development of high-efficient photovoltaics based on the principle of concentrated solar radiation conversion has designated a number of requirements to the simulation of the sunlight parameters under laboratory conditions. So besides exact simulation of irradiance and spectral composition of incident radiation, what is necessary also in investigating of non-concentrator solar cells, the necessity to ensure the radiation divergence of 32 angular minutes in the light flux arises. However, simultaneous simulation of three main parameters “irradiance-spectrum-divergence” on solar simulators (SSs) appears to be rather complicated technical task requiring substantial material expenses. For this reason, depending on the purpose, on application regimes and on the type of measurement tasks being solved, specialized SSs are developed and created.

By virtue of wide application of lens concentrating optics in PV modules with inherent to it chromatic aberration and of multijunction solar cells (MJ SCs) sensitive to spectral characteristics of incident concentrated radiation, it obvious that it is necessary to determine mandatory groups of sunlight parameters for simulation:
- “spectrum + angular divergence” in investigating optical and power characteristics of refracting sunlight concentrators (Fresnel lenses);
- “irradiance + spectrum” in estimating PV parameters of MJ SCs.

Accordingly, in the work proposed are solutions for simulating sunlight parameters under laboratory conditions, which are necessary and sufficient for solving tasks on investigation of optical and power characteristics of lens concentrators and MJ SC I-V characteristics.
2. Sunlight simulator for investigating Fresnel lens characteristics

Fresnel lenses are rather complicated objects for experimental estimation of their concentrating capability and optical efficiency.

At sunlight concentrating, occurs spatial (due to radiation angular divergence in the primary light flux) and spectral (due to chromatic aberrations) irradiation redistribution in the focal plane. Thus, in each point of the focal spot, the radiation spectral composition differs from the solar one. The direct influence and the immediate dependence of the concentration ratio, focal spot size and of the FL optical efficiency (capability to focus radiation in a small-size spot) from parameters of radiation incident on the lens surface are obvious. In total, the mentioned above peculiarities of the object under study and of the experimental infrastructure change the radiation power distribution character in the focal plane “blurring” the focal spot.

In simulating the pair of parameters “spectrum + angular divergence” on the SS, one can ensure conditions for correct determination of optical and power characteristics of Fresnel lenses, and obtain true information on both the irradiance distribution profile within the focal spot and the lens efficiency.

The “second”, but no less significant, level of requirements includes such parameters of the light flux, as uniformity of irradiance on the tested object surface and long-term stability at the period of the optical and power characteristic recording. Success in producing uniform irradiance will depend substantially on the choice of the initial radiation source and of an optical scheme for forming the light flux. Temporal stability is easily ensured in using standard continuous Xe bulbs and a stabilized power supply source together with irradiance feedback.

To realize successively procedures for recording spatial and spectral power distribution in the FL focal plane, the SLS has been developed, scheme of which is depicted in Fig.1. A high pressure Xe discharge bulb playing a role of the initial light source is placed in the ellipsoidal reflector focus. The choice of the source is determined by a small size of the plasma area within a discharge area, by high luminous efficiency and by the proximity of the radiation spectral composition to the solar spectrum. The light flux is focused on the input of an integrating sphere playing a role of a homogenizer of the initial light flux and, at the same time, of a spatially uniform emitter. Such a constructive layout solution ensures formation of a light flux with heterogeneity of irradiance distribution in the plane of location of the tested lens within 3% (class B in correspondence with [1] by the “nonuniformity” criterion).

Tuning of the light flux spectral composition is provided by optical filters installed above the integrating sphere input port. The estimates of the “color” balance show a possibility to satisfy the “class A” requirements on the “radiation spectral composition” parameter in the range of 400-1400nm in correspondence with [1]. The light flux is focused towards the tested object by a collimating mirror, and the radiation angular divergence (about 32 min. of arc) is created owing to the matching between sphere output port diameter with collimator focal length.

Optical axis tracking along the path “sphere-collimator-object” and then towards the detector registering the irradiance distribution profile is ensured by a laser sight. A PV converter with precise (50-500µm) aperture is used as a profiling detector. This allows receiving the irradiance spatial distribution in the concentrator focus with a high resolution. By virtue of a low level of irradiance on the tested sample and, hence, in the focal spot, registration of the current signal from the PV detector is carried out by lock-in technique, and the obtained results are reduced to spectral irradiance standard conditions (1000W/m²) by normalizing in correspondence with the initial indicators of the light flux incident on a Fresnel lens.
3. Sunlight simulator for investigating MJ SCs

For investigating characteristics of MJ SCs converting the concentrated sunlight, SSs are necessary, in which the main parameter to be simulated is the spectral irradiance conserved for a wide range of variation of the total irradiance (up to 5000 concentration ratio or 500W/cm²). At the same time, it is required to ensure light flux stability within the “flat” part of the pulse, during which I-V characteristic is recorded (not less than 1msec according to [2]). Strict requirements for the correspondence of the radiation angular divergence of 32 angular minutes are not listed. However, in case of difficulties in eliminating spectral deviations in definite wavelength bands, one can use the M-factor method for re-counting and correcting in correspondence with [3].

To register MJ SC I-V characteristics in the mode of concentrated irradiation, a pulsed SS having an option of adjustment of spectral composition has been chosen (Fig.3). Two closely located U-shape Xe bulbs operating in a mode of short single light pulses are used as the initial emitter. Thanks to the use of double-bulb source and a white reflector located behind them, a powerful light flux can be formed, which, in passing through an optical window with a correcting interference light-filter, simulates quite well the sunlight spectral composition. A close mutual location of the bulbs allows realizing additionally an option to tune the spectral irradiance using the principle of radiation reabsorption by one bulb in the gas discharge plasma of the second one, and vise a versa. In increasing voltage on the bulbs power supply, variation of the efficiency of such absorption takes place: the “blue/red” ratio in the radiation spectrum shifts towards increasing a portion of “blue” light at partial smoothing out the xenon peaks. Thus, precise realignment of the “blue/red” ratio in the light flux is ensured. As a summary, spectral mismatch in the light flux with respect to standard terrestrial conditions (AM1.5D) in the range of 0.4 – 1.2 μm is presented in Fig.4. It is seen that, in increasing voltage on the bulbs, improvement of “quality” of the radiation spectral composition to the “class A” takes place (at voltages on the bulbs of 700-800V) [1].

As the distance between the cell and the illuminator decreases (in moving the latter along vertical direction), the irradiance level on SC increases. Control of the radiation concentration is performed by a single-junction GaAs photo-detector with a known dependence of the photocurrent on illumination determined by the procedure described in [4, 5]. The monitor photo-detector was located in the vicinity of the tested MJ SC to ensure similar irradiation conditions. An electronic system for controlling the SS ensures recording the MJ SC I-V curve during the “flat” part of the light pulse.
Figure 3 Optical scheme of the Spectrally Adjustable Pulsed SS.

Figure 4 Spectral irradiance produced by Spectrally Adjustable Pulsed SS with respect to Class A requirements (Spectral match to AM1.5D spectrum is in 100-nm wide spectral ranges).

4. Conclusions
The Solar Simulators presented in the work allow to simulate sunlight parameters required for solving specific research tasks. To investigate spatial and spectral power distribution in the focal plane of sunlight concentrators, one of the developed simulator reproduces two necessary parameters – angular divergence and spectral composition. In this case, the requirements for irradiance uniformity on the surface of the investigated concentrator and long-term stability of incoming light during the full cycle of the optical-power characteristic registration remain to be high. The second simulator is focused on investigating MJ CS I-V characteristics. Such a device having in basis a pulsed radiation source allows simulating the spectral distribution in the light flux with tuning in a wide range of values the total irradiance (up to 500X) in the plane of the tested sample location.

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