SPACE FRESNEL LENS CONCENTRATOR MODULES WITH TRIPLE-JUNCTION SOLAR CELLS

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GENERAL

The work presented in this paper is concerned with fabrication of an improved concentrator module based on linear Fresnel lenses and photoreceivers with GaInP/GaAs/Ge triple junction (TJ) cells. The manufactured module consists of: four linear Fresnel lenses with focal distance of 30 mm and dimensions of 2.5x10 cm^2 each; four linear photoreceivers of 10 cm in length with 12 TJ solar cells each; heat sink made of thin copper metallized dielectric plate. Linear Fresnel lenses with optical efficiency of 82-84% were made of silicone formed on shockproof radiation-resistant UV-protective glass 0.2 mm thick. The solar cells intended for use in linear receivers have efficiencies of 23-24% (AM0, 25^0 C) at geometrical sunlight concentration of 6-9x. The estimated module efficiency is about 21% (AM0).

INTRODUCTION

During the last decade the concentrator modules based on Fresnel lens concentrators of different configurations have been developed for space applications [1-6]. To make concentrator modules acceptable for large-scale space applications it necessary to fabricate the modules with the following parameters: module thickness has to be comparable with that of conventional planar arrays; BOL specific power - higher than 300 W/m^2; EOL power remaining factor - more than 90% after 1E15 e^-/cm^2 1 MeV equivalent irradiation; specific weight - less than 3 kg/m^2; accurate pointing - only for 1 axis, with possibility to keep the main spacecraft operational functions at wider ($\pm30^0$ and more) off-pointing angles. Concentrator modules with linear Fresnel lens concentrators have many advantages, such as only one axis precise tracking, simplicity of module assembly, etc. This paper presents a recently developed improved concentrator module prototype based on linear Fresnel lenses and GaInP/GaAs/Ge triple junction cells.

FRESNEL LENS DESIGN AND DEVELOPMENT

Previously we have published the results of a computer direct ray trace analysis for short focal length (23 mm) lenses incorporating two types of Fresnel profiles: conventional refractive profile for a central zone, and profile with total internal reflection of light (TIR-profile) for peripheral zones [5]. However, our practical experience has revealed certain problems in manufacturing the TIR profile due to, first of all, the requirements to teeth geometry being sufficiently stronger than in the case of conventional profile. To avoid the use of TIR-profile zones and, in the same time, to keep the lens optical efficiency at a level around 85%, the new linear Fresnel lenses with conventional profile have been developed.

To predict lens performance as solar concentrator, an improved computerized model was used. The following factors were considered in this model:

- definite angular size of the Sun;
- lens tracking errors (probable lens optical axis deviation from precise direction to the Sun);
- dependence of the lens material refraction index on wavelength (chromatic aberrations);
- local geometrical error of the refractive surface;
- optical losses in the lens assembly due to face and interface reflections.

This model traces bundles of rays incident on all portions of the whole lens aperture. For each finite element of the lens aperture, 320 rays are traced from the solar disc to the lens focal plane, corresponding to 64 points on the solar disc and to 5 wavelength bands for each solar disc point. The following parameters are under variation: Fresnel lens pitch (0.3, 0.4, or 0.5 mm); focal distance (23, 25, 30, or 35 mm); lens width (12-30 mm). Sun concentration and lens optical efficiency were calculated (see Fig. 1-4). Averaged sun concentration was calculated for receiver width of 2.8 mm (see below).

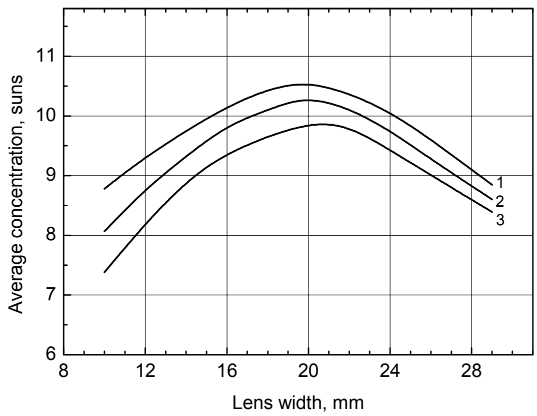

Fig. 1. Average concentration values as a function of linear lens width for 30 mm focal distance. Lens pitch: 1 – 0.3 mm, 2 – 0.4 mm, 3 – 0.5 mm.

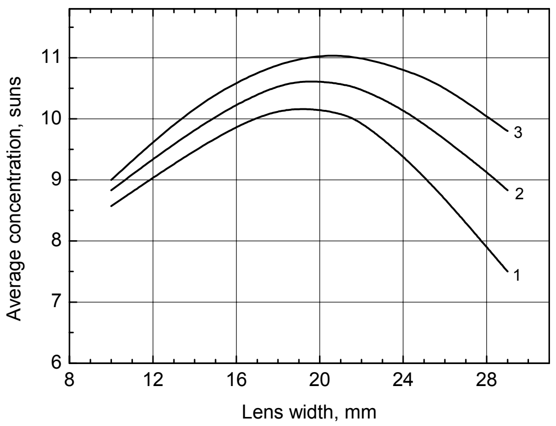

Fig. 2. Average concentration values as a function of linear lens width. Focal distance: 1 – 25 mm, 2 – 30 mm, 3 – 35 mm. Lens pitch is 0.3 mm.

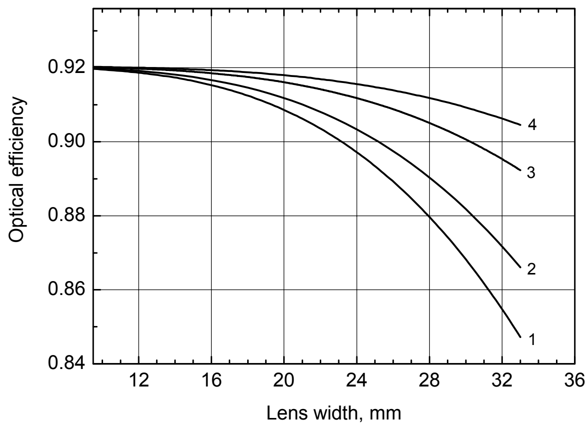

Fig. 3. Dependence of the optical efficiency on linear lens aperture: Focal distance: 1 – 23 mm, 2 – 25 mm, 3 – 30 mm, 4 – 35 mm.

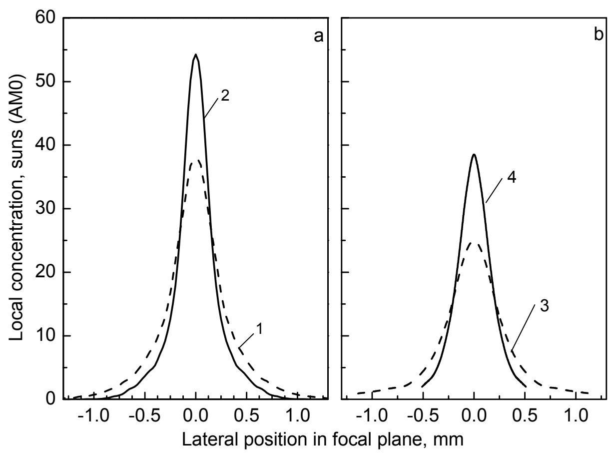

Fig. 4. Calculated (a) and experimentally measured (b) focal plane irradiance profiles produced by a linear Fresnel lens: 1, 3 – without a secondary lens, 2, 4 – with a secondary semicylindrical lens (r=2.4 mm).

On the bases of the theoretical calculations and allowing for the space module height restrictions the following lens parameters were chosen: 30 mm focal distance and 25 mm width. It follows from the calculated local light intensity distribution in the focal plane, that the cell aperture should not be narrower than 2.8 mm. In this case the off-pointing tolerance of $\pm1^0$ is ensured at the level of 0.9 of the nominal power. The use of secondary semicylindrical lenses leads to a significant increase in local concentration in the centre of the focal line and to a decrease in focal line width (see Fig. 4). The pointing of $\pm2^0$ for the nominal power level of 0.9 has been calculated in the strings with aperture width of 2.8 mm in the case of 2.4 mm in radius secondary lens.

The Fresnel lenses were formed at room-temperature polymerization of high-transparent silicone in a negatively profiled mold. They were bonded to the 0.2 mm thick ceria-doped flat glass superstrates 100 x 50 mm^2 in size.

The measurement results on light intensity distribution in the focal plane of the developed linear Fresnel lenses (F=30 mm) are presented in Fig. 4 by dotted lines. Certain discrepancy between theoretical and experimental curves may attribute to geometrical imperfections of the molds for lens fabrication and instrument error at measurements.

TRIPLE-JUNCTION CELLS

Metal-organic vapor phase epitaxy (MOVPE) has been used at ENE (Brussels, Belgium) for growth of InGaP/GaAs/Ge cell structures. The wafers were delivered to the Ioffe Institute for fabrication of solar cells for linear receivers.

Rectangular 8.2x3.4 mm^2 InGaP/GaAs/Ge TJ solar cells were fabricated (see Fig. 5). The designated illumination area width of 2.8 mm is shadowed by 10 μm in width contact fingers arranged with 200 μm spacing. Two busbars with two pads for contacting are situated on the cell surface.

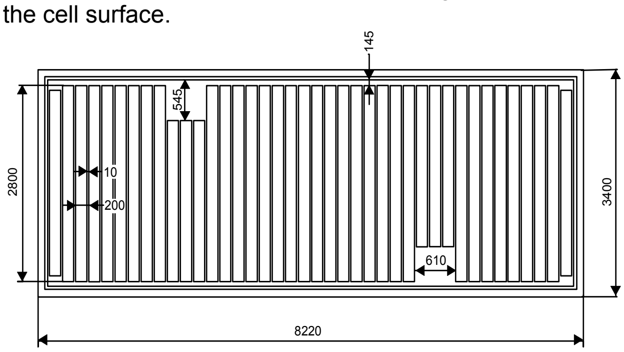

Fig. 5. Top view of the TJ cell contact pattern.

Fig. 6 shows the external quantum efficiency data for the concentrator InGaP/GaAs/Ge TJ cell. From spectral curves the photocurrent densities for each of three p-n junctions were calculated at AM0 sun spectrum conditions. The following photocurrent densities are typical for cells in the concentrator module prototype: j_{top}= 15.3 mA/cm^2, j_{mid}= 15.3 mA/cm^2, j_{bot}= 23.4 mA/cm^2.

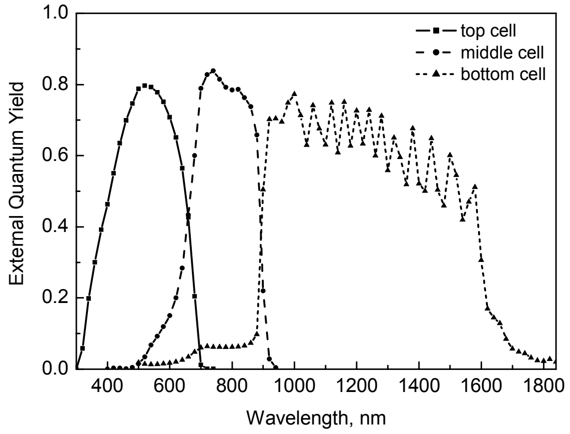

Fig. 6. External quantum efficiency of a concentrator TJ cell.

The I-V curves were measured by a developed multi-zone flash solar tester with adjustable spectrum, the optical layout of which is presented in Figure 7.

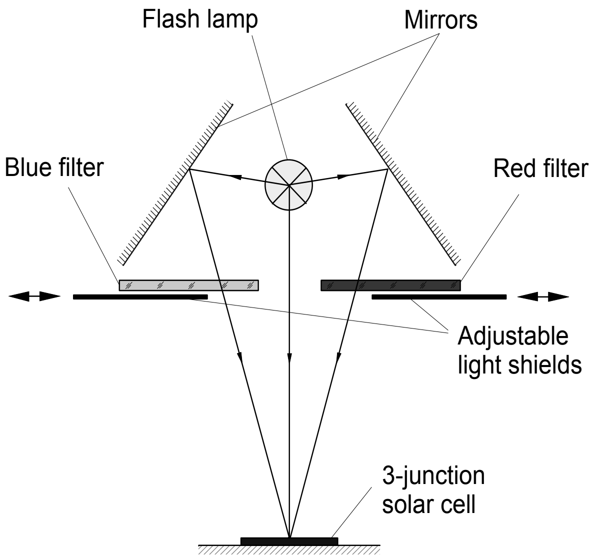

Fig. 7. Optical layout of the three-channel solar simulator.

In this tester, the flash Xe-lamp produces the main part of illumination light intensity directly, without filtering. There are two mirrors forming additional fluxes filtered by blue and red glasses. Therefore, mixed flux in the measurement plane is characterized by excess light of these parts of spectrum, if adjustable shields are open. The procedure of tester adjustment is the following. Let us suppose, that in TJ cell the Ge-based sub-cell generates the highest photocurrent density, whereas InGaP and GaAs ones generate the lowest and intermediate current densities, correspondingly. Let the photocurrent is limited by the Ge-based sub-cell at fully opened shields. The sun concentration ratio, required for I-V measurement, is established by varying the distance between the illumination system and the cell under test, bearing in view one-sun current from spectrum for bottom sub-cell. By gradual closing the “red” shield, the conditions are achieved, when photocurrent is limited by the GaAs sub-cell at a photocurrent value, derived from spectrum for the middle sub-cell. Corresponding position of the “red” shield is being kept in mind, but this shield is being opened again. A similar procedure is being done for “blue” shield. After this, both filters should be installed in right positions. The measured value of the I-V curve fill factor should be correct under these conditions of illumination. By introducing an IR filter and adjustable shield into the central channel of the illumination system, one can modify conditions of the experiment.

TJ cells were tested at concentration ratios in the range of 1 - 50 suns to select samples with better potential for operation under real non-uniform light intensity distribution (see Fig. 4,b). The cell parameters vs. sunlight concentration are presented in Fig. 8.

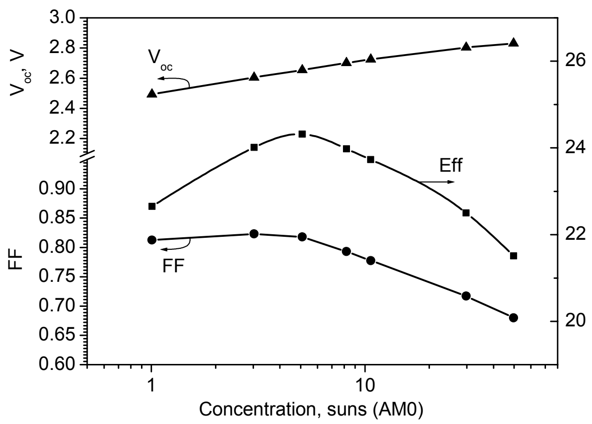

Fig. 8. Dependences of V_{oc} , FF and Efficiency on sun concentration for the TJ cells.

Efficiency of 23.9% (AM0, 8 suns) has been achieved. This efficiency may be increased up to 26% (AM0; 15-20 suns) by means of antireflection coating optimization and by prismatic covering for gain in photocurrent. A higher fill factor may be obtained owing to further ohmic losses reduction.

MODULE DESIGN AND PERFORMANCE

Module prototype 32 mm thick with aperture area of 112x108 mm^2 has been fabricated. It consists of:

- four 25x100 mm^2 linear Fresnel lenses with focal distance of 30 mm, which are arranged as two lens panels, with two lenses on each;
- two 50 mm x 108 mm thermoconductive boards of 0.2 mm in thickness. On each board two photoreceivers are arranged;

- four linear photoreceivers. Each photoreceiver consists of 12 triple-junction solar cells connected in parallel on an insulating holder with a metallized electroconductive pattern;
- module body made of copper metallized perforated material of 0.5 mm in thickness.

The module external view is presented in a photo (see Fig. 9).

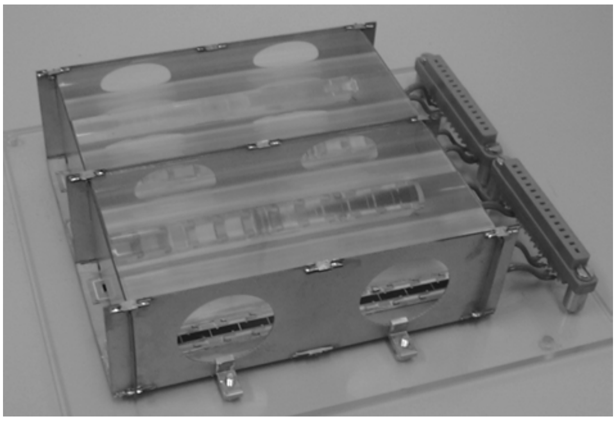

Fig. 9. Space module prototype with four linear Fresnel lenses on two glass superstrates.

The cells in linear receivers were mounted by means of electroconductive epoxy. The specially designed thermocompensating leds for the top busbar contacting were used (see Fig. 10). The electroconductive pattern of an insulating board connected cells in a parallel circuit. The photoreceivers were mounted on the metallized base by thermoconductive compound.

The efficiency around 20.1% (AM0, 25^0 C) of a lens/cell stacks was preliminary estimated under a flash solar simulator with collimating optical system, reproducing the divergence of the Sun rays (32 ±2 min. of arc). The tests of the fully operational module with respect to space environments are in progress now.

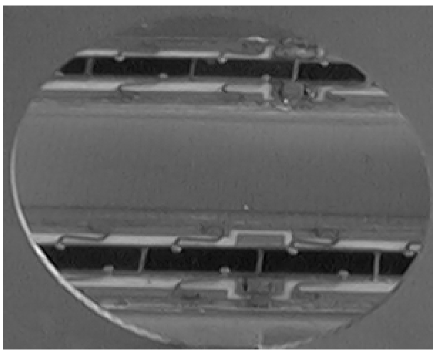

Fig. 10. The fragments of linear photoreceivers consisting of 8.2 x3.4 mm^2 in area solar cells.

CONCLUSION

Optical characteristics of the small-aperture area linear-focus Fresnel lenses made of silicone on thin glass sheets have been calculated and measured. 48 TJ cells with efficiency of 23-24% (AM0, 25^0 C) have been selected for concentrator photoreceivers by using a specially designed PV tester with adjustable spectrum.

Space module prototype based on four linear lenses with total aperture area of 10x10 cm^2 has been designed and manufactured. The laboratory measurements of lens/cell pairs by using a PV flash tester with collimating flux enabled us to estimate the module efficiency in the range of 20.1% (AM0, 25^0 C).

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