EXPERIMENTAL AND THEORETICAL DESIGN FOR A NEW ARRAY MICRO-LENSES SILICON SOLAR CELL CONCENTRATOR

Ali H. Al-Hamdani
Department of Laser and Optoelectronics Engineering, University of Technology, Bagdad, Iraq
E-Mail: ali_alhamdani2003@yahoo.com

ABSTRACT

In this paper, a new model for array of micro-lenses concentrator was designed. This concentrator consists of array of micro-lenses (MLA) to focus solar light on four rectangular slaps of photovoltaic Si solar cell. The design aim to reduce the cost of the concentrators by reduces the effective area of the high cost silicon material area and simplified the structure of the system. The solar cell with the MLA- concentrator adds energy conversion efficiency (11.98%) and reducing the total cost.

Keywords: solar cell, concentrator, ray tracing program, cell efficiency.

INTRODUCTION

Silicon-based photovoltaic (PV) convert less than 20% of incident sunlight into electrical energy. High-efficiency solar cells developed for the space industry have demonstrated more than 41% conversion efficiency by layering multiple semiconductor junctions that capture large portions of the solar spectrum [1]. Fabrication and material costs limit these cells to only a few square centimeters, making them impractical for flat-panel installations. Concentrator photovoltaic (CPV) incorporate large-area optics that collect and deposit energy onto small, efficient solar cells with the promise of reducing electricity-generation costs compared to silicon-based PV [2].

For CPV systems to be cost-effective, the complete cost of the optics, assembly and mechanical tracking must not exceed the cost savings gained from using small area PV cells. Solar ray tracing programs was used to find new types of solar lens concentrator to save the cost by reducing the area of PV cells [3].

High-flux concentrators typically consist of a large primary optic to focus sunlight and a secondary optical element for flux homogenization. A common design approach divides the upward-facing primary into several small apertures, each with its own individual secondary element and solar cell [4].

The energy issue has been gaining a lot of attention in many countries in recent years. Among the kinds of energies, the solar energy is one of the most interesting topics of them. In addition to the fabrication process and raw material, another focal point aims at solar concentrator. This paper shows a new and easy way to increase the solar energy efficiency. We utilize the micro-optics principle to design and fabricate a micro-lens array of the solar concentrator. With this concentrator, it can enhance the amount of focused sunlight on the solar cell so the optical absorption on the solar cell is improved.

The micro-lens array concentrator (MLA-concentrator) is different from the conventional concentrator. The MLA-concentrator does not need any electric equipment to follow the sunlight (sun tracker is not required), and it is easy to manufacture. The size is smaller than conventional concentrator, especially. The MLA-concentrator can decrease the reflection of light at oblique angles and increases the second reflection at the interface between concentrator and solar cell, which makes the sunlight uniform. This new-type MLA-concentrator is fabricated by using LIGA-like process, and then it is integrated to the solar cell for electricity generation. Most important, this kind of structure can be combined with all kinds of solar cell.

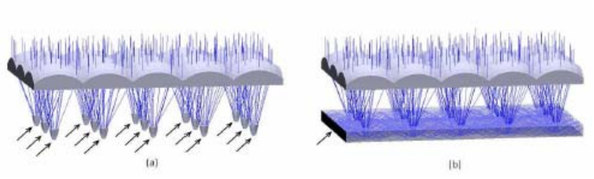

Figure-1. Individual secondary optics requires multiple PV cells (a). Each lens concentrate on individual secondary optics (b) Replace the secondary optics by waveguide. Arrows indicate PV cell locations. [4].

However, integrating hundreds of small PV cells all aligned to their respective optics leads to large-scale connectivity and cost concerns. A planer concentrator was investigated by replacing the secondary optics and their associated cell with a single waveguide connected to a shared PV cell [4].

In this paper, we investigate an alternative approach for planar concentration by replacing multiple nonimaging secondary optics and their associated PV cells with small rectangular slaps of PV silicon cell (see Figure-2) to reduce the number of mounting, alignment and electrical connection cost.

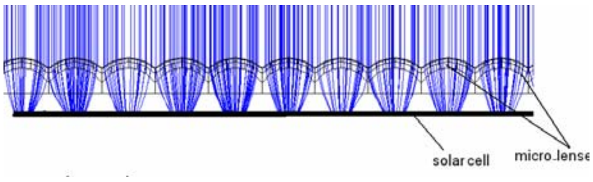

Figure-2. New design of micro-lenses concentrator.

Concentrator geometry

The geometric concentration ratio is the ratio of input to output areas of the optical system [4]. Every lens array aperture forms a demagnetized image of the sun which subtends ± 0.26° [5]. The aberration-free solar image height was calculated using 2 f tan θ where *f* is the lens focal length and θ is the acceptance half-angle. Each lens element has its own two dimensional geometric concentration defined by, [5].

$$C_{lens} = \frac{1}{(2F^{\#}\tan\Theta)^2} \qquad (1)$$

The lens aperture to image area is expressed in terms of the lens focal length to diameter ratio, or F-number (F/#), and acceptance half-angle.

A ray tracing ZEMAX EE non-sequential analysis software [6] was used to design and optimize the efficiency of this micro-array optic concentrator. The analysis assumed spherical, plano-convex refractive lenses forming a focus on a slab of the PV. Lens aberrations, Encircled energy, illumination distribution on the PV cell and material absorption were included in optical efficiency calculations. Simulations used weighted AM1.5 sunlight from 0.4 to 1.06µm at ± 0.26° field angles.

The simulated design used PMMA lens material (n_d= 1.49 lens array) [7]. The new rectangular concentrator consists of array of 22x12 micro-lenses along x and y direction, respectively (Figure-2) with total area 66x36 mm. Each an individual lens has rectangular aperture with 3.0mm diameter, 2.6 mm radius of curvature, 2.0 mm thickness and PMMA material (refractive index=1.491). There is air gab between the array lenses and the solar cell of 1.1 mm. This array of micro-lenses was used to focus sun light onto four rectangular Si PV solar cell of dimension (6.4x60 mm for each), so the total effective cell area equal to 14.81cm^2. The distance between the slaps is 3.0 mm. (Figure-3). The total thickness of the concentrator didn't exceed 4 mm. Air thickness between lenses and slap cells was optimized to give a uniform illumination on all area of the silicon cell.

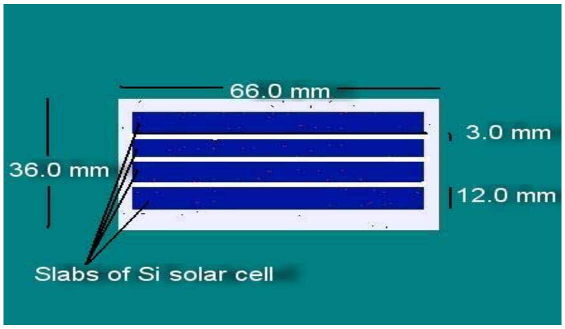

Figure-3. Solar cell consists of four rectangular slabs.

Practical work

For current - voltage measurement, a Keithly-616 digital electrometer, Tektronics CDM 250 multimeter and a dual Farnel LT30/2 (-3 to 3) V power supply were used. The forward current was recorded when a positive voltage was applied to Al metal contact with the nanostructure layer with respect to Al electrode on the crystalline silicon substrate and calculated the ideal factor n of this structure by using the relation[8]:

$$n = \frac{q}{KT}\frac{dV}{d\ln\frac{I}{I_0}} \qquad (2)$$

Where $\frac{dV}{d\ln I}$ is the slope of the linear region of (I-V) plots, q is electron charge, K Boltezman's constant and T temperature.

The scanning electron microscopy SEM was used to examine the surface structure. The illumination was applied under simulated air mass (AM1) condition (100mW/cm^2) by a halogen lamp type (Philips) with 120W power. This lamp was connected to a variac and calibrated by a Si power meter. We measured V_{OC} and I_{SC} to calculate the fill factor (FF) and the efficiency (η %) of the micro-structured solar cell using the relations [9, 10].

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \qquad (3)$$

$$\eta = \frac{FF I_{sc} V_{oc}}{P_{in}} \% \qquad (4)$$

Where V_m is maximum voltage and I_m is maximum current, this represents the maximum power output of the solar cell.

The current voltage characteristics for the PV were measured with and without concentrator by using the electric circuit shown in Figure-3. The 100 Watt Xenon lamp model Splender E27 Flood from Philips company was used and two multi-meter model DM-9960 to measure the current and voltage of the solar cell.

RESULTS AND CONCLUSIONS

Figure-4 represents the current-voltage characteristics curve for of PV cell with and without the new concentrators. This figure indicates the improvement in solar cell characteristics.

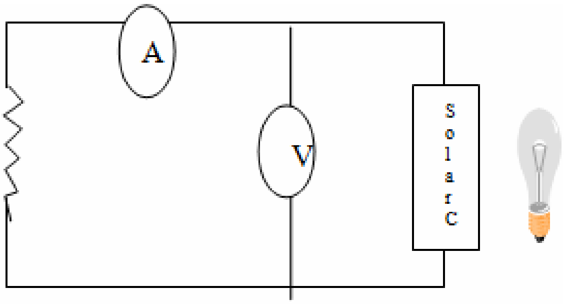

Figure-4. Electrical diagram represent I-V characteristic measurements circuit.

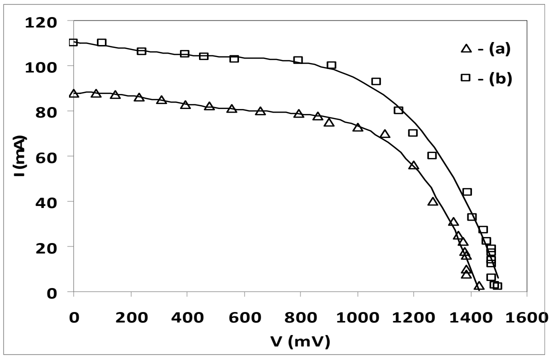

Figure-5. The current-voltage characteristics for PV Si cell without (a) and with (b) array micro-lens.

Table-1 shows the current short circuit I_{sc}, voltage open circuit V_{oc}, maximum output power P_{max} full factor FF, and efficiency η% for PV without and with array concentrator. Also the improvement in efficiency Δη %. is shown.

As table shows, the efficiency improved from 6.75% to 8.7% without and with the new concentrator respectively, i.e., there is Δη = 11.98% improvement in the efficiency of PV with concentrator. One concludes that there is an improvement in the system cost by reducing the high cost Si material.

Table-1. Performance parameters for PV without and with concentrator.

	Without concentrator	With concentrator	Improvement %
I_{sc} mA	88	110	25
V_{oc} mV	1430	1497	4.6
P_{max} mW	77000	99510	29.2
FF	125840	164670	30.85
η%	6.75	8.7	11.98

ZEMAX-EE code is used to study the distribution of the energy on the solar cell slabs. And the results from this code gives that 62% of the incident solar radiation is on the solar cell arranged as (13%, 18.5% , 13.7% and 16.0% on first, second ,third and fourth slab respectively).

The illumination distribution also examined by using ZEMAX physical propagation properties, Figure-6 shows that the illumination distribution along x and y coordinates of the PV slaps has a mean illumination value 90% of the total input illumination which indicate the good lens array concentrator design. Also Seidel aberrations were analyzed, the results show that the designed array lenses concentrator suffer from spherical aberration (0.0029λ) and total aberration variance 0.0045.

Figure-7 shows the amounts of energy accumulated on the cell. This figure indicates that the circle radius at 90% of the accumulated energy is 1mm. which is smaller than the solar cell diameter (12 mm). One must satisfy the conditions placed on the FOV are: size of solar cell (one slab) must be imposed that the image length will not be larger than the pitch (the distance from one lens center to the adjacent lens center is known as the pitch) must be observed.

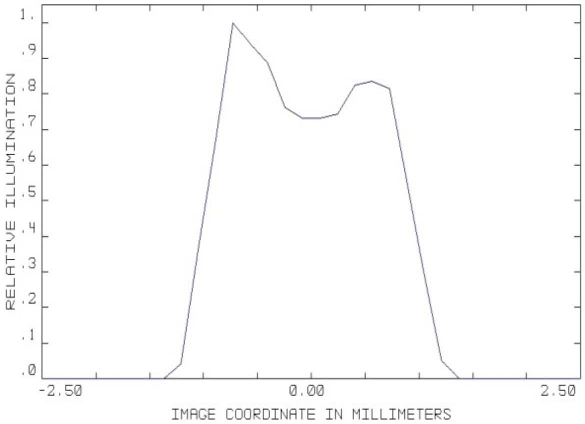

Figure-6. Illumination distribution on the PV cell slap.

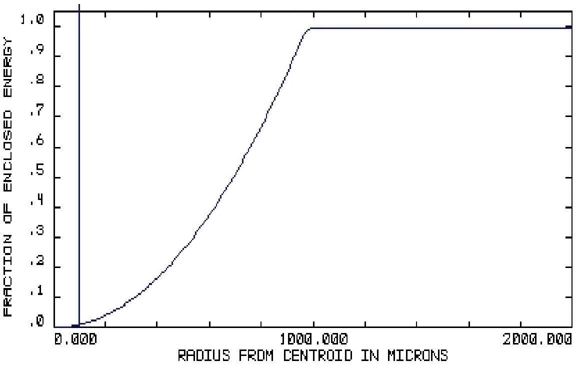

Figure-7. Encircled energy on the PV cell.

REFERENCES

[1] Green M. A., K. Emery, Y. Hishikawa and W. Warta. 2009. Solar cell efficiency tables (Version 34), Prog. Photovolt. Res. Appl. 17: 320-326.

[2] Al-Hamdani, H. Ali and Mohamed H.H. 2004. Solar ray tracing programs to find new types of solar concentrator. J. of Um-Salama for science. 1: 76-79.

[3] Al-Hamdani, Ali H., Al-Ani S.K. and Blawa B.D. Performance of two - stages solar concentrator. J. of Um-Salama for science. 1(2): 317-320.

[4] Jason H. Karp, Eric J. Tremblay and Joseph E. Ford. 2010. Planar micro-optic solar concentrator. Optics express. 18(2): 1122-1133.

[5] Rabl A. 1985. Active solar collectors and their applications. Oxford university press, New York, USA.

[6] Kaplin G.M. 1985. Understanding Solar Concentrators. VITA.

[7] Mbewe D.J., Cordand H.C. and Cord D.C. 1985. A model of silicone Solar Cell for Concentrator Photovoltaic and Photovoltaic Thermal System Design. Solar energy. 35(3): 247.

[8] ZEMAX-EE optical design program, version 6, 2003, www.zemax.com.

[9] Laybourn P.J.R., Gambling W.A. and Jones D.T. 1971. Measurement of attenuation in low - loss optical glass. Opt. Quantum Electronic. 3: 137-144.

[10] Tuzun S.O. Altindal and T. S. Mammadov. 2006. Electrical characterization of novel Si solar cells. Thin Solid Films. 511-512, pp. 258-264.