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# CONCENTRATOR PV MODULES OF "ALL-GLASS" DESIGN WITH MODIFIED STRUCTURE

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## ABSTRACT

A modified structure of the high concentration "all-glass" PV modules with III-V solar cells is presented. In the "all-glass" module design, the secondary small aperture smooth surface lenses arranged in an intermediate composite (glass-silicone) panel are inserted between a panel of the primary composite Fresnel lens concentrators (each of 40 x 40 $mm^2$) and a panel of the solar cells. Such a design allows fabricating the modules of large total area (up to 0,5 x 1 $m^2$) and improving environmental protection of the cells. The cells as small as 1.2 mm in designated area diameter operating at very high concentration ratio (more than 1000x) can be used in the developed PV modules.

## 1. INTRODUCTION

Concentrators are regarded as a way towards cost-competitive generation of "solar" electricity. Concentrating PV systems may provide economic advantages combining the high-efficiency multi-junction cells with cheap optical concentrators, if high concentration ratio (500-1000x and more) is used in a system. Considerable efforts are directed towards the development of the efficient III-V based multi-junction solar cells that work well under highly concentrated light [1-4]. It is evident that optically effective and low-cost PV module structure is the principal consideration in successful realization of the concentrator concept.

The team of the Ioffe Institute has been involved in the development of high-concentration terrestrial PV systems [5, 6]. Main structural features of the concentrator modules under development are the following: small aperture area short focal length Fresnel lenses as the primary concentrators; lens panels with a composite (glass-silicone) structure; "all-glass" module design, which implies that all the main parts of a module cabinet are made of conventional silicate glass. In each submodule, a small aperture area Fresnel lens (40 x 40 $mm^2$), characterized by high concentration ratio, illuminates a small size cell (2 mm in photoactive area diameter, or less). This approach allows reducing the losses arising at photocurrent collection and heat dissipation. Fresnel lens panels are manufactured at room temperature polymerization of a transparent silicone compound in a negatively profiled mould, using a silicate glass sheet as a superstrate. In experimental modules, developed in co-operation with Fraunhofer ISE (Freiburg) and equipped with fabricated at ISE advanced two-junction GaInP/GaInAs cells, the outdoor efficiencies as high as 24.9% (in a 12-lens module) and 22.7% (in a 48-lens module) were measured [7, 8].

The module design should be kept deliberately simple to ensure low-cost manufacturing. Also, long-term operation abilities are of vital importance for concentrator approach. In the case of the modules under development, a very stable, cheap and easy-to-cut silicate glass is used as exterior material. Module cabinet is totally hermetized, what ensures reliable protection of the cells. Small-sized cells eliminate thermal expansion mismatch problems and allow (potentially) using the high-productive mounting processes developed in optoelectronics industry.

Meanwhile there are certain limitations on operational and geometric parameters of the described modules. In particular, increase in average concentration ratio is restricted by Fresnel lens chromatic aberration and facet imperfections. Module aperture area should be chosen taking into account strength properties of the glass sheets, because internal air pressure is under significant variation, when module temperature varies. The latter limitation determines the choice of configuration and sizes for totally hermetized "all-glass" modules, whereas developed manufacturing technology allows producing the lens panels of much larger sizes (see photograph in Fig. 1).

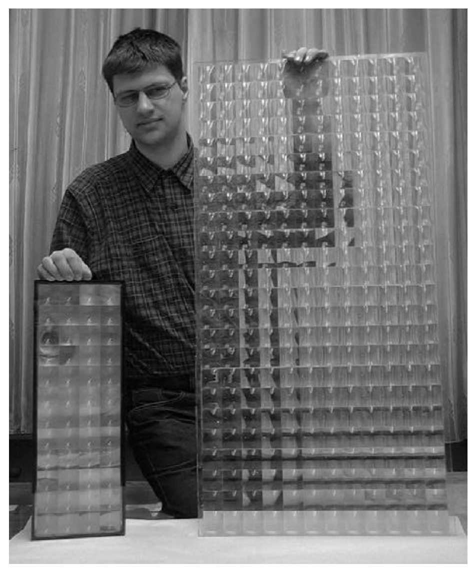

**Fig. 1.** Photograph of the totally hermetized 48-lens "all-glass" module and the 288-lens panel manufactured in PV Lab of the Ioffe Institute.

The present paper describes structural modifications related to insert of the secondary lenses in the module scheme. Secondary lenses are introduced in the form of intermediate panel, what gives a possibility to increase operational concentration ratio and to arrange cell protection by hermetization of bodies of air much reduced in size. Also, results of optical efficiency measurements of the “primary-secondary” concentrator systems as well as module prototype activity are described.

## 2. MODIFIED MODULE DESIGN

In between Fresnel-type primary lens (PL) and solar cell a smooth-surface convex secondary lens (SL) may be inserted. This can maximize the operational concentration ratio and make wider off-normal curve of a module at given cell diameter. Advantages of such an approach were discussed in our previous paper [6]. In particular, if a SL is installed with a gap in respect to a cell, lens bulk is irradiated by defocused light. Also, a room is got for wiring to the upper cell contact. It was proposed to introduce the SLs in a module in the form of an intermediate panel. The SL panel can be manufactured in the same way as it takes place for a Fresnel PL panel – by polymerization of the silicone compound on a glass sheet.

Two versions of the submodule optical scheme with incorporated SL are shown in Fig. 2. A difference between these versions consists in arrangement of the SL. In both cases, a rear glass sheet serves as a basis for the SL panel. In the scheme Fig. 2, a, the SL is placed on lower (along the sunrays) side of the glass sheet, whereas in scheme Fig. 2, b it is placed on the upper side. In the first case resulting focal distance of a (PL + SL) system is practically equal to the focal distance of the PL. To provide a high optical efficiency of such a system at reduced focal spot diameter, it is necessary to use a SL of special aspherical shape. In the second case inserting the SL leads to shortening the resulting focal distance in the system. The SL of a spherical shape with reduced (in average) thickness can be used. The sunrays are incident on the air/SL interface close to the normal, so that lower reflection losses are expected in this case.

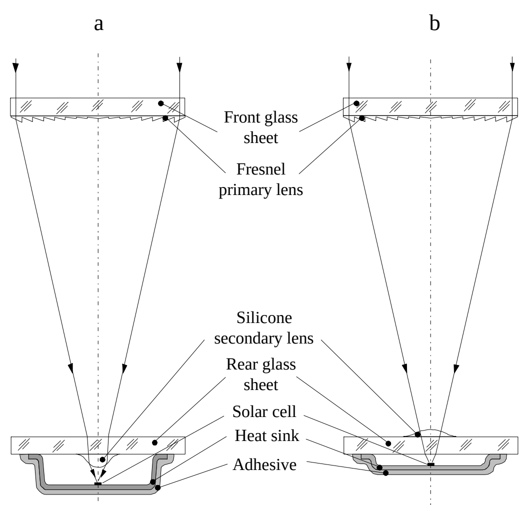


**Fig. 2.** Two versions of the submodules with silicone secondary lenses. The version “b” has been chosen for further development.

In both schemes in Fig. 2, a solar cell together with a heat sink has to be fixed by adhesive on the outer surface of a module cabinet. An interspace between rear glass sheet and metallic heat sink should be hermetically sealed for environmental protection of the cells. Adhesive layer covering the heat sink plays the role of both electrical insulator and protector against corrosion. Silicone compound is inert to water. It means that the most part of the module, namely, an interspace between front glass sheet with PL and rear one with SL, could operate without hermetization, being protected from dust and supplied with ventilating channels. Thus, the total aperture area of a module could be made larger.

The scheme in Fig. 2, b has been chosen for further development. In addition to advanced optical properties, this version is characterized by reduced depth of the shaped heat sink, what is an actual advantage at development of the cell mounting procedure.

## 3. OPTICAL EFFICIENCY OF THE “PL + SL” SYSTEM

A compromise to achieve reasonable optical efficiency at proper structural details gave the following geometric parameters of the “PL + SL” system: Fresnel PL aperture area of 40 x 40 $mm^2$ at focal distance F = 80÷85 mm; front and rear glass sheets 4 mm thick; curvature radius of the silicone SL of 5 mm; total average silicone thickness in the “PL + SL” system no more than 1.5 mm; the depth of the shaped heat sink of 3 mm. Low-iron glass is assumed for the use in the modules.

First of all a spectral transmittance experiment had been performed with the help of the special test specimens (see Fig. 3 and insert). In these specimens, as well as in the actual “PL + SL” system under study, no antireflection coatings (ARC) were applied. It is seen from Fig. 3 that in the spectral range of about $\lambda$ = 370÷1000 nm the transmittance is controlled only by Fresnel reflections from the air/glass and air/silicone interfaces. In the longer wavelength part of the spectrum, certain selective absorption takes place, but low enough for it to be treated as an obstacle at high-efficient operation of the advanced multi-junction cells.

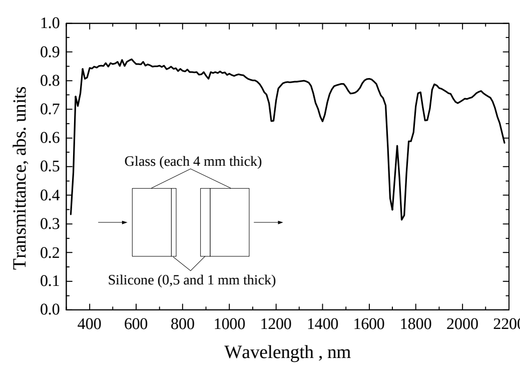


**Fig. 3.** Spectral transmittance of the test specimens simulating behavior of the submodule under study (see Fig. 2, *b*).

Optical efficiency measurements should help to choose the designated area diameter of a solar cell operating with the “PL + SL” system. For such measurements a light source reproducing angular size of the sun and consisting of tungsten lamp, optical fiber homogenizer, diaphragm, filter and collimating lens was used. Single-junction AlGaAs/GaAs cell of 3 mm in designated area diameter served as a photoreceiver. To vary the photoreceiver diameter, the diaphragms superimposed on the cell surface were employed. A thin smooth-surface quartz lens characterized by definite optical efficiency of 91% at definite (and low enough) aperture area was involved in the measurement procedure as a "reference" lens.

Fig.4 presents the results of the optical efficiency measurements in dependence on photoreceiver diameter. There are four variants of measurements: 1) quartz "reference" lens (F = 85 mm) is installed without SL and rear glass sheet for set-up calibration; 2) quartz lens is installed with silicone SL to obtain an "idealized" situation concerning the optical efficiency, when the "PL + SL" system is practically free from lens aberrations and surface imperfections; 3) the 40 x 40 $mm^2$ Fresnel lens (F = 80 mm) is installed without silicone SL; 4) finally, the diagram of Fig. 2, *b* is represented for measurements.

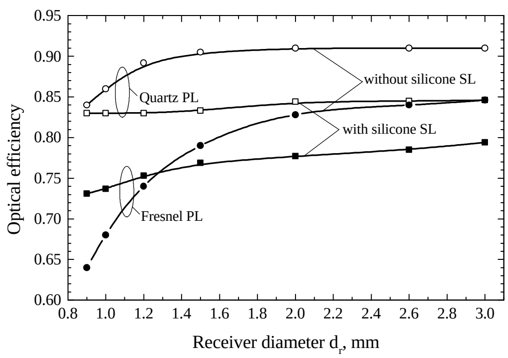


**Fig. 4.** Dependences of optical efficiency on receiver diameter. Upper curves – the quartz "reference" lens is used as primary concentrator without and with silicone SL. Lower curves – the 40 x 40 $mm^2$ composite Fresnel lens is used as the primary concentrator.

One can see from Fig. 4 that inserting the SL improves considerably the optical efficiency curve in the practical "Fresnel PL + silicone SL" system at smaller $d_r$. Initial drop in efficiency caused by Fresnel reflections on two additional interfaces can be compensated in part by applying an ARC. If for a concentrator system without SL the $d_r$ = 2 mm is a reasonable choice, as it takes place in practical modules [7, 8], for the "PL + SL" system such a choice could be $d_r$ = 1.2 mm leading to increase in averaged concentration ratio by a factor of ~ 2.5.

Of great importance is off-normal accuracy, which has to be realized in a concentrator system. Corresponding results of measurements are presented in Fig. 5. The upper diagram shows off-normal behavior of the submodules without SL at $d_r$ = 2 mm, whereas the lower ones are for the case of the "PL + SL" systems at $d_r$ = 1.2 mm. The main result from the Fig. 5 is that off-normal behavior of the "Fresnel PL + silicone SL" system at $d_r$ = 1.2 mm is quite similar to that of the Fresnel lens concentrator alone at $d_r$ = 2 mm. Due to slightly larger focal spot, the optical efficiency is lower, than in the case of the 'ideal" system with quartz PL at normal position and higher starting from definite off-normal angles.

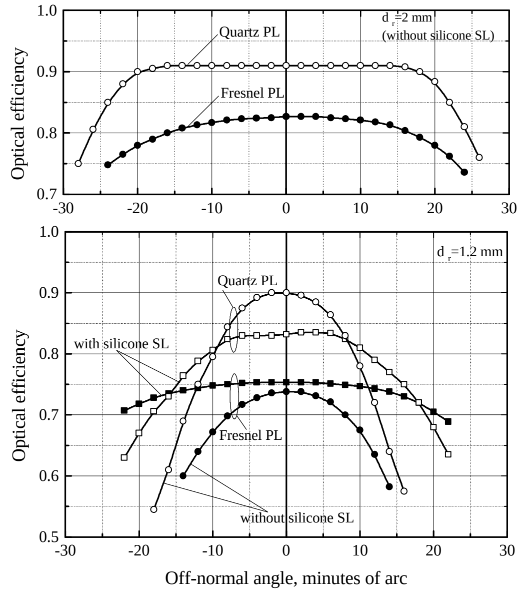


**Fig. 5.** Off-normal curves for the test submodules under study.

## 4. LOCAL CONCENTRATION RATIO MEASUREMENTS

It is clear that in the high-concentration systems the local concentration ratios may significantly exceed an averaged value. That is why we had undertaken such measurements. A procedure consisted in formation of a focal spot by "Fresnel PL + silicone SL" system at its illumination from flash solar simulator reproducing spectrum, intensity and angular size of the sun [9]. The focal spot was scanned by a cell equipped with a diaphragm of 0.12 mm in diameter and calibrated with respect to photocurrent. Corresponding results for the cases with and without silicone SL are shown in Fig. 6. Concentration ratio as high as 3200x has been measured for the "PL + SL" system under development. This value has to be taken into account at the structure and contact grid optimization of the cells intended for use with such concentrator systems.

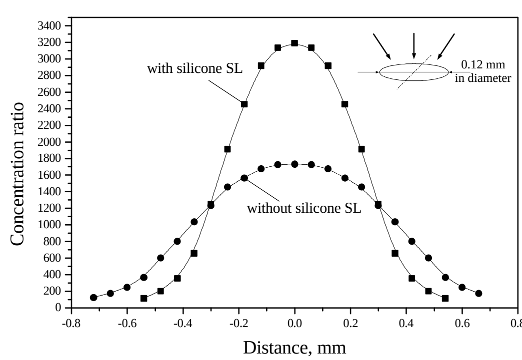


**Fig. 6.** Evaluation of the local concentration ratios across focal spot in the system "Fresnel PL with/without silicone SL".

## 5. TEST MODULE PROTOTYPE

At present stage of work the module prototypes with reduced number of the incorporated submodules are under development for optimization of the assembling procedure. Single-junction concentrator AlGaAs/GaAs solar cells similar to those described in [10] have been manufactured to equip the test modules. The cells have two configurations (see photograph in Fig. 7). The first ones are of 2 mm in diameter (100 µm grid spacing). They will be installed in "reference" modules without secondary lenses. Second ones are of 1.2 mm in designated area diameter with 50 µm spaced contact grid. They are intended for the use at outdoor experiments with "PL + SL" system. A group of several cells is mounted as a unit on a common heat sink. Copper 0.5 mm thick or soft steel 1 mm thick serves as a material for shaped heat sink. A photograph of the 6-lens module parts is shown in Fig. 8.

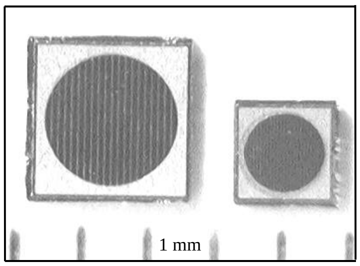


**Fig. 7.** Microphotograph of the AlGaAs/GaAs high concentration solar cells.

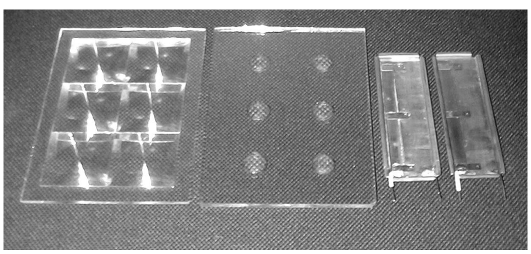

**Fig. 8.** Photograph of the test module parts (from left to right): Fresnel PL panel; silicone SL panel; two units with AlGaAs/GaAs cells of 1.2 mm in diameter (three parallel connected cells in each unit) mounted on the shaped heat sinks made of copper.

## 6. CONCLUSION

A practical design has been developed for the "all-glass" high concentration modules with two lens panels – the front panel incorporating primary Fresnel lenses, and rear panel incorporating secondary smooth surface minilenses. Both panels are fabricated as a composite structure with silicate glass sheet as a basis and environmental protector, and refractive profile made of transparent silicone compound. Optical efficiency measurements have shown that in submodules with 40 x 40 $mm^2$ primary lenses the cells as small as 1.2 mm in designated area diameter can be used. Off-normal and local concentration ratio measurements have also been performed. Module prototypes for outdoor tests are in progress.

## 7. ACKNOWLEDGMENTS

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