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OPTICS, QUANTUM ELECTRONICS

Parameter Optimization of Solar Modules Based on Lens Concentrators of Radiation and Cascade Photovoltaic Converters

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Abstract—Two main issues governing the design of a solar concentrator module with triple-junction nanoheterostructure photovoltaic converters (PVCs) are considered: the effective concentration of radiation using Fresnel lenses and effective heat removal from PVCs. By theoretically and experimentally simulating these processes, the design parameters of module's elements are determined. A test batch of full-size modules has been fabricated. Each module consists of a front panel of small-size Fresnel lenses (a total of 144 lenses arranged as a 12 × 12 array) and the corresponding number of multilayer InGaP/GaAs/Ge PVCs. The PVCs are mounted on heat-distributing plates and are also integrated into a panel. The efficiency of the concentrator module with a 0.5 × 0.5-m entrance aperture measured under outdoor conditions is 24.3%, which is more than twice as high as the efficiency of standard (concentrator-free) silicon modules. In smaller test modules, the efficiency corrected for the PVC standard temperature (25°C) reaches 26.5%.

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INTRODUCTION

The world economy has already been matured for switching to "new power engineering" that implies a wider utilization of solar power. The underlying reasons are both the problems having accrued in traditional power engineering (ecological hazards, depletion of fossil fuels, and the fossil fuel nonuniform distribution over countries) and great advances in the development of semiconductor photovoltaic converters (PVCs) and solar power systems on their basis. The power program of the European Union forecasts that no less than 3% of electric power will be accounted for by solar power plants by 2020 and that a price parity between solar-generated and traditional electricity will be established in most European countries by that time [1]. The Solar America Initiative foresees competitive prices for solar power as soon as 2015 and predicts the photovoltaics market volume at a level of 5–10 billion dollars by that time with an increase to 20–30 billion by 2030 [2].

The cost of solar power can be cut by using efficient nanoheterostructure PVCs in tandem with cheap optical solar power concentrators, such as circular Fresnel lenses [3–6]. Recently developed cascade PVCs based on III–V semiconductors offer high efficiency: up to 41% with 50% in sight under terrestrial conditions [7–9]. The PVC's surface area needed to generate desired electric power decreases with increasing the radiation concentration ratio (reaching 500× or more). Today, triple-junction (Al)GaInP/Ga(In)As/Ge heterostructure PVCs are produced. Three photoactive p–n junctions in this structure are serried-connected using built-in tunnel p^+–n^+ junctions.

Although the cascade PVC is the key element of the solar power system, the development of the concentrator photovoltaic module requires that its components, namely, an optical concentrator, PVC, heat-removing unit, and Sun tracker, be matched to each other. We will consider concentrator modules that have been designed in recent years in the laboratory of photovoltaic converters at the Ioffe Physico-Technical Institute [6, 10, 11]. The subject of consideration in this work is parameter optimization of the module's units and module as a whole.

DESIGN OF THE SOLAR CONCENTRATOR MODULE

The concentrator module is made in the form of a front lens panel connected to a rear energy-generating panel with aluminum walls. The panels are the focal distance of the lenses apart. The lens panel represents a sheet of silicate glass with small-size Fresnel lenses right up to each other on its inner surface. The Fresnel lenses are made of a silicone compound. The light-sensitive (receiving) part of the panel consists of 144 40 × 40-mm square lenses arranged into a 12 × 12 array. Each lens focuses solar radiation onto an underlying PVC with a photosensitive surface area diameter of 1.7 or 2.3 mm. Each of the 144 PVC chips is mounted on

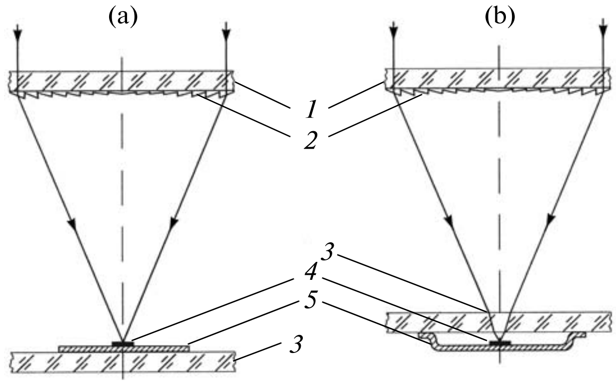

Fig. 1. Optical schemes of the modules: (*1*) front glass panel, (*2*) silicone profile of the Fresnel lens, (*3*) rear glass base, (*4*) PVC, and (*5*) heat-distributing plate.

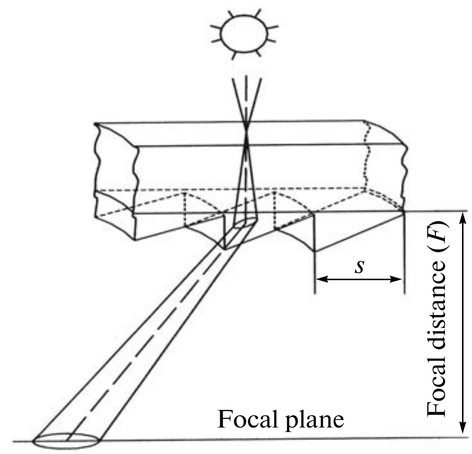

Fig. 2. Ray diagram in the mathematical model of radiation concentration.

a heat-distributing plate made of sheet copper. The heat-distributing plates are glued to the bearing surface of the module, which is made of silicate glass and through which the heat is removed. On the energy-generating panel thus formed, PVCs are interconnected so as to produce a series–parallel circuit. The advantages of such a design approach are (i) the ease of extracting the current being generated and the ease of removing the heat from small-size PVCs; (ii) the reduced consumption of structural materials, since the focal distance of solar power concentrators is short; and (iii) the use of cheap and extremely stable (under atmospheric conditions) silicate glass as the basic material. These advantages were described in detail, e.g., in [4, 6].

The versions of optical schemes for a lens–PVC pair in the modules being designed are shown in Fig. 1. In Fig. 1a, the PVC is inside the inner space of the module. The front and rear glass panels, as well as the walls of the module, protect it against the environment. Note that the inner space of the module cannot be sealed off completely because of the considerable variation of the working temperature and an attendant pressure drop relative to the ambient. The air interconnecting channel must be equipped with a device protecting against dust and moisture. In Fig. 1b, the PVC is placed on the outer side of the rear glass base of the module. Here, protection against the environment is provided by hermetical sealing of a thin air gap between the shaped heat-distribution plate and glass base. However, the optics includes an additional element—a flat glass panel.

Below, we consider the strategy for optimizing the lens shape as applied to triple-junction PVCs. The selection of a concentrator–PVC pair entering into the module depicted in Fig. 1a is substantiated. Obviously, the same optimization strategy is applicable to the design in Fig. 1b.

CALCULATION OF THE EFFICIENCY OF THE CONCENTRATOR–PVC FOR DETERMINING FRESNEL LENS PARAMETERS

The efficiency of each concentrator–PVC pair in the photovoltaic module depends on the Fresnel lens size, Fresnel lens focal distance, and diameter of the PVC's photosensitive area. The values of these parameters, in turn, depend on manufacturing conditions and design limitations. Economically, it is necessary that the PVC, the cost of which makes up a major fraction of the total cost of a solar system, occupy an area as small as possible and, accordingly, the concentration ratio be as high as possible. Here, limitations are associated with the ability of the PVC to operate with high densities of the photocurrent. However, this point is beyond the scope of this article.

For an angular dimension of the Sun of 32′, the minimal size of the focal spot is $0.0093F$, where F is the focal distance of the lens. In the design of the module under consideration, circular Fresnel lenses with conic microprisms with constant width s are applied. The focal spot increases by this value. The profile pitch was taken to be equal to 0.25 mm starting from the limitations imposed by the fabrication technology of precision moulds for Fresnel lenses. In this case, the focal spot size increases mainly because of a chromatic aberration, as follows from simple estimations.

To determine other parameters that are optimal for the concentrator–PVC pair, a mathematical model was worked out to describe the passage (through the Fresnel lens) the part of the solar radiation that, being absorbed in the PVC, contributes to the photocurrent. Incident radiation is represented as a set of cones formed by monochromatic rays with a cone angle equal to the angular dimension of the Sun (Fig. 2). The tops of the cones equidistant from each other lie on the front surface of the glass base of the lens. We consider the refraction of the outer rays of the cone by the inclined surface of the microprism with the aim of determining their positions in the focal plane. Each site on the focal plane that was bounded by outer rays was assigned the radiation power of all rays from the initial cone with allowance for reflection losses on interfaces between media with different refraction indices. The power difference within the cone that arises after refraction and the Sun limb darkening were ignored: the influence of these effects is minor and would have decreased the focal spot insignificantly.

The radiation intensity monochromatic distribution on the focal plane results from the summation of the contributions from the initial cones. The general distribution is obtained by summing the distributions constructed for a sequence of wavelengths with a constant step. The step of the sequence and the density of ray cones are selected so that their values do not influence the final result. Each monochromatic distribution is assigned the fraction of the solar radiation that is proportional to its contribution to the PVC photocurrent. This fraction is found from the AM1.5 standard solar spectrum (direct radiation) and the typical photosensitivity spectrum of an efficient triple-junction PVC (see Fig. 3). The wavelength range is limited: it includes wavelengths falling into the range bounded by wavelengths equal to the selected one plus/minus half the step of the sequence.

To calculate the trajectories of the rays, it is necessary to know how the refractive index of the lens depends on the wavelength and temperature. We constructed a dispersion curve for two-component ELASTOSIL RT 604 silicone (Wacker Co.) at room temperature in the wavelength range 350–1600 nm by determining ray deflection angles with a test prism. The temperature dependence of the refractive index was measured at a single wavelength ($\lambda = 633$ nm) in the range 5–45°C. It was assumed that, as the temperature rises, the form of the dispersion curve remains unchanged: the curve just wholly shifts along the refractive index axis.

The optical efficiency of the concentrator–PVC pair is estimated from the radiation distribution in the focal plane by integrating over the PVC photosensitive area (grid shadowing is ignored here, since it is embodied in the value of the external quantum yield of the PVC; see Fig. 3). It is known that the photocurrent in a PVC with a monolithic InGaP/GaAs/Ge isoperiodic structure equals the least one among the currents of each cascade. The optical efficiency of the lens was therefore estimated for each cascade separately. The resulting optical efficiency was taken to be equal to the least of the efficiencies of the top and middle PVC cascades; the lens efficiency of the bottom cascade should be multiplied by a factor of 1.5 in this case in order to take into account the generation of an extra current in the cascade.

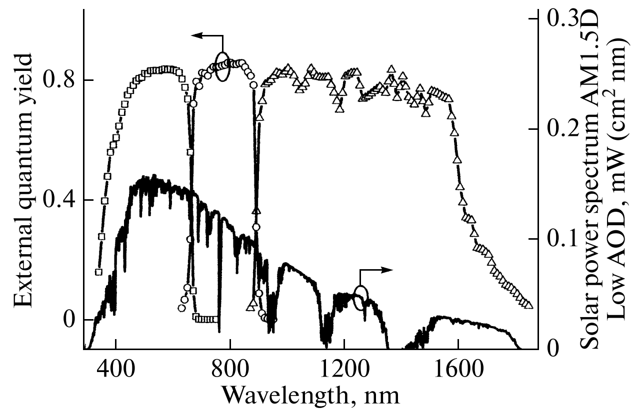

Fig. 3. AM1.5 direct solar spectrum and the photosensitivity spectrum of the triple-junction PVC.

OPTIMIZATION OF FRESNEL LENS PARAMETERS

The inclination angle of each microprism is calculated from the condition that the ray incident normally to the base of the lens deflects in the middle of the inclined surface and crosses the optical axis in the focal plane at given focal distance F. The angle of inclination depends on the position of the microprism and refractive index n used in calculations. According to the dispersion curve, it is at this value of n that distance F will be the focal distance of the lens for a ray with an appropriate wavelength at a given temperature. It is necessary that the rays be optimally defocused in all other spectral intervals ensuring the maximal efficiency of the concentrator–PVC pair. When determining the angles of inclination of all microprisms for a given lens, the refractive index used in calculations remained the same. Parameter n was selected using a computer program. For given parameters (focal distance, lens size, and diameter d of the PVC's photosensitive area) and a variable refractive index, we constructed the profile of the Fresnel lens and calculated its optical efficiency. The profile was considered optimal when the optical efficiency of the concentrator–PVC pair was the highest.

Figure 4 (upper panels) shows the solar radiation concentration ratios calculated along the photosensitive area radius for three cascades of the PVC at lens–PVC distance $F = 95$, 80, 65, and 55 mm. The lower panels of Fig. 4 plot the optical efficiency of the lenses versus the PVC diameter for the same values of F. Parameter n was selected for each 40×40-mm lens kept at 25°C and a PVC with $d = 1.7$ mm. Using the distributions shown in Fig. 4, one can estimate the advantages and disadvantages of lenses with different focal distances.

It is known that the longer the focal distance, the more uniform the PVC illumination; however, as the focal spot expands, the PVC surface area does not meet the minimum condition any longer. With a

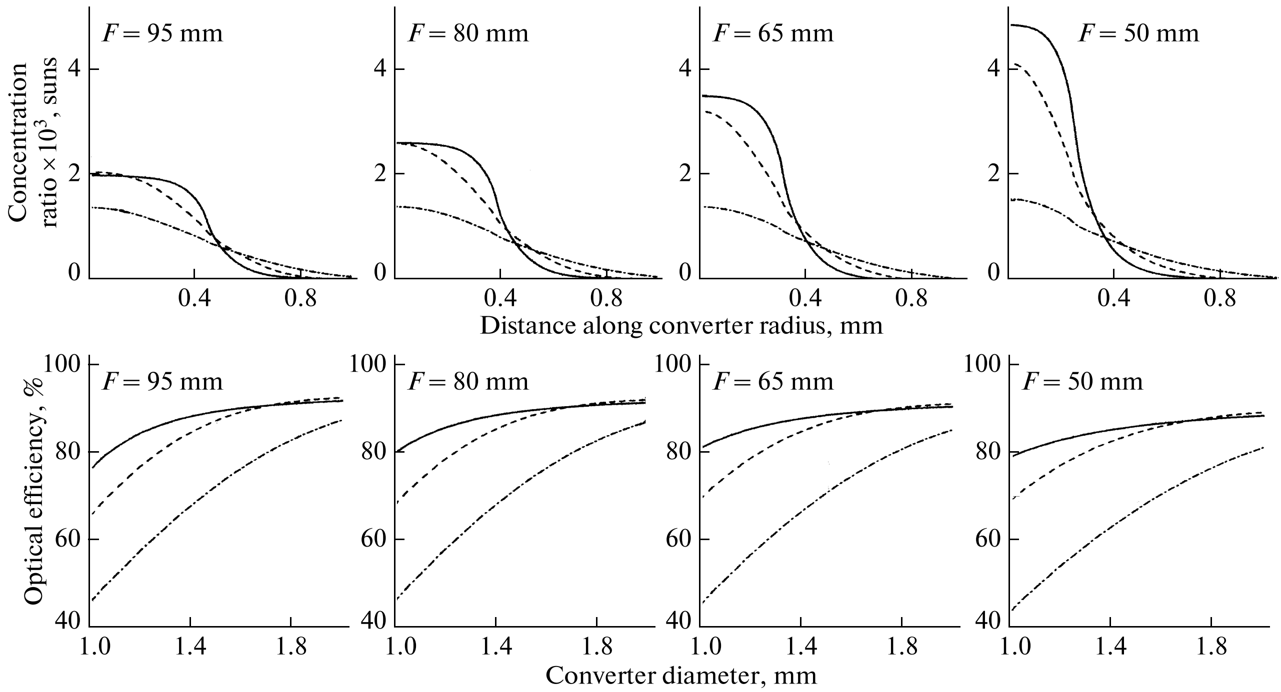

Fig. 4. Distribution of the solar radiation concentration ratio along the PVC radius (upper panels) and the optical efficiency of the lenses vs. the PVC diameter (lower panels). Solid, dashed, and dash-and-dot lines refer to the upper, middle, and lower cascades, respectively.

decrease in the focal distance, the misorientation characteristic of the module is improved. At short focal distances (small focal spots), however, the mismatch between local concentrations in different cascades grows, as a result of which lateral currents passing between the cascades of the structure increase; that is, ohmic losses rise. A considerable increase in the solar radiation concentration ratio at the center may impose limitations due to ohmic losses in the contact grid and a local overheating of the PVC. In general, Fig. 4 can be used as a tentative assessment in selecting the focal distance of the lens and the diameter of the PVC with regard to its specific photovoltaic properties (the ability to operate under a high level of illumination) and a reasonable value of the optical efficiency of a concentrating system. For example, the optical efficiency reaches a near-ultimate value when sufficiently "long-focus" lenses and PVCs 1.7 mm or more in diameter are used.

The effect of temperature on the Fresnel lens characteristics was studied at the final stage (2008) of the FULLSPECTRUM Project financed by the European Commission. Figure 5 (top panel) shows the influence of the calculated refractive index on the temperature dependence of the lens–PVC pair optical efficiency ($F = 70$ mm, $d = 1.7$ mm). It is seen that the module with lenses for which the calculation was carried out at 35°C is the most efficient. The efficiency versus temperature curve is symmetric in the most feasible operating range (10–45°C). For the profiles of the lenses designed for 35°C, we constructed resulting temperature dependences in the range $F = 50$–90 mm (Fig. 5, bottom panel). The preferred focal distance for 40 × 40-mm lenses and a triple-junction PVC with $d = 1.7$ mm is seen to fall into the range 70–90 mm.

Note that the above results can be extended for lenses with other sizes if the focal distance and PVC diameter are scaled. In the case of scaling-down, the fixed pitch of Fresnel lens grooves may have a detrimental effect. Another negative factor may be a too much scaling-down of the PVC, which may cause troubles in mounting and interconnection. If the concentrating lens increases in size, the condition for effective heat removal from the PVC becomes the most critical. When designing solar concentrator modules, we selected two sizes of Fresnel lenses: 40 × 40 mm for $F = 70$ mm and 60 × 60 mm for $F = 105$ mm. The diameter of the PVC's photosensitive area was 1.7 and 2.3 mm, respectively.

PHYSICAL SIMULATION OF HEAT REMOVAL FROM THE CASCADE PVC

Provision of appropriate thermal conditions for the PVC operation is a key point in optimizing the design of the solar photovoltaic module. Heat removal from the PVC is accomplished first by distributing the heat flux over the copper plate and then by rejecting the heat into the environment via radiation and contact with the ambient air. Owing to the considerable reduc-

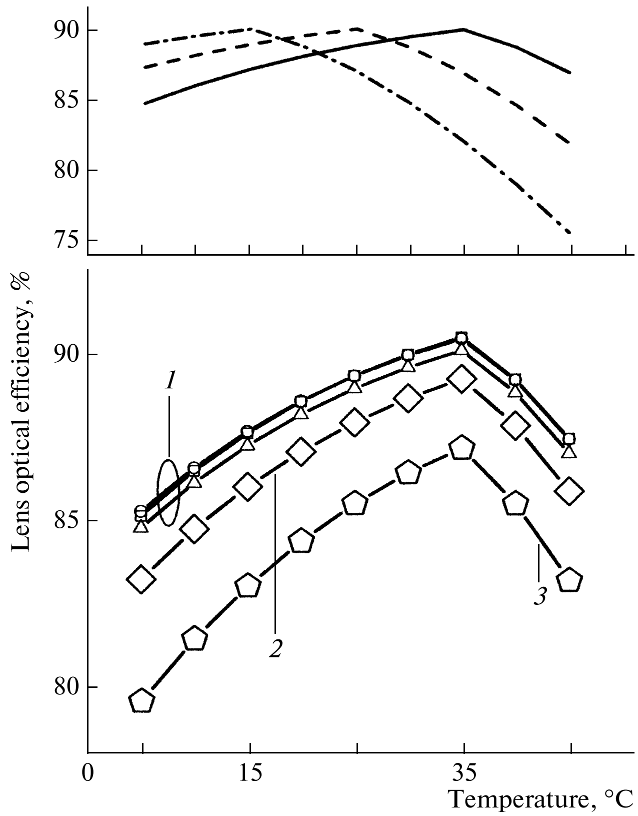

Fig. 5. Resulting optical efficiency of the lenses vs. the temperature. Solid, dashed, and dash-and-dot lines in the upper panel are calculated for the lens with $F = 70$ mm and T = 35, 25, and 15°C, respectively. In the lower panel, F = (*1*) 90, 80, and 70; (*2*) 60; and (*3*) 50 mm.

tion of the heat flux density, which becomes comparable to the power density of the incident solar radiation before concentration, the heat can be effectively removed through the rear glass base of the module, although the thermal conductivity of the glass is low. It should be noted that the rear base could be made of a cheaper material with a higher thermal conductivity, for example, of sheet steel. However, silicate glass is extremely stable against environmental impacts, has a low thermal expansion coefficient (focal spots shift little relative to the PVC's photosensitive areas with varying temperature), and offers good insulating properties (mounted PVCs can be arbitrarily interconnected into a series–parallel circuit if the electrical safety of the module is provided). In addition, silicate glass can be used as a PVC-protecting material (Fig. 1b). Each PVC is soldered to a heat-conducting copper plate, and this plate, in turn, is glued to the rear base of the module.

Because of uncertainties associated with the properties of thermal contacts in the system and conditions of heat transfer by air convection, thermal conditions for a PVC in the module were predicted using the physical, rather than computer-aided, simulation of heat removal. We prepared fragments of the rear base

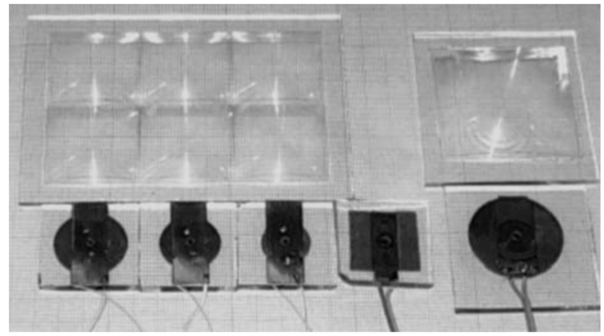

Fig. 6. Images of the 40 × 40- and 60 × 60-mm test Fresnel lenses and physical models of corresponding heatsinks with cascade PVCs mounted on them.

with sizes corresponding to those of single Fresnel lenses (Fig. 6).

Each fragment represented a heat-distributing copper plate with a variable size and a triple-junction PVC mounted on it. Heat release in the PVC was provided by passing current from an external dc source. The current through and the voltage across the PVC were selected such that the released power was equal to the thermal power released in the PVC when it was exposed to concentrated solar illumination and connected to an electrical load with optimal parameters. For example, for an ideal 40 × 40-mm Fresnel lens and a direct solar radiation power density of 850 W/mm^2, the radiation with a power of 1.36 W would have been incident on the PVC. With allowance for losses in the lens (mainly reflection losses) and the escape of about one-third of the current-generated power into the external load, the heat release in the PVC to be dissipated was set equal to 1 W. For 60 × 60-mm^2 Fresnel lenses, the power delivered to the PVC in the experiment was equal to 2.2 W. The temperature immediately beneath the PVC and the ambient temperature were measured with thermocouples. Heatsinks were placed at an angle of 45° to the horizon, similar to the conditions in a real module at Sun tracking. In a number of experiments, air flowed about the rear side of the heatsinks with a slow velocity of 1–2 m/s. To approximate the PVC operating conditions in the module more closely, the side of each heatsink "facing" the Sun was covered by a heat-insulating box with a glass top, the height of the box being equal to the focal distance of the Fresnel lens. In this way, air convection in the closed volume of the "module" and partial heat transfer to its front surface were provided. As is shown in Fig. 1, the heat-distributing copper plates were glued to both the inner and outer sides of the rear base. In the former case, the copper plate was covered by a special paint to control the temperature.

The overheat ΔT of PVC chips relative to the ambient temperature versus the diameter of the heat-distributing copper plate under various experimental conditions is plotted in Fig. 7 and listed in Tables 1 and 2.

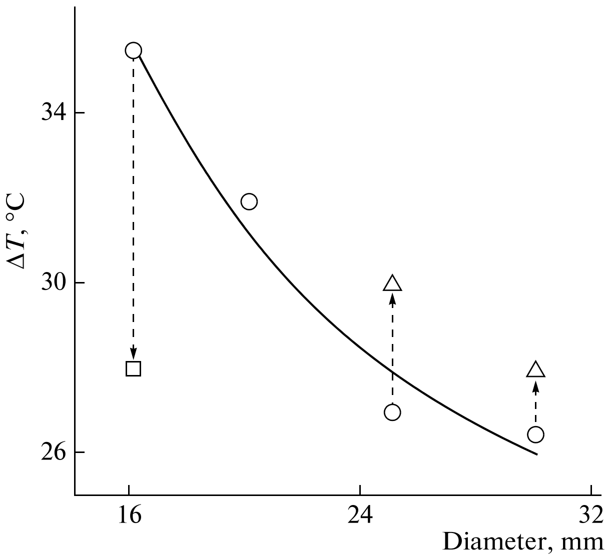

Fig. 7. Overheat ΔT of PVC chips relative to the ambient temperature vs. the diameter of the heat-distributing copper plate. Circles and triangles refer to the plates 1.0 and 0.5 mm thick, respectively, which are glued to the glass base 4 mm thick; squares refer to the steel plate 1 mm thick. The heat removal area corresponds to the 40 × 40-mm square concentrator lens (the delivered thermal power is 1 W).

Fig. 8. Modules mounted on the test bench in the Ioffe Physico-Technical Institute.

Figure 7 shows the influence of the diameter of the heat-distributing copper plate for the case when it is placed inside the module and the heat loading is appropriate for a 40 × 40-mm Fresnel lens. Also shown is the variation of ΔT when the thickness of the plate decreases from 1.0 to 0.5 mm and the glass base is replaced by a steel one.

The data summarized in Table 1 were obtained under more intense heat removal corresponding to illumination from the larger (60 × 60 mm) Fresnel lens. From the data in Table 2, one can estimate the effect of the heat-controlling paint on the copper plates and of the air flow around the plates placed on the outer side of the module.

Generalizing the data given in Fig. 7 and in the tables, one can conclude that, when the copper plate is inside the module and the PVC operates with the 40 × 40-mm lens, one can expect an overheating of 25–30°C. When the copper plate is arranged on the outer side and is covered by a paint with a high emissivity, the overheating diminishes. Even a weak flow about the plate considerably decreases the overheating; in this case, however, the paint is undesirable, since it increases the thermal resistance at heat removal.

Table 1. Overheating ΔT of PVC chips relative to the ambient temperature for different conditions of heat removal with a concentrator lens 60 mm on a side (the heat-distributing plate is inside the module, the delivered thermal power is 2.2 W)

Dimensions of heat-distributing copper plate, mm	ΔT, plate is glued	
	on 4-mm-thick glass base	on 1-mm-thick steel base
∅24 × 1	49	–
∅40 × 1	34	32
∅40 × 0.5	40	–

It seems that an overheating of 15°C can be considered typical of PVCs under full-scale operating conditions of the photovoltaic module with heat-distributing plates mounted on the outer side of the rear base. If the plates are mounted inside, the overheating may rise to 25°C even in the case of an air flow around them, since thick glass has a high thermal resistance. An increase in the size of the Fresnel lens combined with an increase in the size of the heat-distributing plate also causes a slight rise in the PVC overheat.

OUTPUT CHARACTERISTICS OF FULL-SIZE CONCENTRATOR MODULES

At the present stage of research, full-size modules integrating 144 lens–PVC pairs were prepared with the optical scheme depicted in Fig. 1a: the size of a single Fresnel lens is 40 × 40 mm and the diameter of the PVC's photosensitive area is 2.3 mm. The selection of the larger diameter PVC is associated with tolerances on the alignment of the optical centers of a great number of lenses and a PVC in one module under laboratory conditions. As before [6], lens panels were made by polymerizing the silicone compound in a negative mould that was in contact with silicate glass. The rear energy-generating panel had a glass base to which heat-distributing copper plates 24 mm in diameter were attached. To these plates, in turn, PVC chips were soldered. Each 12 PVCs arranged into linear arrays were connected in parallel, and the resulting 12 arrays were connected in series. In the module, triple-junction InGaP/GaAs/Ge PVCs with an efficiency of about 33% were used (the efficiency was measured by a pulsed sunlight imitator at 25°C). The images of the modules on a test bench equipped with a Sun tracker,

Table 2. Influence of the air flow around the module on the overheat ΔT of PVC chips relative to the ambient temperature when the heat-distributing plate is mounted on the outer surface of the module (the concentrator lens 40 mm on a side, the delivered thermal power 1 W)

Heat-distributing copper plate measuring 30 × 30 × 0.5 mm	ΔT, °C
Uncovered copper surface	
no flow about module, surface makes an angle of 45° with horizon	26.5
flow about module at a wind velocity of 1–2 m/s	10
Surface is covered by temperature-controlling paint	
no flow about module, surface makes an angle of 45° with horizon	22
flow about module at a wind velocity of 1–2 m/s	12

which was mounted on the roof of the Ioffe Physico-Technical Institute, are shown in Fig. 8.

The efficiencies of the modules were measured under the full-sun conditions in September 2008, and the density E of the direct solar radiation power was measured with a Kipp and Zonen CH-1 calibrated pyrheliometer. At $E = 870$ W/mm^2, the output power was 48.8 W and the efficiency reached 24.3% (see load I–V characteristic *1* in Fig. 9). Although the ambient temperature during the full-scale measurements was relatively low (10°C), the temperature of the PVC exceeded 25°C, which is taken to be standard in efficiency measurements. The difference between the efficiencies of the PVC (33%) and of the concentrator module as a whole is due to several reasons: optical losses in the lens panel, the nonideal alignment of the centers of lens–PVC pairs, electrical losses in the case of parallel–series connection of PVCs with slightly differing output parameters, and a PVC overheat relative to the certification temperature. This is confirmed by the fact that, when the parameters of smaller test modules were corrected for the standard temperature of the PVC (25°C), the efficiency reached 26.5% (see load I–V characteristics *2* and *3* in Fig. 9).

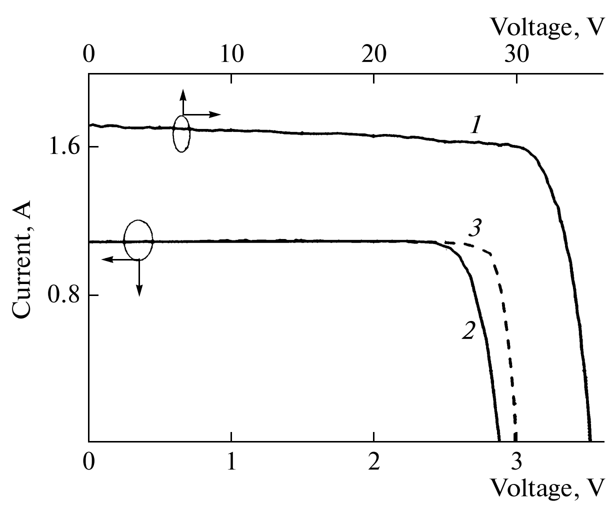

Fig. 9. I–V characteristic of the full-size (0.5 × 0.5-m) concentrator module under solar illumination (curve *1*, the efficiency is 24.3%) and the I–V characteristics of the eight-lens test module that were taken under full-scale (curve *2*) and laboratory (curve *3*) conditions. The efficiencies are (*2*) 24.5 and (*3*) 26.5%.

When the automated mass production of PVCs is organized and their efficiency is improved to 38–39%, the efficiency of solar concentrator modules is expected to reach 30% or higher.

CONCLUSIONS

We considered issues that must receive primary attention when designing solar concentrator modules: effective focusing of the solar radiation by Fresnel lenses and residual heat effective removal from the PVC. Using the experimental and theoretical simulation of these processes, the design parameters of the corresponding units of the module are determined. The efficiency of full-size modules used in practice reaches 24.3% when measured under full-scale conditions. In test modules with a correction for the standard measurement temperature, the efficiency increases to 26.5%, which far exceeds the efficiency of conventional silicon modules. With the problems of improving the assembling quality and using higher efficiency PVCs solved, the efficiency of the concentrator module may attain 30%.

The next stage of the research is aimed at designing modules that can automatically keep track of the Sun over the solar day and at refining the optics of the focusing system to increase the concentration ratio and extend the angular range of solar radiation acceptance by the PVC.

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