Concentrator photovoltaic modules based on short-focus Fresnel lenses with a combined profile

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The characteristics of concentrator photovoltaic modules based on short-focus Fresnel lenses (60×60 mm, $F = 85$ mm) and high-efficient GaInP/GaAs/Ge solar cells have been studied. It is shown that optimization of the lens profile makes it possible to reduce the negative effects of reducing the focal length in the form of an increase in the local radiation concentration. The efficiency of modules based on lenses with a combined profile is higher by 0.7–0.9 abs.% compared to lenses with a classic profile and with a comparable focal length. At acceptance angles above 1°, the characteristics of modules with short-focus lenses will correspond to modules based on lenses with $F = 125$ mm.

Keywords: Fresnel lens, lens profile, multijunction solar cell, concentrator photovoltaic module, efficiency, acceptance angle.

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The profitability of solar power plants, which determines the feasibility of their construction, is determined by the cost of unit installed capacity and the operating costs [1,2]. The cost of unit installed capacity depends on the efficiency and cost of solar panels or concentrator photovoltaic modules (CPVMs) in a tracking solar photovoltaic array (SPVA). The SPVA cost is determined by the cost of expensive III–V heterostructure solar cells (SCs), the material requirements of a CPVM set by its height (determined by the focal length of an optical concentrator), and the cost of supporting structures of a tracking system.

Since CPVMs based on Fresnel lenses (FLs) of the „silicone-on-glass" type are relatively cheap and easy to produce, they are of considerable interest for photovoltaics. The efficiency of the best current modules exceeds 34% [3.4] and 36% [5.6] for designs with three-junction GaInP/GaAs/Ge and four-junction GaInP/GaAs//GaInAsP/GaInAs SCs, respectively.

It was demonstrated in [7] that an FL with given aperture and profile tooth pitch values has a specific focal length providing the maximum average radiation concentration ratio at a minimum light spot diameter. This length for an FL with an aperture of 60×60 mm and a pitch of 0.35 mm, which is determined by the profile manufacturing error, is 125 mm. Compromise solutions proposed in [8] (formation of a CPVM with a structural module height reduced by 32%) provide an opportunity to reduce the FL focal length from 125 to 85 mm while keeping the optical efficiency of lenses above 83% at an average (geometric) ratio of radiation concentration on the SC surface of more than 100X and a permissible acceptance angle up to 1.1°. However, this solution has a drawback in that the maximum local radiation concentration ratio on the SC surface increases from 2200X to 3230X, which leads to an increase in resistive losses and may reduce the efficiency of a concentrator photovoltaic module.

The authors of [7,9] proposed FL refractive profile designs that provide a reduction in the local radiation concentration ratio on the SC surface while preserving virtually the same focal spot diameter and average concentration ratio.

Two FL design options are examined in the present study with the aim of improving the uniformity of illumination and reducing the associated efficiency losses:

— combined lens with a regular pitch of refractive profile teeth (hereinafter referred to as a CFL; the criterion for choosing the angles of teeth inclination was discussed in [9]);

— FL with a variable (irregular) pitch of refractive profile teeth (VFL). The criterion for choosing the width of the refractive facet and the angle of its inclination here corresponded to the CFL option with the only difference being that the search for a new FL profile was carried out by increasing the teeth pitch in the central part of a lens.

The ray tracing model [7] yielded spectral (within the sensitivity ranges of subcells of a multijunction SC) distributions of irradiance at the focus of the analyzed FL. These spectral distributions of irradiance were used to obtain spatial distributions of photocurrent densities for subcells of a three-junction GaInP/GaAs/Ge solar cell. The main parameters of the simulated SC are listed in the table. The SC efficiency exceeded 41% (concentration ratio (500–2000)X) under uniform irradiation of its photoreceiving surface 2.8×2.8 mm in size. The characteristics of modules with a CFL and a VFL were compared to the characteristics of modules with classical-profile FLs (hereinafter classical FLs) with a regular refractive profile teeth pitch and the angle of teeth inclination chosen

GaInP/GaAs/Ge SC parameters used in modeling of current–voltage curves

Parameter	Value		
	GaInP	GaAs	Ge
Photocurrent density for subcells (AM1.5D, 1000 W/cm^2), mA/cm^2	15.87	15.03	19.23
Density of the injection (diffusion) current of the $p-n$ junction, A/cm^2	$3.0 \cdot 10^{-27}$	$4.9 \cdot 10^{-21}$	$3.4 \cdot 10^{-6}$
Density of the recombination current of the $p-n$ junction, A/cm^2	$3.1 \cdot 10^{-14}$	$2.2 \cdot 10^{-12}$	–
Sheet resistance under the contact grid, $\Omega/\square$	1190		
Sheet resistance between GaInP and GaAs subcells, $\Omega/\square$	200		
Sheet resistance between GaAs and Ge subcells, $\Omega/\square$	150		
Specific resistance of the contact grid material (gold), $\Omega \cdot$ cm	$2.35 \cdot 10^{-6}$		
Contact bar width/thickness, μm	4/4		

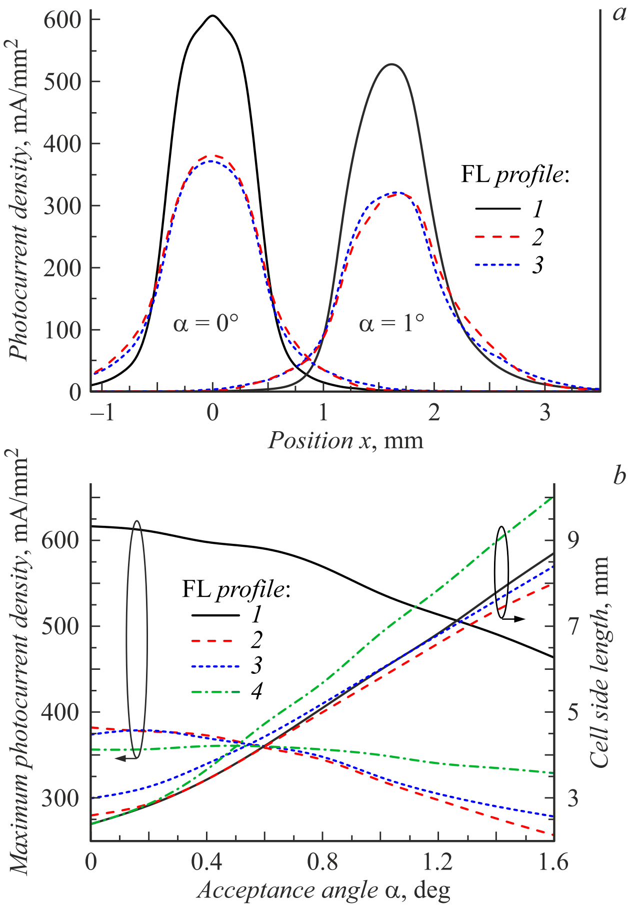

Figure 1. Photocurrent distributions in a GaInP subcell of a GaInP/GaAs/Ge SC operating with an FL (a) and dependences of the maximum photocurrent density and the SC side length required for interception of 95% of radiation transmitted through the FL (b) on angle α of misalignment between the CPVM and the Sun vector. *1*, *4* — FL with a classical profile; *2* — FL with a combined profile (CFL); *3* — FL with a combined profile and a variable tooth pitch (VFL). $F = 85$ (*1–3*) and 125 mm (*4*).

according to the criterion of focusing of a beam parallel to the optical axis [7].

Figure 1, a shows the profiles of photocurrent generated in the GaInP subcell of the experimental SC corresponding to different acceptance angles α and three FL designs. Note that the permissible acceptance angle value for a CPVM is related explicitly to the SC dimensions. In the present study, an acceptance angle at which 95% of solar radiation passing through the FL is concentrated on the SC surface is considered permissible. The maximum photocurrent density at the center of the light spot of a classical FL remains 1.5 times higher than the one for the CFL and VFL designs within the entire range of angles. A dependence corresponding to a CPVM based on a classical FL with a focal length of 125 mm, which is the optimum one for a size of 60x60 mm [7,8], was added to Fig. 1, b for comparison. A reduction in focal length of the classical FL from 125 to 85 mm leads to a significant increase in the maximum photocurrent density, while the density for two examined FL options is only slightly higher than that for the classical FL with focal length $F = 125$ mm.

The CFL and VFL characteristics are close. It should be noted that the maximum photocurrent density in the SC decreases with increasing acceptance angle for all FLs with $F = 85$ mm. Owing to the specifics of profile formation, the VFL is characterized by a slightly more pronounced blurring of the light spot than the CFL and requires the use of a larger-sized solar cell at small permissible acceptance angle values. At permissible acceptance angle $\alpha_{\max} = 1.0°$, the required SC side length is 5.8 mm for the CFL and 6.0 mm for the classical FL or the VFL (all with $F = 85$ mm); i.e., the SC area is reduced by 7%. For comparison, if the classical FL design with $F = 125$ mm is used, the photoreceiver side length needed to ensure $\alpha_{\max} = 1.0°$ is 6.9 mm, which verifies the advantages of short-focus FLs with an SC area reduction of 19%.

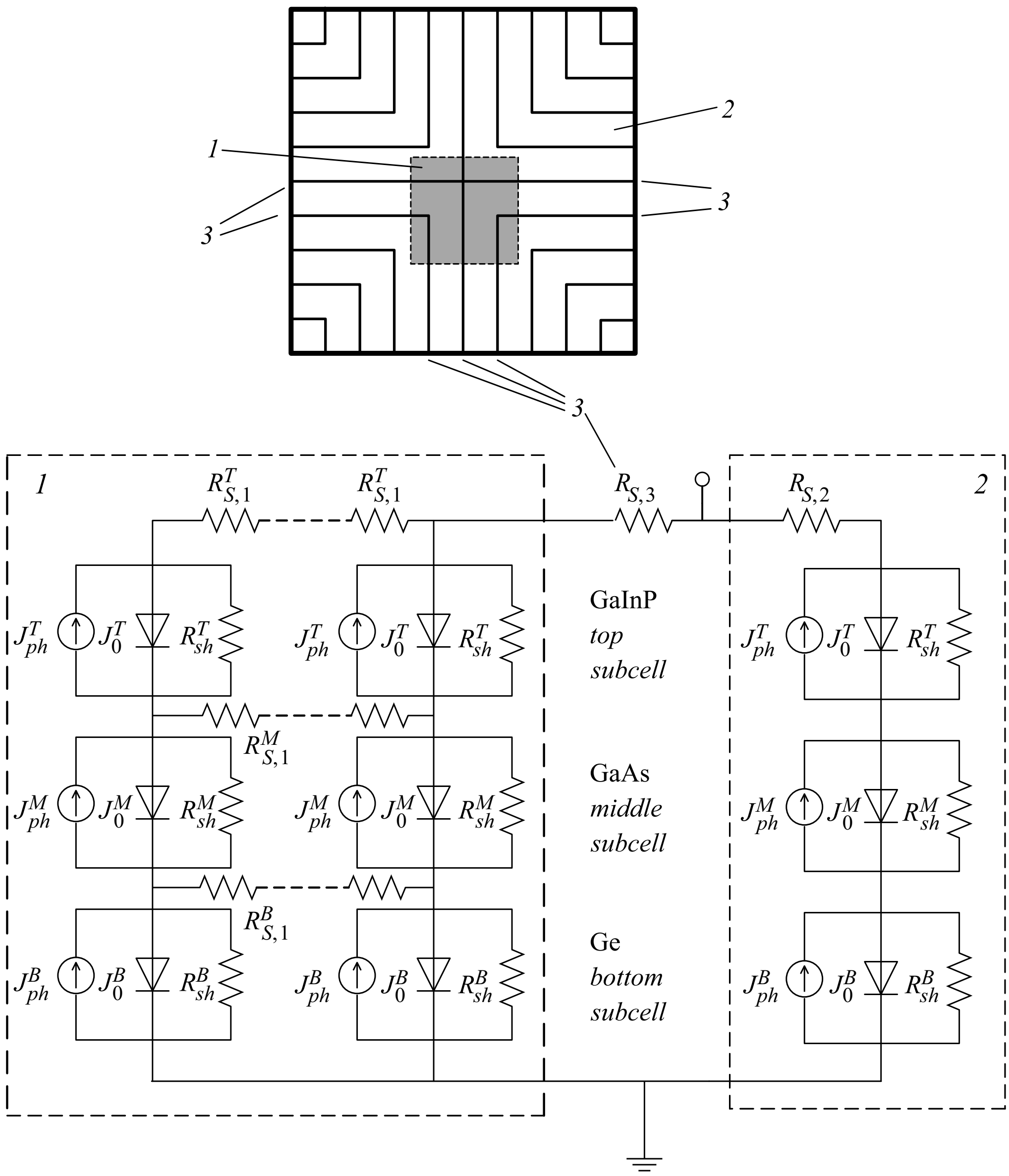

Figure 2. Equivalent circuit for modeling of the current–voltage curves of the GaInP/GaAs/Ge SC. *1* — High irradiance region, *2* — low irradiance region, and *3* — contact bars that output current to the external circuit from the high irradiance region. J^T_{ph}, J^M_{ph}, and J^B_{ph} — photocurrent densities for the top (GaInP), middle (GaAs), and bottom (Ge) subcells; J^T_0, J^M_0 J^B_0 and R^T_{sh}, R^M_{sh}, R^B_{sh} — reverse saturation current densities and specific shunt resistances for the same subcells, respectively; and $R^T_{S,1}$, $R^M_{S,1}$, $R^B_{S,1}$, $R_{S,2}$, and $R_{S,3}$ — equivalent series resistances of different layers of the structure and the contact grid.

The presented photocurrent dependences (Fig. 1) made it possible to estimate the efficiency of a concentrator photovoltaic module with a reduced structural height. The two-component model (Fig. 2) including a distributed equivalent circuit for the region of conversion of highly concentrated radiation and a single-element model for the peripheral region was used in simulation.

The efficiency of the CPVM with the SC (with its parameters corresponding to those given in the table) was determined. Connection losses arising when individual photovoltaic cells are combined into a single module were neglected in calculations. The used model (Fig. 2) provides the needed accuracy of simulation of the CPVM current–voltage curves with account for nonlinear resistive losses, which are determined by the flow of lateral currents in the SC structure, both in the region of high irradiance and in peripheral regions with significantly lower values of current density per unit SC area. The obtained efficiency estimates are presented in Fig. 3.

The optimum values of the contact grid pitch for the SC with the adopted structure parameters (see the table) and the considered FL optical profiles are close to 50 μm: 45 and 55 μm for the classical FL and the CFL, respectively. The highest efficiency of 33.3 abs.% for the CFL/SC pair is

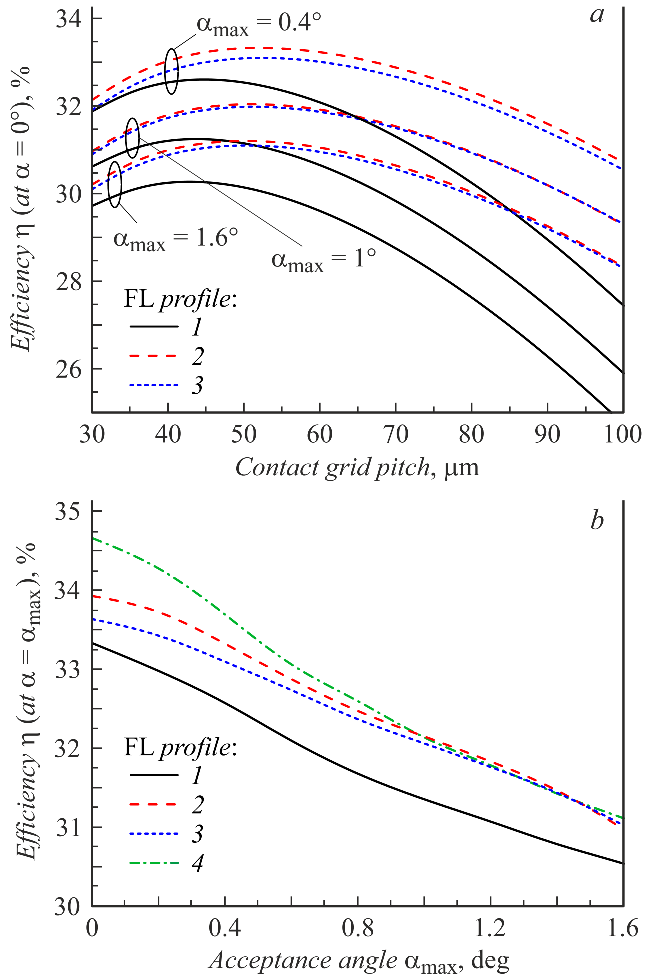

Figure 3. Modeled dependences of the efficiency of a concentrator photovoltaic module based on a GaInP/GaAs/Ge SC and an FL with different profiles on the contact grid pitch (*a*) and permissible acceptance angle α_{max} at the optimum contact grid pitch of $50\,\mu$m (*b*). *1*, *4* — FL with a classical profile; *2* — FL with a combined profile (CFL); *3* — FL with a combined profile and a variable tooth pitch (VFL). $F = 85$ (*1–3*) and 125 mm (*4*). CPVM irradiation conditions: AM1.5D; 1000 W/m^2.

predicted at a permissible acceptance angle no greater than $\alpha_{max} = 0.4°$, while the efficiency for the classical FL/SC under the same conditions does not exceed 32.6 abs.%. The difference becomes more profound when the acceptance angle increases to $\alpha_{max} = 1.0°$: the efficiency is 32.2 abs.% for the CFL versus 31.3 abs.% for the classic FL. At small acceptance angle values, the VFL/SC pair has slightly worse performance due to the greater initial blurring of the light spot of concentrated radiation (Fig. 1). At angles above $\alpha_{max} = 1°$, the characteristics of CPVMs with the CFL and the VFL are virtually identical. In terms of efficiency, they reach the level of the classical FL with a focal length of 125 mm.

Thus, the use of a „silicone-on-glass" FL with a combined profile in a photovoltaic module allows for a 32% reduction in the structural height of modules without compromising the efficiency relative to a CPVM based on an FL with the optimum focal length [7,8]. This reduction in structural height implies that a smaller amount of materials and financial resources is needed to construct an SPVA. In addition, the use of short-focus FLs with a combined profile relaxes the requirements as to the area of expensive SC heterostructures, which also helps reduce the cost of power plants.

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Conflict of interest

The authors declare that they have no conflict of interest.

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