A 28 % EFFICIENT, 400 X AND 200 WP CONCENTRATOR MODULE

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ABSTRACT: The status of the development of a new concentrator module in Japan is discussed based on three arguments, performance, reliability and cost. Considering uncertainty of DNI measurement, the current most probable efficiency is 26.8 ± 1.5 percent. In performance, annual power generation is discussed as well as conversion efficiency. In reliability, new degradation modes inherent to high concentration III-V solar cell system were discussed. In cost, overall scenario in the reduction of material cost was discussed.
Keywords: Concentrator Cells, Concentrators, Encapsulation, High-Efficiency, Multijunction Solar Cell, PV Module

1 INTRODUCTION

Concentrator modules using high efficiency multi-junction solar cells are expected to reduce the cost of PV significantly [1]. There are, however, only two companies, Amonix and Solar Systems, in the world successfully doing business with concentrator solar electricity. McConnel at NREL said there are three hurdles that concentrator solar electricity technology must clear for long-term growth and success in market place [2].

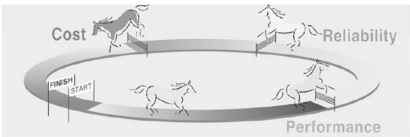

Figure 1: Three hurdles for concentrator technologies [2]

The three hurdles correspond;
High Performance:
High conversion efficiency of sunlight to electricity
High Reliability:
Long-term effective operation in the field.
Low cost:
Cost competitive, and potential to lower cost as manufacturing growth.

This paper describes the up-to-date concentrator module technologies developed by NEDO project according to those three views.

2 PERFORMANCE

2.1 Technology overview

The module described in this paper (see Fig. 2) was developed by the following new technologies.

- Super-high pressure and vacuum-free lamination of the solar cell that suppresses the temperature rise to only 4 to 8 degrees under 400 X geometrical concentration illumination of sun beam [3][4].
- Direct and voids-free soldering technologies of the fat metal ribbon to the solar cell, suppressing hot-spots and reducing the resistance, thereby allowing a current 400 times higher than normal non-concentration operation to be passed [4]
- A new encapsulating polymer that survives exposure to high concentration UV and heat cycles [5]
- Beam-shaping technologies that illuminates the square aperture of the solar cell, from a round concentration spot. [6][7]
- Homogenizer technologies that give a uniform flux and prevent the conversion losses that stem from chromatic aberration and surface voltage variation. [6][7]
- Allowing an assembly tolerance of up to 1.75 mm. There is no need of special optical alignment. Even local mechanical industries can assemble the main body

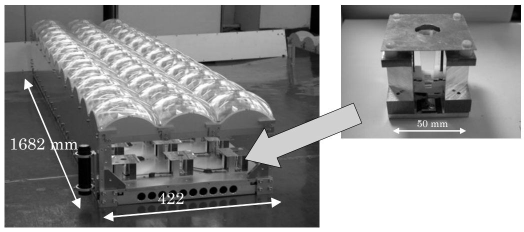

Figure 2: Picture of the concentrator module

2.2 Conversion efficiency

Fig. 3 shows the typical outdoor I-V curve of the modules. All the cells were connected in series. Compared with commercial crystalline silicon solar panels, a lower current and higher voltage was obtained. Since, the receiver had sufficient assemble margins and the variation among lenses were small, the step in the I-V curve that can result from current mismatching was scarcely seen.

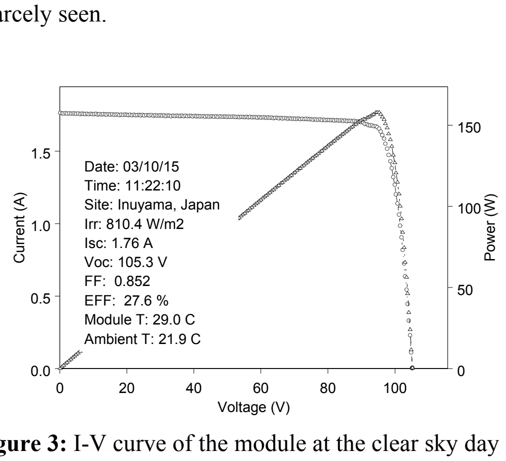

Figure 3: I-V curve of the module at the clear sky day

The averaged outdoor efficiency in Inuyama in the best day (summer) was 26.3 %, corresponding to 28.1 % after temperature compensation to 25 C. The averaged efficiency in Toyohashi site in the best day (autumn) was 27.9 %, corresponding 28.1 % after temperature correction. The 28.1 % efficiency was confirmed in both Inuyama and Toyohashi sites. Because of possible error in DNI measurement, the current most probable efficiency would be 26.8±1.5% (25 C). The remarkable efficiency boost from previous modules [4], is a result from an improved design after identifying key technological aspects of the concentrator operation.

2.3 Power generation

The above-mentioned high efficiency was not always achieved on the regular basis. Sometimes, the tracker failed to align the sun beam and other times the lens did not work properly on account of internal fog by water condensation. The lenses gradually lost transparency by dust accumulation before they were washed by rainfall. The most common power loss was spectrum mismatching by increase of air-mass in the period of low sun height. The output current of the cell was always constrained by its top junction in the real direct beam. With increase of the air-mass, the blue component of the direct beam is more scattered and thus constrain the output current (see Fig. 4). Therefore, the output efficiency dropped sharply in the early morning and late evening or humid climates.

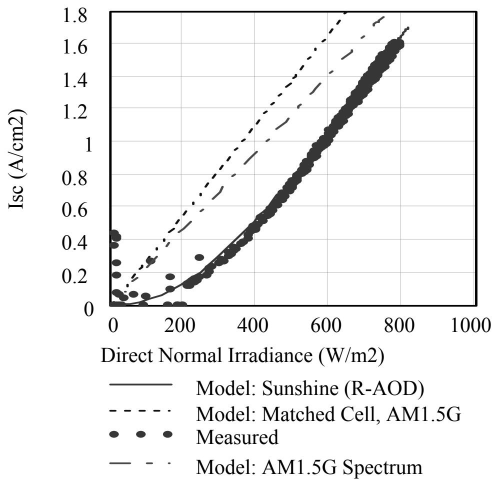

Figure 4: Nonlinear current output due to spectrum mismatching

Another major reason for decreasing annual power generation was lens-fog resulted from water condensation inside the module (See Fig. 5). It was often observed in autumn or winter morning after rainfall and hampered the power generation until it was cleared up.

In order to avoid the fog problem and maintain power generation in the winter morning, we are developing the water condensation trap and coating technology for the lens. Alternative technology developed by Ioffe and Fraunhofer ISE is completely sealed structure [8][9].

Continuous observation of power generation was done in Toyohashi site (See Fig. 6). As expected, the integrated efficiency in a course of the day decreased in winter period. However, the average power generation was comparable to the flat-plate module with the same rating power, in spite of the fact, the prototype system had experienced many troubles and output power was lost in this period associated with challenges of new technologies.

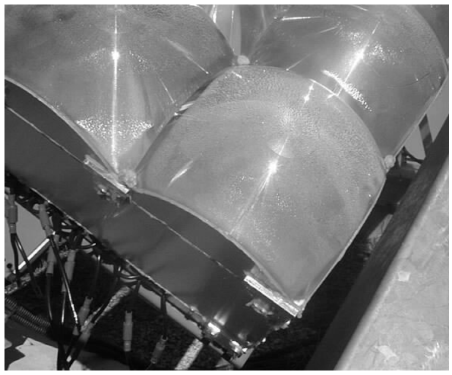

Figure 5: Lens fog in the winter morning

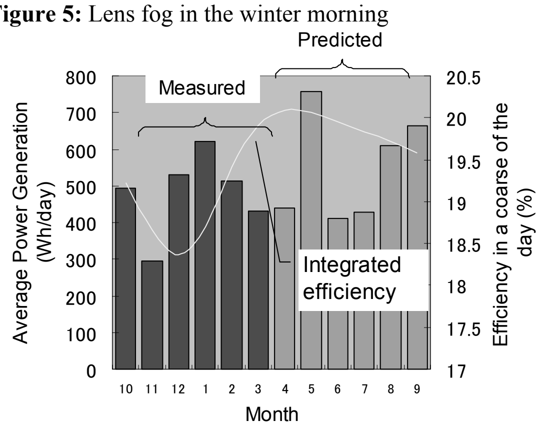

Figure 6: Power generation in each month (Toyohashi Japan, Latitude: N35 deg. Lenses were not washed.)

It was believed for a long time that the concentrator solar electricity was not suitable to Japan because the direct beam is believed less than half of the total irradiance. On the contrary the recorded power generation by the concentrator module (28 % rating efficiency and 200 Wp rating power) was found comparable to 200 Wp non-tracking flat-plate module.

3 RELIABILITY

Since the concentrator module using environmentally sensitive III-V concentrator cells is a new technology, we confronted various difficulties in reliability issues. Most of them are to be overcome, soon.

3.1 Reliability of plastic lenses

The dome Fresnel lens was fabricated by injection molding. It is the new technology suitable to low-cost and volume production. However, massive residual stress is left and may have bad influences to long-term performance.

It was found that residual stress might induce fine crack in humid or freezing environment, leading to efficiency drop (See Fig 7 and 8). The cracks were found only at the area where residual stress was supposed to be concentrated. As far as we experienced, such degradation was not seen in dry conditions, including heat cycle tests.

It is expected that this problem will be overcome by improving molding conditions and additional annealing process common to the process of automobile plastic components.

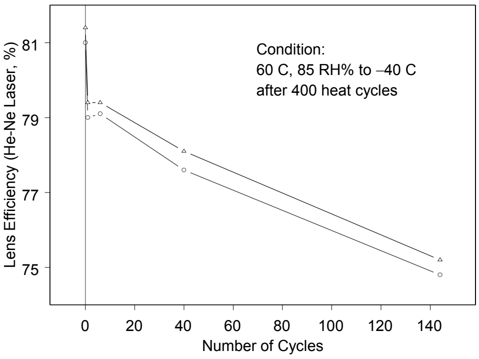

Figure 7: Example of optical efficiency measurement of the injection-molded Fresnel lens after freezing cycle test

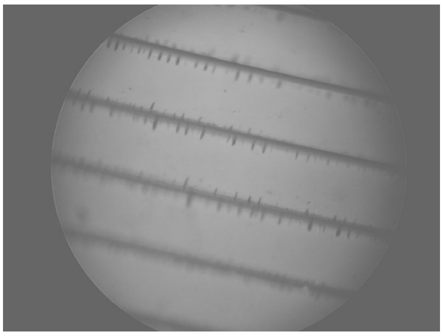

Figure 8: Fine cracks appeared in high residual stress region of the lens after successive freezing cycles

In order to avoid the reliability issues of the lens including lens-fog, a mini module was fabricated and subject to be tested (see Fig. 9).

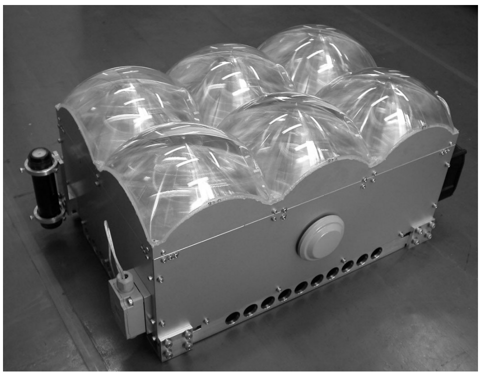

Figure 9: Mini module with Fresnel lenses by lower injection pressure, anti-fog coating and breathing hole for water condensation trap and ventilation

It had Fresnel lenses with lower injection pressure and anti-fog coating. The reduced injection pressure decreased the lens optical efficiency (81.0 % in average from 85.4 % peak optical efficiency achieved by high-pressure injection) but it had advantages for stability of the efficiency as well as prolongation of the lifetime of the molding die. The anti-fog coating absorbed short wavelength region of the direct beam and lower the short circuit current of the solar cell, but it boosted the daily-integrated efficiency by about 1 % in January and February in Toyohashi site. It also had a breathing hole for water condensation trap and ventilation of moisture. The peak efficiency of this module measured by Fraunhofer ISE was 24.43 % on Apr. 21 after about one month of testing.

3.2 Reliability under concentrated sunlight

Another reliability issue inherent to the high concentration III-V solar cell application is the complete protection of the cell against humidity. [10][11] III-V solar cell is more chemically reactive than the well-established back-contact concentrator silicon solar cells. In order to passivate the cell, it should be packed by a transparent sealing polymer. However, most of the transparent polymer does not survive under strong irradiation. Degradation of the sealing polymer was found often accelerated by the presence of moisture.

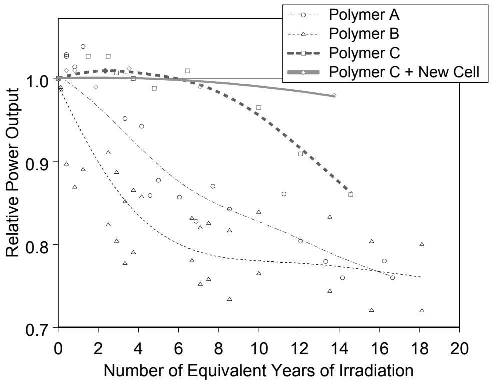

Figure 10: Acceleration test by compound stress of simultaneous concentrated UV irradiation and water condensation.

We are developing and testing robust sealing structure against concentrated sunlight. We found the sealing structure that passed the environmental chamber test (hot-wet, thermal cycle, freezing cycle) did not always survive the concentrated sunlight test. Some polymers (weather-tough silicone resin) degraded after several months of equivalent accumulated irradiation (see Fig. 10). The Polymer B present in the module of Fig. 2 and Fig. 9 has recently shown rapid degradation, due to the compound stress of moisture and concentrated UV in a cold environment, although it survived by various environmental chamber tests, water dipping test, and UV irradiation test in hot dry environment. We are now testing new materials including the Polymer A and C in Fig 10, which may survive compound stress associated with concentrated UV as well as a robust III-V cell provided by SHARP. A new material combined with new sealing structure and the robust cell design is expected to result in a concentrator receiver that may survive more than 20 years of concentrated irradiation.

4 COST

Various aspects including capital cost, labor and material cost determine the cost of the PV module. With the effort of PV industries as well as the expansion of the scale of the management, the ratio of capital cost and labor cost are decreasing. The final effort is to be devoted to reduction of the material cost. The material cost will be an indication on potential to lower cost as manufacturing growth.

The concentrator modules in the past had been believed to be massive and heavy metal works. It was true when they used big heat sinks or water-cooling system. Many present concentrator modules including Amonix's module successfully spread concentrated heat to the back body and do not rely on heat sinks [12]. Our module succeeded to reduce the weight comparable to the typical thin-film solar panels (see Fig. 11). It is expected to overwhelm the typical multi-crystalline silicon module after some technical innovations.

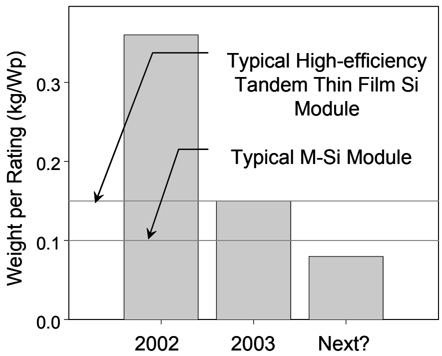

Figure 11: Module weight with comparison to flat-plate technologies.

Another advantage for the concentrator module regarding the material cost, is most of the weight come from metal and plastic works and very few from expensive semiconductor materials. It is well known that the motive force for thin film technologies is to reduce the material cost for the semiconductor. The concentrator module, however, does not rely on the reduction of semiconductor material cost but are heading further away.

One of the concerns for the lightweight design is capability of heat spreading. However, it is not a problem unless aluminum alloy is used for the body (see Fig. 12).

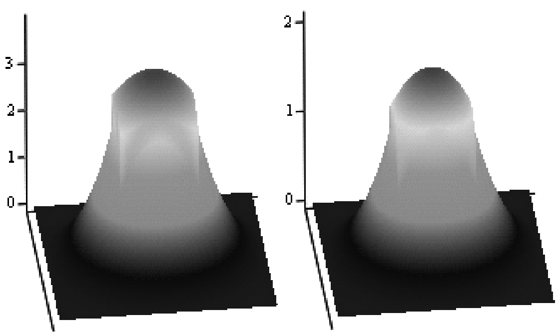

Figure 12: Temperature distribution on the module body Left: Light weight design, Right: Current body thickness

5 CONCLUSION

There are three hurdles, performance, reliability and cost that concentrator solar electricity technology must clear for long-term growth and success in the market place.

Performance: 28 % module efficiency (26.8 ± 1.5 % considering possible DNI measurement errors) was achieved. 24.4 % module efficiency was also achieved by the module with reliability-enhanced lenses. The expected annual power generation was comparable to the flat-plate module with the same rating even in the Japanese climate which was thought unsuitable for concentrator applications due to insufficient direct beam irradiation.

Reliability: It is expected but not proven, yet. Our current focuses are reliabilities of Fresnel lens (fog and degradation by residual stress) and recently found compound stress by concentrated UV and moisture to the sealing material of the concentrator solar cells. But extensive studies on the reliabilities of the next generation III-V HCPV module were done. These problems are expected to be overcome, soon.

Cost: It is expected but not proven yet. The reduction of module weight has already caught up with the thin film module. Considering most of the material in the concentrator module is inexpensive plastic and metal works, it is expected to overwhelm both M-Si and thin film modules in the near future.

6 ACKNOWLEDGEMENT

This work was supported by the Incorporated Administrative Agency New Energy and Industrial Technology Development Organization (NEDO) under Ministry of Economy, Trade and Industry (METI).

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