Thermal Regimes of Fresnel Lenses and Cells in "All-Glass" HCPV Modules

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Abstract: We report on research carried out at the Ioffe Physical Technical Institute in the field of operational conditions of the high-concentration photovoltaic (HCPV) module components. The subject of investigations are thermal regimes of the primary Fresnel lenses and multijunction solar cells. Two main issues governing the design of a solar concentrator module with III-V triple-junction solar cells (SCs) are considered: the effective concentration of radiation using Fresnel lenses, and effective heat removal from SCs. By theoretical and experimental simulating these processes, the design parameters of modules' elements have been found. A test batch of sub-modules (HCPV modules based on individual Fresnel lenses) has been fabricated and tested. The influence of different operation temperatures on the optical efficiency of Fresnel lenses and conversion efficiency of solar cells have been estimated.

Keywords: Fresnel lens, III-V solar cell; Thermal regime; High concentration.
PACS: 88.40.jp; 88.40.fc; 88.40ff; 84.60.Jt

INTRODUCTION

HCPV modules with small aperture area glass-silicone Fresnel lenses and multijunction III-V solar cells are being developed at the Ioffe Physical Technical Institute over the last years [1-3]. For $40x40mm^2$ or $60x60mm^2$ Fresnel lenses and solar cells 1.7 or 2.3 mm in diameter mounted on passive copper heat spreaders, the optimal thermal regimes can be realized in a very simple design with low consumption of the materials involved in fabrication of all parts of the HCPV modules. Proper choice of the heat spreader parameters is one of the aims of this work.

Another aim consisted in analysing such a "new" problem as thermal regimes of the glass-silicone Fresnel lenses The effect of temperature on the Fresnel lens characteristics was studied in Ioffe team both theoretically and experimentally at the final stage (2008) of the FULLSPECTRUM Project financed by the European Commission, and theoretically in the work [4]. For the lenses made of PMMA material, temperature effects are considered only from the point of view of a geometrical stability and long-term operational capabilities. For the lenses of a composite structure with silicone microprisms, two temperature-dependent issues are of significant importance– strong temperature dependence of the silicone refraction index and appreciable difference in thermal expansion coefficients of the glass base plate and silicone microprisms.

TEMPERATURE PROPERTIES OF THE GLASS-SILICONE FRESNEL LENSES

Figure 1 shows design of the small-aperture area HCPV sub-modules under investigation.

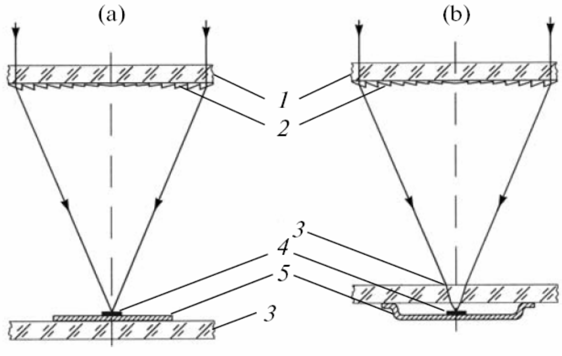

FIGURE 1. Optical schemes of the modules: (*1*) front glass panel, (*2*) silicone profile of the Fresnel lens, (*3*) rear glass base, (*4*) SC, and (*5*) heat distributing plate.

The concentrator module is made in a form of a front lens panel connected with a rear energy-generating panel with glass or aluminum walls. Each lens focuses solar radiation onto an underlying SC with a photosensitive surface area diameter of 1.7 or 2.3 mm. The heat-distributing plates are glued to the inner or outer surface of the rear module plate, which is made of silicate glass and through which the heat is removed.

The effect of the Fresnel lens temperature on its optical efficiency is presented in Fig. 2. Computation of the tilt angles of the refracting facets was carried out for the refraction index *n* chosen for two cases: $T_o = 35^\circ$C and $T_o = 25^\circ$C. It is seen from the curves for the focal distance of 85 mm that the choice of the rated temperature for determining *n* affects significantly the efficiency at lens operation temperature.

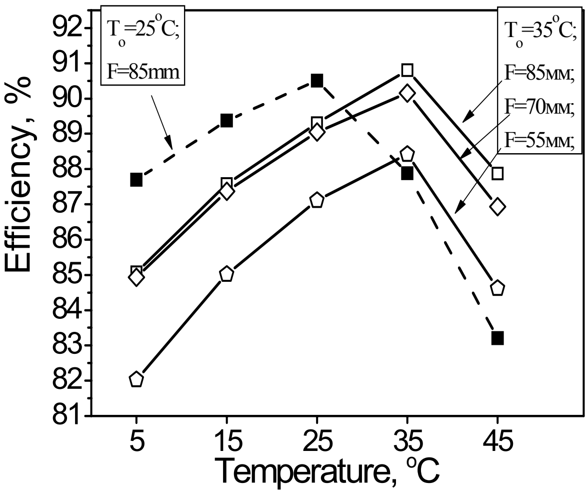

FIGURE 2. Calculated dependences of the optical efficiency on operation temperature for lenses with different focal distances *F*. Lens area is 40x40mm^2, SC diameter is 1.7 mm.

The influence of difference in the thermal expansion coefficients of the glass base and silicone prisms has been revealed by using a macro-model (see the pictures in Fig. 3). Glass strips 2 cm wide served as a base for polymerization of silicone in a view of a lengthy prism. These samples were heated to different temperatures. A picture of the net with square mesh obtained after reflection from the sloping facet was taken indicating the changes in geometry of the prism refractive facet. It is seen from the pictures of the net at T=25 and 46 C that the lines parallel to the prism edges are located more close at higher temperature. This corresponds to shaping the facet in a form of a convex cylindrical surface. Therefore, optical properties of the lenses should be more sensitive to temperature variations in comparison with results of Fig. 2.

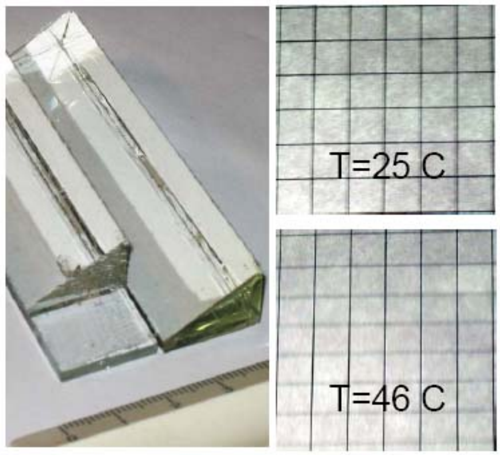

FIGURE 3. Macro-model of the silicone prisms on glass base (left) and the pictures of the net with square mesh obtained after reflection from the sloping prism facet at different temperatures of prism material (right).

A special holder for lenses has been designed (see Fig. 4). In this holder, a resistive heating element was placed under a tested lens. Thermo-isolating screens around the lens prevented heat dissipation. A SC was covered by a reflective foil. Lens temperature was monitored in the central and peripheral areas. The lens-to-cell distance was varied to ensure the maximum signal in a range from room temperature up to 50 C. Dependence of the focal distance on lens temperature is shown in Fig. 5. For this experiment a silicone-on-glass lens sample was polymerized at the temperature about 25 C. As a result, it may be recommended to polymerize the lenses at temperature close to that at which lenses will really operate.

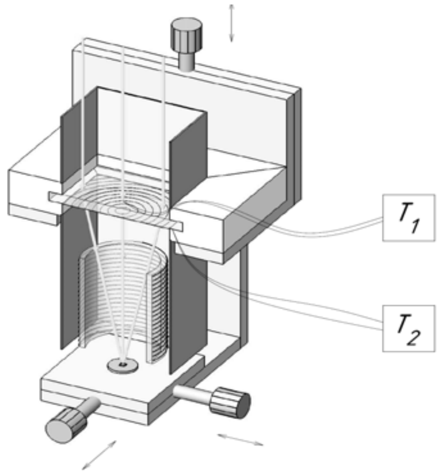

FIGURE 4. Lens holder for experiments with variable temperature of the lens.

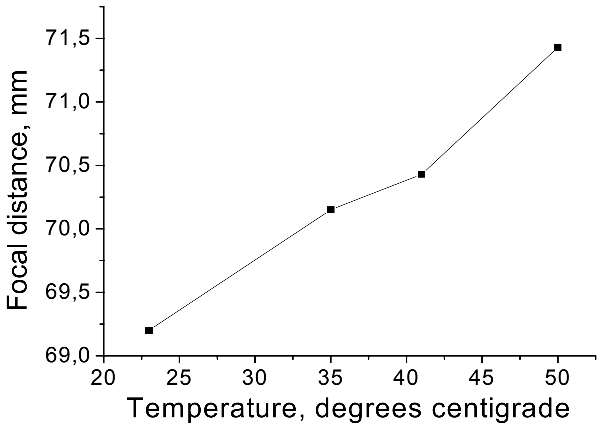

FIGURE 5. Dependence of the focal distance on lens temperature. Polymerization temperature at lens profile formation was about 25 C.

HEAT REMOVAL FROM A SC

Ensurance of the appropriate thermal conditions for SC operation is a key point in optimizing the design of a solar photovoltaic module. Heat removal from a SC is accomplished at the first step by distributing the heat flux over the copper plate and then by dissipating heat into the environment via radiation and contact with the ambient air. The first step is characterized by a considerable decrease in the heat flux density. It becomes comparable to the power density of the incident solar radiation before concentration. Hence, heat can be effectively removed through the rear glass base of the module, although the thermal conductivity of glass is low. It should be noted that the rear base could be made of a cheaper material with higher thermal conductivity, for instance, of sheet steel. However, silicate glass is extremely stable against environmental impacts, has a low thermal expansion coefficient (focal spots shift little with respect to the SC photosensitive areas with varying temperature), and offers good insulating properties (mounted SCs can be interconnected into a series–parallel circuit and the electrical safety of the module would be provided). In addition, silicate glass can serve as a cover glass for the SCs (see Fig. 1). Each SC is soldered to a heat-conductive 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 module structure, and conditions of heat transfer by air convection, thermal conditions for a SC in a module were estimated using the physical, rather than computer-aided, simulation of heat removal. The fragments of the rear base with sizes corresponding to those of individual Fresnel lenses have been prepared in this work (Fig. 6). Comparison of the individual "lens-cell" pairs have been done for lens linear sizes of 4 and 6 cm.

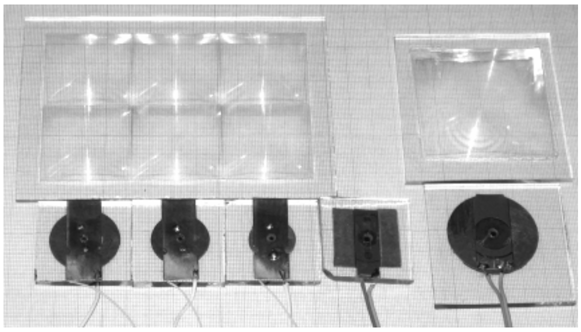

FIGURE 6. Pictures of the 40 x 40-mm and 60 x 60-mm Fresnel lenses and physical models of corresponding heat sinks with triple-junction SCs mounted on them.

Each fragment represented a heat-distributing copper plate of a variable size and a triple-junction SC mounted on it. Heat release in the SC was provided by passing the forward current from an external DC source. The current through and the voltage across the SC were chosen in such a way that the released power would be equal to the thermal power released in the SC when it would be exposed to a concentrated solar illumination and connected to an electrical load with optimal parameters. For instance, for an ideal 40 x 40 mm^2 Fresnel lens and a direct solar power density of 850 W/m^2, light power of 1.36 W would have been incident on the SC surface. With allowance for losses in the lens (mainly reflection losses) and the escape of about one-third of the generated electric power into the external load, the heat release in the SC to be dissipated would be equal to 1 W. For 60 x 60 mm^2 Fresnel lenses, the power delivered to the SC in the experiment was equal to 2.2 W. The temperature just beneath the SC and the ambient temperature were measured by thermocouples. Heat sinks were placed at the slope of 45° to the horizon, close to the conditions in the real modules at the Sun tracking. In the experiments with air blowing, it flowed over the rear side of the heat sinks with the velocity of 1–2 m/s. To simulate the SC operating conditions in a module more accurately, the side of each heat sink "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. As it is shown in Fig. 6, the heat-distributing copper plates were glued to both the inner and the outer sides of the rear base. In the former case, the copper plate was covered by a special paint to control temperature.

The overheating ΔT of the SC 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.

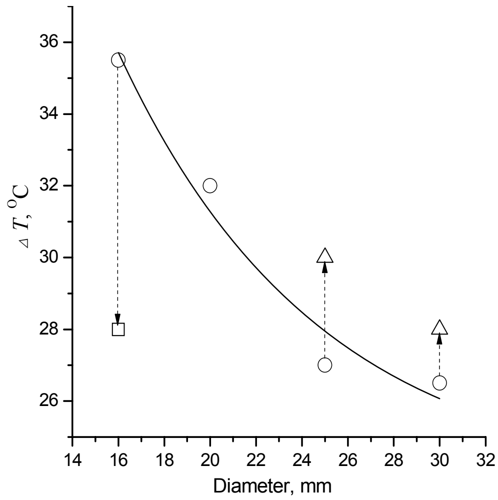

FIGURE 7. Overheating ΔT of a SC chip compared to the ambient temperature vs. diameter of the heat-distributing copper plate. Circles and triangles refer to the plates 1 and 0.5 mm thick, respectively, which are glued to the glass base 4 mm thick; square refers to the steel plate 1 mm thick. The heat removal area corresponds to the 40 x 40 mm^2 concentrator lens (delivered thermal power is 1 W).

TABLE 1. Overheating ΔT of a SC chip compared to the ambient temperature for the case of a 60x60 mm^2 concentrator lens (the heat-distributing plate is inside the module, the delivered thermal power is 2.2 W)

Dimensions of a heat-distributing copper plate, mm	ΔT; plate is glued:	
	on 4 mm thick glass base	on 1 mm thick steel base
Ø24 x 1	49	-
Ø40 x 1	34	32
Ø40 x 0.5	40	-

TABLE 2. Influence of the air flow around the module on the overheating ΔT of a SC chip; the heat-distributing plate was mounted on the outer side of the module (concentrator lens is 40x40 mm^2, delivered thermal power 1 W)

Heat-distributing copper plate dimensions are 30 x 30 x 0.5 mm	ΔT, °C
Uncovered copper surface:	
no flow over the module, the surface is at 45° to the horizon	26.5
flow over the module at a wind velocity of 1–2 m/s	10
Surface is covered by temperature-controlling paint:	
no flow over the module, the surface is at 45° to the horizon	22
flow over the module at a wind velocity of 1–2 m/s	12

The data summarized in Table 1 were obtained at more intensive heat removal corresponding to illumination from a larger (60 x 60 mm^2) 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 over 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 placed inside the module and the SC operates with the 40 x 40 mm^2 lens, one can expect an overheating of 25–30 C. When the copper plate is mounted on the outer side and is covered by a paint with a high emissivity, the overheating diminishes. Even a weak flow over the plate decreases considerably the overheating; in this case, however, the paint is undesirable, since it increases the thermal resistance at heat removal.

It seems that an overheating of 15°C can be considered as a typical one for the SCs in outdoor operation conditions of the photovoltaic module with heat sinks mounted on the outer side of the rear glass plate. If they are mounted inside, the overheating may rise to 25°C even in the case of an air flow over a module, since thick glass has a high thermal resistance. An increase in the size of the Fresnel lenses together with corresponding increase in the size of the heat sinks results in a gradual increase in the SC overheating.

ACKNOWLEDGMENTS

This work has been supported by the Russian Foundation for the Basic Research (Grant 09-08-00412-a and 09-08-12202).

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