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# Investigation of focusing properties of photovoltaic module concentrator in a wide temperature range

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In the current work properties of a solar radiance concentrator with Fresnel lens made of Elastosil RT604 silicon made by Wacker have been investigated. The dependence of concentrator focal distance on temperature has been determined. Impact of variation of temperature-dependent concentrator focusing properties on the magnitude of short current of photovoltaic submodule has been determined by direct measurements using solar simulator. Using formalized model of modules based on the studied concentrator and solar cells with three and six $p-n$-junctions dimensions of a solar image in a wavelength range corresponding to an absorption profile of individual $p-n$- junctions has been calculated for the temperature range 10−60°C. It has been concluded that in the case of three $p-n$- junctions the minimum size of solar image at focal plane was 4.7 mm with the distance between the concentrator and solar cell being equal to 106.25 mm, and in the case of six $p-n$- junctions, the minimum size was 4.8 mm with the distance between concentrator and solar cell being equal to 106.5 mm.

**Keywords:** silicone lens, Wacker RT604, concentrator photovoltaic module, multijunction solar cells.

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## Introduction

Presently, due to predicted increase of worldwide energy consumption renewable energy sources play a more and more significant role, primarily, the sun energy. In the solar power industry, the electric energy is output by the most-spread solar panels based on polycrystalline silicon $\sim$ 18%. The record-breaking efficiency of conversion of solar energy to electricity, which is 26.7%, is produced in a cell of crystalline silicon [1], but the prospects of further increase of the efficiency in the silicon panels are quite limited. The higher efficiencies for conversion of solar radiation are provided in multi-junction solar cells (SC). Presently, the highest efficiency of conversion of 47.1% has been obtained in the six-junction solar cells [2]. The efficiency of conversion of solar radiation in commercial three-junction solar cells is 42−43% at the solar radiation concentration multiplicity above $100^x$ [1,3]. The multijunction solar cells are also advantageous in maintaining high efficiencies when the density of the conversed radiation exceeds the maximum densities of solar radiation on the Earth surface in hundred times. Taking into account the technological complexities in manufacturing the high-efficient multijunction solar cells in comparison with silicon-based solar cells, their „terrestrial" application is economically justified only together with concentrators of solar radiation. The record-breaking efficiency of a concentrator module as obtained in laboratory conditions is 36.7% [4], but the efficiency of the full-sized in-situ concentrator modules is about 32% [5]. Studying characteristics of the concentrator systems, impact of the environmental conditions on focusing properties of the concentrators will allow increasing the efficiency of solar radiation conversion in the photovoltaic concentrator modules.

A concept of a solar energy installation is widely spread, and it is designed to provide two-axis tracking of a sun position and includes photovoltaic modules with a radiation concentrator panel and a panel of solar cells located in the concentrator focuses, like in [5,6]. The concentrator panel is a glass plate with a connected assembly of adjacent square concentrators made of an optically transparent silicone. The silicone transparency within the wideband spectrum range is not inferior to the glass transparency, while the focusing quality corresponds to similar glass refraction concentrators [7]. However, unlike glass, due to its rubber-like structure the silicone is characterized by significant temperature change of the density, thereby resulting in noticeable changes of its refraction index within the whole spectrum range. Additionally, due to the difference of the linear expansion coefficients of the glass and silicone, the temperature changes include changes of a form of refraction surfaces of the Fresnel lens profile. The present work studies the impact of the change of the concentrator temperature on its focusing properties by a calculation method and by a method of direct measurements of output parameters of the concentrator-solar cell while maintaining the constant temperature of the solar cell.

## 1. Temperature dependence of dispersion of the refraction index of silicone Elastosil RT604

The refractometer IRF-22 was used to determine the dependence of the refraction index $n_D$ of the silicone rubber of the Elastosil RT604 (Wacker) grade on the temperature $T$ at the wavelength of 589 nm. The investigation of the rubber-like substance has required modification of the standard measurement procedure for IRF-22. A measurement prism pre-processed with an silane-based adhesive compound had liquid silicone rubber applied, and the center includes a measurement contact of the thermocouple, whereas a layer was pressed by the lighting prism to create a silicone film between the prisms. After transition of the silicone into the rubber-like state, the prisms were heated to 100°C by the stream of hot air. The one-time values of $n_D$ and $T$ have been obtained at natural cooling. At the temperature within the range 0−100°C

$$n_D(T) = (1.4147 \cdot 10^{-4} - 3.7781 \cdot 10^{-4}) \cdot T. \quad (1)$$

The dispersion of the refraction index of the silicone rubber is presented in the work [8]. The approximation was made that the temperature change includes only shift of the dispersion curve along the ordinate, but without the change of its form. Then, the dependence of the refraction index of the Elastosil RT604 silicone on the wavelength $\lambda$ and the temperature $T$ took the following form

$$n(\lambda, T) = a_0 + a_1 \cdot \exp(-\lambda/k_1) + a_2 \cdot \exp(-\lambda/k_2) - a_3 \cdot T, \quad (2)$$

where $a_0$, $a_1$, $a_2$, $a_3$, $k_1$, $k_2$ are 1.4015, 0.716, 0.039, $3.7781 \cdot 10^{-4}$, 93.55, 489.8, respectively.

The concentrator's Fresnel profile is made of concentric facets with the radial symmetry and the straight generatrix of the refraction surfaces. Due to the small width of the refraction surfaces (0.2−0.5 mm) the Fresnel profile implements an analogue of the aspherical lens. The concentrator's Fresnel profile was typically calculated provided that the beam with the wavelength $\lambda_c$ passing through the middle point of the refraction surface is incident to the center of a photoreceiving surface of the solar cell. The formula for calculation of the Fresnel profile includes the coordinates of the refraction surface, the nominal focal distance and the calculation refraction index $n_c$, which corresponds to the calculation wavelength $\lambda_c$ from the spectrum characteristic (2) at the temperature $T_c$. At the temperature different from $T_c$, in accordance with (2), the calculation wavelength $\lambda_c$ will be in correspondence with another BIP, and this lens will have the focal distance (FD) changed.

The present work studies the Fresnel lens sized as $60 \times 60$ mm with a profile pitch of 0.25 mm and the nominal focal distance of 105 mm at the temperature of 23°C, which is made of the silicone rubber of the Elastosil RT604 (Wacker) grade on the glass plate 4 mm thick. Using the formula for calculation of the profile of this lens, the ray with the wavelength $\lambda_c$ refracting in the facet center had the focal distance calculated with varying the concentrator temperature taking into account the corresponding (2) change of the refraction index (Fig. 1).

With increase of the concentrator temperature, the focal distance of the facets is linearly growing, while the further

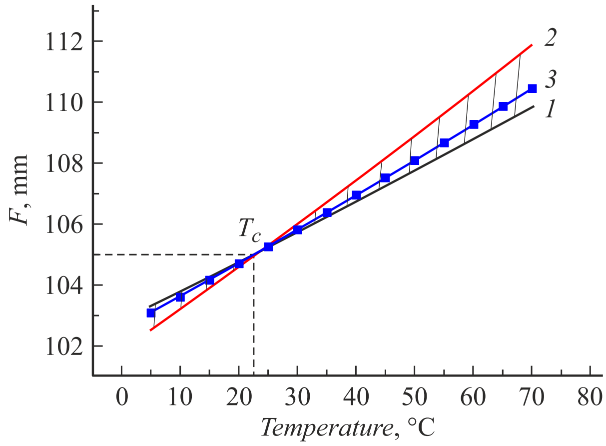


**Figure 1.** Focal distance of the refraction surfaces of the Fresnel lens for the beam $\lambda_c$ depending on the temperature: *1* — the central facet, *2* — the extreme facet, the dashed area —the other facets of the Fresnel lens, *3* — the focal distance of the lens for the beam $\lambda_c$.

away the facet from the center, in the bigger degree its focal distance increases. As the temperature deviates from the calculated one ($T_c = 23$°C), the difference between the focal distance of the central and extreme facets is growing (Fig. 1, the lines *1, 2*). The temperature dependence of the focal distance of the concentrator is obtained by averaging the data for the each facets taking int account their areas (Fig. 1, the line *3*). Due to a small portion of the area occupied by the extreme facets of the concentrator, the averaged line *3* is closed to the line *1* of the dependence plotted for the central facet. Thus, there is the difference in the focal distance on the temperature between the central and extreme facets of the lens, but its contribution to blurring of the focal spot is small, if the concentrator has a square aperture.

The linear temperature variation of the concentrator focal distance in relation to the nominal one results in the corresponding increase of the size of the focal spot. Therefore, in order to use the solar cell of the smallest size in the photovoltaic module, the calculation temperature $T_c$ in the formula for calculation of the Fresnel profile must be in the middle of the interval of the temperatures, at which it is planned to operate the photovoltaic module.

## 2. Methods of determination of the temperature characteristics of the concentrator

When designing the photovoltaic module with the Fresnel lens made of silicone rubber, with the known limits of the operation temperatures it is important to know how the dependence of the focal distance of the concentrator on its temperature will determine the limit sizes of the focal spot so that the design area of the solar cell would be sufficient for conversion of the entire focused solar radiation.

The focal spot can be sized by the method of computer experiment with a formalized model of the photovoltaic module and by the method of direct measurements of the module prototype based on the solar simulator. The method of computer experiment is more preferable both when designing the photovoltaic module and when analyzing operation of the prototype in the conditions which are problematic to create in the measurement experiment.

The size and the energy structure of the radiation spot redirected by the studied concentrator depends on the distance between the concentrator and the receiver, the width of the concentrator aperture, the spectrum interval and the slope of the dependence of the refraction index of the concentrator material within this spectrum interval and on the width of the refraction facet. All these factors are included in the formalized model of the photovoltaic module used in the computer experiment. The computer experiment calculates the radiation focusing by the concentrators of the various temperatures; the changes of their optical properties are described in a dispersion dependence (2). The measurement on the solar simulator makes it possible to determine the output parameters of the prototype, which are conditioned by features of the real concentrator beside the listed factors.

The present work has used the modified pulse radiation simulator based on a xenon flash lamp, which is designed to form the light flux of the density of $920\,\mathrm{W/m^2}$ (the spectrum AM1.5D) and the angular divergence of $32'$ identical to the divergence of the light flux coming from the solar disc [9]. The simulator included a system for positioning the optical elements in the light flux designed to ensure their fixing and mutual movement in the three coordinates, and a recording system designed to record the current-voltage curves (CVC) and calculate the optical electrical parameters of the concentrator-solar cell pair for the time of a single light pulse of the flash lamp. During the study the Fresnel lens was installed in a special chamber fixed in the simulator on the lens holder. By heating up the internal volume of air in the chamber using the electrospirals the lens was heated to maintain the specified lens temperature within the measurement cycle. The specified temperature of the Fresnel lens could be maintained within the interval from the room temperature to 60°C. The temperature was controlled using two sensors installed on the lens periphery. During the measurements at the higher temperature of the lens, the temperature of the solar cell was maintained by the system of thermal stabilization at $23 \pm 1$°C.

The measurement studies using the thermal imager Testo 875-2i included evaluation of dispersion of the temperature across the lens surface at the different heat-up levels. At the laboratory temperature, the difference of the temperatures of separate portions of the lens was within $\pm 0.1$°C. At the average temperature of the lens 40°C this difference was $\pm 1.7$°C and at the average temperature of the lens 60°C the dispersion of the temperature across the surface increased to $\pm 3.8$°C.

## 3. Temperature dependence of the focal distance of the concentrator

A series of measurements of the output parameters of the module prototype and the corresponding computer experiments with its formalized model were carried out to study the temperature dependence of focal distance of the concentrator. The determination of the focal distance of the concentrator is ambiguous when studying the focusing by the concentrator of the wideband radiation with an precipitous part of he refraction index dependencecurve of the concentrator material on the wavelength (for Elastosil RT604 it is a spectrum range below 550 nm). The determination of the focal distance as a concentrator-solar cell distance, at which all the focused radiation occupies the smallest area, does not reflect actual distribution of the wideband radiation, as there is a wide peripheric area (but with a small number of photons) of the focal spot, which is formed by the radiation with the wavelength below 550 nm as refracted by extreme facets of the concentrator.

The present work presents four temperature dependences of the concentrator focal distance with the above-said parameters, in which the focal distance was determined using the four different methods.

The first method has investigated the concentrator's focusing of the radiation of the flash lamp of the solar simulator to the photoreceiving surface of the solar cell based on the GaAs structure with one p-n junction with the spectrum sensitivity within 400–900 nm, sized as $4 \times 4$ mm. The GaAs-based solar cell was characterized by the fact that the simulator measurements with varying the concentrator-solar cell distance exhibited a distinct minimum of the current-voltage curve fill factor. This minimum means the biggest losses at the internal resistance, which were caused by the biggest local density of the generated current carriers. Therefore, the concentrator focal distance was determined as corresponding to such a concentrator-solar cell distance, at which the fill factor is the least.

The second method has determined, during the computer experiments, the concentrator focal distance as a concentrator-solar cell distance, at which the focal spot containing 95% of the generated current carriers has the minimal size.

The third method of the focal distance determination has presented the result of the computer experiments as the dependences $I_{sc}(b)$ calculated for the various concentrator-solar cell distances $D$ (Fig. 2, the line group *1*), where $I_{sc}$[A] — the short-circuit current of generated electric power when converting radiation passed through the square holes with a side size $b$[mm] from a set of conditional concentric square diaphragms centered on the solar cell. The dependence $I_{sc}(b)$ characterizes the increment of the number of the generated current carriers from a center to an edge of the focal spot. If the current carriers generated in the solar cell are uniformly distributed across the photoreceiving surface of the solar cell, then the increment of the carriers would be described by the square

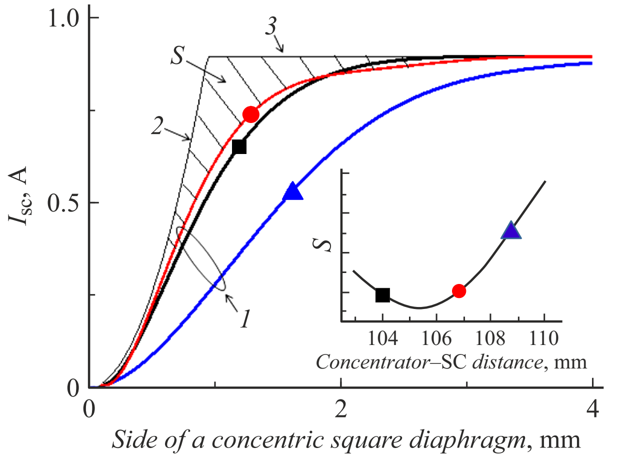


**Figure 2.** Dependences of the short-circuit current $I_{sc}$ generated in the solar cell areas, which are limited by concentric square diaphragms, depending on a side size of the square diaphragm $b$; a series of the plots is constructed for the various concentrator-solar cell distances $D$ (the line group *1*). The square dependence of distribution of the current carrier increment (the line *2*), the maximum current level (the line *3*), $S$ — the area of the dashed region — the parameter $S$. The insert has the dependence of the parameter $S$ on the concentrator-solar cell distance $D$.

dependence as the size $b$ of the conditional square centered diaphragms increases. But the concentration of the current carriers in the focal spot always decreases from the center to the edge of the spot. The focal distance has been determined by calculating the parameter $S[\mathrm{A \cdot mm}]$ as an area of a figure limited by the curve of the square increment of the carriers $b^2$ (Fig. 2, the line *2*), the straight line at the maximum current level (Fig. 2, the line *3*) and one of the curves $I_{sc}(b)$ (Fig. 2, one of the group lines *1*). The $S$ has been calculated while varying the concentrator-solar cell distance $D$. The dependence $S(D)$ (the insert of Fig. 2) has a distinct minimum corresponding to the biggest approximation of the dependence $I_{sc}(b)$ to the square distribution. The concentrator focal distance has been determined to be equal to the distance $D$, at which the parameter $S$ has the minimum value.

The fourth method has investigated the concentrator's focusing of the radiation of the simulator to the photoreceiving surface of the solar cell based on the InGaP/GaInAs/Ge structure with the three p-n junctions, sized as $3 \times 3$ mm, which is used in the photovoltaic modules. The concentrator focal distance has been determined to be equal to the concentrator-solar cell distance, at which there is a distinct maximum of the short-circuit current $I_{sc}$ in the pair current-voltage curve. In case of the multi-junction solar cell the maximum $I_{sc}$ corresponded to the maximum composure of the generated carriers contributing to the solar cell photocurrent around the optical axis, as at the solar cell size of $3 \times 3$ mm the deviation of the concentrator-solar cell distance in relation to the focal distance is associated with radiation exposure outside the solar cell.

The temperature dependences of the focal distance determined by the first and fourth method have been obtained using the solar radiation simulator (Fig. 3, the lines *1, 4*). The temperature dependences of the focal distance determined by the second and third methods have been obtained by the computer experiment method for the formalized model of the concentrator & GaAs-based solar cell pair, as used when determining the focal distance on the solar simulator by the first method. These temperature dependences of the focal distance are almost straight lines and coincide (Fig. 3, the lines *2, 3*), thereby demonstrating the identity of the two corresponding methods of determining the focal distance of the concentrator.

The linear run of the temperature dependence of the focal distance of the concentrator (Fig. 3, the lines *2, 3*) well agrees with the temperature dependence of the focal distance for the ray with the wavelength $\lambda_c$ refracting in the facet middle (Fig. 1). It means that for this concentrator the temperature variation of the optical properties of the silicone rubber is a priority factor, which determines a blurring degree of the focal spot in the concentrator-solar cell pair.

The measured temperature dependence of the focal distance in the pair with the GaAs-based solar cell (Fig. 3, the line *1*) coincides with the those calculated within the temperature interval 22–45°C, while at the higher temperatures it shows the reduced rate of the focal distance growth in relation to the design one. These differences may be related to a growing error of the measurements with the increase of the concentrator temperature and,

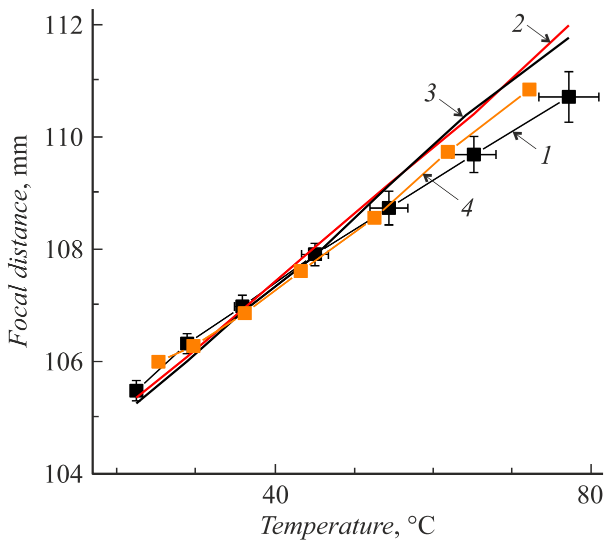


**Figure 3.** Dependences of the concentrator focal distance on the temperature, as measured on the solar simulator with the GaAs solar cell, determined provided that the fill-factor (the line *1*) is the least, calculated in the computer experiment by the minimum value of the parameter $S$ (the line *2*) and by the minimum size of the focal spot containing 95% of the generated carriers (the line *3*) and measured on the simulator with the InGaP/GaInAs/Ge solar cell, determined provided that the short circuit current has the maximum value (the line *4*).

possibly, to contribution by the temperature variation of the shape of the refraction surfaces of the facets. The coincidence of the measured and calculated dependences within the temperature interval 22−45°C shows objectivity of simulation of the focusing process based on (2).

The temperature dependence of the focal distance of the concentrator as measured with the three-junction solar cell sized as $3 \times 3$ mm, (Fig. 3, the line *4*) almost coincides with the above-discussed dependences. This dependence can be used for primary adjustment of the concentrator-solar cell distance in the photovoltaic modules, if the solar power unit will be operated at the average temperatures, which are different from that, for which the profile of the Fresnel lenses has been calculated.

Thus, based on the results of the calculations with the formalized concentrator-solar cell model and on the measurements on the simulator of the output parameters of the module prototype it can be concluded that heating or cooling of the concentrator made as the Fresnel lens of the Elastosil RT604 (Wacker) silicone on the glass by 10°C results in increase/decrease of its focal distance by 1.1−1.2 mm.

## 4. Investigation of the parameters of the prototype of the photovoltaic module within the extended temperature range

The concentrator-solar cell pair is a repeatable unit of the photovoltaic module and the temperature properties of its output parameters fully correspond to the temperature properties of the photovoltaic module. The solar simulator was used to carry out two series of the measurements of the output characteristics of the pair of the studied concentrator and the InGaP/InGaAs/Ge-based solar cell, sized as $3 \times 3$ mm, at the laboratory temperature (26°C) and with heating the concentrator in accordance with the above-described procedure to 49°C.

It has been investigated with a selected current-voltage curve parameter — the short circuit current $I_{sc}$. In the pair with this three-junction solar cell, when converting the simulator radiation of the wide spectrum composition $I_{sc}$ is determined by a number of the current carriers generated in a p-n junction, in which their generated number is less. When changing the distance between the concentrator and the solar cell of this size or when changing the concentrator temperature, the reduction of $I_{sc}$ is related to exposure of a part of radiation of the focused spot related to the limiting p-n junction outside the photovoltaic-active area of the solar cell.

The plot (Fig. 4, *a*) shows the values of $I_{sc}$ of the studied pair at the concentrator temperatures 26 and 49°C. It is found that at the concentrator temperatures 26 and 49°C $I_{sc}$ gets to its maximum at the distances between the concentrator and the solar cell differing by $\sim 2$ mm. In case of specifying a rated distance in the concentrator-solar cell pair (105 mm), heating the concentrator from 26 to 49°C results in the reduction of $I_{sc}$ by 10%.

Additionally, a series of experiments was carried out to compare the sizes of the light spots in the concentrator focus at the concentrator temperatures 26 and 49°C and several different distances in the concentrator-solar cell pair. The InGaP/InGaAs/Ge-based solar cell sized as $3 \times 3$ mm was moved with the 0.1 mm-step along the light spot in the concentrator focus to determine the values of $I_{sc}$ of the current-voltage curve when converting the radiation of the simulator flash lamp. If the light spot is less than the solar cell, then it is possible to determine the size of the light spot by a value of solar cell's travel along the light spot, whose positions will include an approximately constant value of $I_{sc}$.

Due to the said wide peripheric area (but with a small number of photons) of the focal spot, the boundaries of the light spot would been had to be determined with stipulating for their evaluation.

In order to ensure the comparison of the light spots focused by the concentrator at the various measurement parameters, the boundaries of the light spot were evaluated by the value of $I_{sc} = 0.425$ A, which was selected as per the data of the plot (Fig. 4, *a*) as the value of $I_{sc}$, which is achievable in all the options of the experiment. The case, when the values of $I_{sc}$ are below 0.425 A in the central position, would show that the light spot is bigger than the size of the photovoltaic-active area of the solar cell, and its size is not determined.

As a result of selection of the boundary value of $I_{sc} = 0.425$ A, it was not possible to detect the dependence of the size of the light spot on the distance between the concentrator and the solar cell at the concentrator temperature 26°C (Fig. 4, *b*). But there is still a distinct difference between the sizes of the light spots with the same energy contribution at the concentrator temperature 26 and 49°C. In addition, it is evidently shown (Fig. 4, *b*) that the light spot focused by the heated concentrator is reduced as the distance between the concentrator and the solar cell approaches the actual focal distance for the temperature 49°C. It has been determined that at the rated distance between the concentrator and the solar cell (105 mm) the light spot providing $I_{sc}$ being equal to 0.425 A is 1.1 and 2.7 mm at the concentrator temperatures 26 and 49°C.

## 5. Determination of the sizes of the light spots by the method of computer experiment

In designing the photovoltaic module, when sizing the concentrator and the solar cell, it is important to know the value of the light spot focused by the concentrator within the range of the operating temperatures of the power unit so as to takin into account a margin of the photovoltaic-active area of the solar cell in case of errors in installation of the solar cells and disorientation of the tracking system.

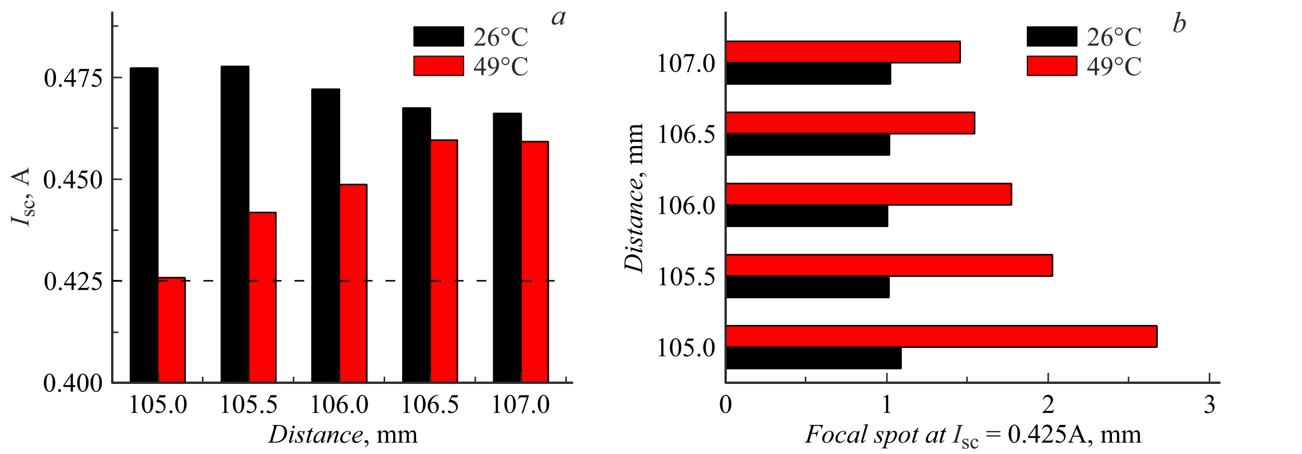


**Figure 4.** *a* — the short circuit currents when converting the radiation of the pair of concentrator-InGaP/InGaAs/Ge-based solar cell; *b* — the width of the focal spot which provides the value of $I_{sc}$ at the level of 0.425 A, at the temperatures 26 and 49°C.

When studying the prototype, the measured size of the light spot to a great extent reflects the properties of incident radiation. The spectral characteristic of the InGaP/InGaAs/Ge-based solar cell [3] has been analyzed to show that when converting the focused simulator radiation (AM1.5) the current is limited in the middle p-n transition, but the current in the upper p-n transition is just a little higher. As the solar radiation spectrum changes, the concentration of the generated current carriers changes in all the p-n junctions of the solar cell. When converting the spectra with the atmospheric mass of at least 2.1 the current is limited in the upper p-n junction of this solar cell due to predominant atmospheric absorption of solar radiation within the spectrum interval relating to the conversion in the upper p-n junction. In the six-junction solar cells [2], as the spectrum of solar radiation changes, the limiting current can be a current of one of the three or more p-n junctions. As the boundaries of distribution of the generated current carriers along the light-receiving surface of the solar cell are different in each p-n junction, when the limiting role is transferred to another p-n junction, then the effective sizes of the light spot will change.

One of the conditions stipulated by a design assignment when developing the terrestrial solar power systems should be their effective functioning with solar radiation of a various spectrum composition at the various horizontal height of the solar disc. The most suitable method of determining the limit size of the light spot is the computer experiment method, which determines the sizes of the light spots for radiation within the absorption ranges of all the p-n junctions of the solar cell.

The computer experiment method for the pair of the concentrator and the InGaP/InGaAs/Ge-based solar cell sized as $3 \times 3$ mm was used to calculate the size of the light spots depending on the concentrator-solar cell distance *D*. The plot (Fig. 5) shows the dependences of the sizes of the light spots (relating to the three active p-n junctions) on the

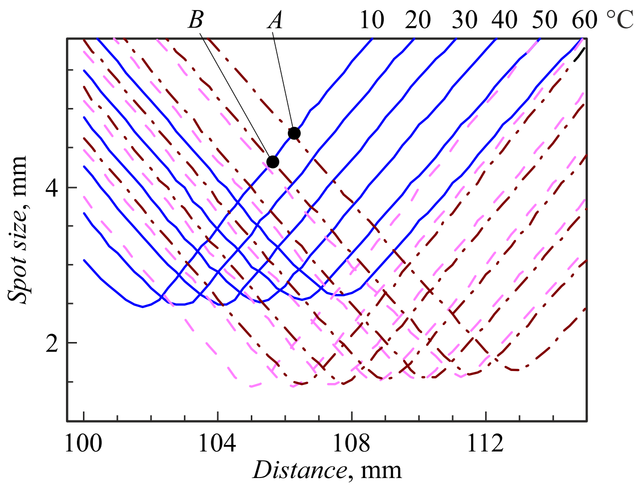


**Figure 5.** Dependences of the sizes of the light spots of radiation converted by the first, second and third p-n junctions, on the concentrator-solar cell distance. Subsequently, from left to right the group lines designate the temperatures 10, 20, 30, 40, 50, 60°C. The solid lines — the first $p-n$-junction, the dashed lines — the second $p-n$- junction, the dash-dotted lines — the third $p-n$-junction. The meaning of the points A and B is explained in the text.

concentrator-solar cell distances, which are calculated for the various concentrator temperature.

Collectively, the given dependences progress to show that there is one optimum value of the concentrator-solar cell distance, at which the size of the light spot will be the least in the specified temperature range. It will be 4.7 mm at the concentrator-solar cell distance 106.25 (the point *A*, Fig. 5). The difference of the optimum distance $D = 106.25$ mm from the design focus distance of the concentrator (105 mm at the laboratory temperature 23°C) is related to a location of the temperature value 23°C closer to the left edge of the studied temperature interval 10–60°C.

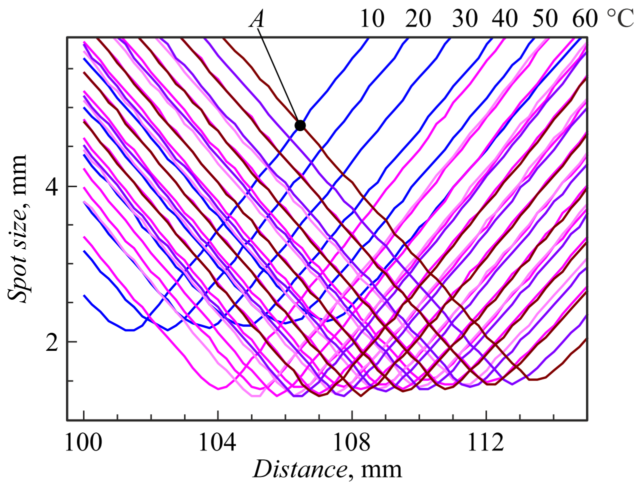


**Figure 6.** Dependences of the sizes of the light spots of radiation converted by the first to sixth p-n junctions, on the concentrator-solar cell distance. Subsequently, from left to right the group lines designate the temperatures 10, 20, 30, 40, 50, 60°C. The meaning of the point $A$ is explained in the text.

Additionally, the similar computer experiment was carried out to investigate the operation of the concentrator with the known parameters and the promising solar cell with the six p-n junctions [2], which is currently developed (Fig. 6). As in the three-junction solar cell, the temperature range 10−60°C has one concentrator-solar cell distance being equal to 106.5 mm, which will have the least size of the light spot being equal to 4.8 mm (the point $A$, Fig. 6).

When determining the solar cell size most suitable for the studied concentrator, by analyzing the data (Fig. 5, 6) it can be taken into account that in the three-junction solar cell the third p-n junction outputs excessive generation of the carriers at all the spectra of solar radiation. Therefore, if the minimum size of the spot is determined by an intersection of a line of the first p-n junction at 10°C and a line of the third p-n junction at 50°C, i.e. to be equal to 4.33 mm at $D = 105.6$ mm (the point $B$, Fig. 5), then it will not result in energy losses within the temperature range 10−60°C. The six-junction solar cell has no excessive generation in any of the p-n junctions, so one should focus on the calculation point of the minimum ($A$, Fig. 6).

## Conclusion

The work has investigated the focal distance of the concentrator of solar radiation in the photovoltaic module with the multi-junction solar cells at the various concentrator temperatures.

It is found that within the temperature interval 20−70°C the heating of the concentrator by each 10°C results in increase of the focal distance by 1.2 mm, by 1.1% of the rated focal distance of the concentrator.

In accordance with the results of the laboratory experiment, the size of the light spots ensuring the equal energy contribution was increased in 1.5 to 2.5 times with varying the concentrator temperature from 26 to 49°C.

The method of computer experiment with the formalized model of the photovoltaic module suits well for determination of the size of the light spot in case of the wide interval of the operating temperatures of the concentrator.

The results of the computer experiment have demonstrated that there is one optimum concentrator-solar cell distance, at which the size of the light spot will be the least in the given temperature range. For the photovoltaic module with the three-junction solar cell, it is calculated that with the variation of the concentrator temperatures 10−60°C the least focal spot is 4.7 mm with the concentrator-solar cell distance 106.25 mm. The similar calculations for the module with the six-junction solar cell have shown that the least focal spot had the width 4.8 mm with the inter-pair distance 106.5 mm.

The obtained results can be used to make a conclusion that it is expedient to use the solar cells sized as $5 \times 5$ mm in order to increase the specific energy removal in the photovoltaic module operating for a long time within the temperature variation interval 10−60°C.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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