Performance of 7-cells Dye Sensitized Solar Module in Z-type Series Interconnection

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Abstract. Dye sensitized solar cells (DSSC) is becoming attractive research topic as third generation solar cells technology since it provides clean energy and low cost fabrication. In this study, DSSC was fabricated into module scale, which is important for practical applications. The module was prepared in sandwich structure consisting of TiO₂ working electrode and Pt counter electrode on conductive substrate with an area of 100 mm x 100 mm, which was distributed into seven active cells. TiO₂ paste was deposited on FTO glass as working electrode with a size of 10 mm x 98 mm per unit cell by screen printing method. Each cell was connected in Z-type series that able to produce high voltage. $I-V$ measurement was applied in two methods consisting of laboratory testing using sun simulator under 500 W/m² of illumination and outdoor testing using a digital multimeter under direct sunlight. The result shows that DSSC module has photoconversion efficiency of 1.08% and 1.17% for laboratory and outdoor testing, respectively. The module was also tested in three different times to monitor its stability performance.

1. Introduction
Dye sensitized solar cells (DSSC) is becoming trending topic in renewable energy research area since Gratzel et al. invented it in 1991 [1]. DSSC offers alternative energy with low cost production, simple process fabrication and flexibility in design, which makes it part of third generation solar cells [2]. DSSC was also reported to have photoconversion efficiency over 11% [3] and it can potentially even reach higher efficiency with further research. Therefore, more research has been conducted to develop the practical implementation of DSSC by scaling up the area in module design.

Some aspects can affect the quality of DSSC such as the presence the additive in the electrolyte or improper sealing [4]. In fabrication of DSSC module particularly, sealing is one of the most challenging factors that determine the photovoltaic performance and lifetime stability. When DSSC module was applied for outdoor use, stability is considered as a major obstacle [5]. Moreover, it was confirmed that photovoltaic performance in module scale was lower than cell scale since the resistance become higher in larger area [6]. Gratzel had reported the fabrication of DSSC module with an efficiency 7% [7]. Wei et al. [8] fabricated grid type module with 7% efficiency. Han et al. [9] developed W-contact DSSC module and received photoconversion efficiency of 8.2%. Nevertheless, the research in module designs have also been improved continuously to achieve optimum performance and could be considered to be widely implemented.

This work reports the fabrication of DSSC module using FTO glass substrate that consists of 7 cells interconnected in Z-type series. Series interconnection is able to produce higher voltage and lower
current, which requires less metal fingers for module design [6]. The performance of DSSC module was evaluated by comparing the results from sun simulator testing as a standard laboratory measurement and outdoor testing to simulate real operating condition. Moreover, the stability of the module was also tested by measuring the performance of module over three different times.

2. Experiments

There were three parts in fabrication of DSSC module, which consisted of preparation of photoelectrode and counter electrode, assembly, and $I - V$ measurement.

Preparation of photoelectrode was preceded by making the module pattern consisting of 7 unit cells with an area of 10 mm x 98 mm for each cell, circuit contact, and sealant as they can be seen in Figure 1. In addition, screen for module was prepared using screen maker according to the patterns.

![Pattern design for DSSC module screen](image)

**Figure 1.** Pattern design for DSSC module screen for (a) TiO$_2$ active cells, (b) sealing area, and (c) circuit contact area.

FTO glass as conductive substrate was used with a size of 100 mm x 100 mm. First, FTO glass was scribed using laser to separate each area of cells. The substrate was then cleaned in DI water using ultrasonic cleaner and rinsed using ethanol for 10 minutes, and then dried naturally. Deposition process of TiO$_2$ semiconductor by screen printing method was applied on clean substrate using 7 cells screen (Figure 1.a) as made before. TiO$_2$ film was then dried in an oven at 100°C for 10 min. TiO$_2$ film was also sintered at 500°C for 45 min for calcination process. The same process was also applied for working electrode on which platinum transparent paste was coated on to substrate by screen printing method using the same pattern as the photo electrode, dried and sintered with the same treatment as the photo electrode.

TiO$_2$ film was subsequently immersed in dye solution (N907 0.5 mM in ethanol) for 24 hours. After the dyes adsorption process, the dyed film was then rinsed with ethanol and dried naturally.

The next step was assembly process. Amosil 4R and amosil 4H (Solaronix) was mixed to obtain the sealant and then deposited on the sealant area (Figure 1.b) of the photo electrode using screen printing method, while Ag paste was deposited on the circuit contact area (Figure 1.c) of the counter electrode using the same method. Both photo electrode and counter electrode were constructed in sandwich structure. Electrolyte liquid was injected into the module through a predrilled hole, which was located on the counter electrode surface.

$I - V$ measurement was conducted on the module prototype to investigate its performance based on the generated curve and photovoltaic parameters. In this work, the module was tested in two conditions consisting of laboratory and outdoor testing. Laboratory testing was applied to the module using sun simulator with an intensity of 500 W/m$^2$ and the result was measured by National Instrumentation source meter. Meanwhile, outdoor testing was applied to the modul by using variable resistor under direct sunlight and the result was measured by digital multimeter.
3. Results and discussion

Herein, the fabricated DSSC module has Z-type series interconnection that has been widely used since it can reduce the area consumption for metal fingers, which consequently can be an effective way to increase the open area ratio [6]. Figure 2 shows the internal structure of DSSC module with series interconnection in cross section view, describing detailed construction of each material. In a module, sealant has an important role to protect each cell and avoid electrolyte leakage between the adjacent cells so that the module will be able to produce high stability. Assemblage technique also takes crucial role since it was done manually in order to construct the photoelectrode and counter electrode in sandwich structure. Top view of prototype of 7-cells DSSC module can be seen in Figure 3.

![Figure 2. Internal structure of DSSC module with series interconnection.](image1)

![Figure 3. Prototype of 7-cell DSSC module designed in sandwich structure.](image2)

As mention before, DSSC module was tested in two conditions consisting of laboratory and outdoor testing. Laboratory testing provides controllable indoor test as it has stable light intensity using sun simulator. Outdoor testing was done to obtain the module performance in real condition, by using variable resistors and was measured using digital multimeter. The weakness of outdoor testing lies on the external factors, such as temperature and irradiance, which are uncontrollable and possibly affect the performance of solar cells [4].

Figure 4 shows the graph that compares the result of laboratory and outdoor testing. Both curves demonstrated photovoltaic performance of the module and it can be clearly seen that the outdoor testing exhibits better $I-V$ curve. However, the outdoor testing has inconstant $I-V$ data at the initial measurement that might be caused by unstable sunlight intensity. Laboratory testing result, which has lower performance than outdoor testing result, exhibits constant $I-V$ data that gives more accurate measurement of module performance.
Figure 4. I-V curve of DSSC module from laboratory and outdoor testing.

Photovoltaic parameters obtained from laboratory and outdoor testing results are listed in Table 1, giving the performance value of each of 7 unit cells and as a module. The photovoltaic parameters show lower performance with nearly identical value for each cell. However, when the cells were accumulate as a module the performance has increased significantly. It indicates that the interconnection between adjacent cells had managed its function as path of electric current. Overall, the outdoor testing result has higher value of PV parameters with slight difference from the laboratory testing result. The highest value of short circuit current density ($J_{sc}$), open circuit voltage ($V_{oc}$) and photoconversion efficiency ($\eta$) was 0.028, 4.720 V, and 1.176%, respectively. The value of $V_{oc}$ can be compared between cells and module form that shows significant difference. The result might be affected by the serial connection between cells since this type of connection can produce high voltage. In this case, serial connection in the module prototype could work properly and was able to increase the voltage in module form.

| Testing Method | Parameter | $J_{sc}$ (mA/cm$^2$) | $V_{oc}$ (V) | $\eta$ (%) |
|----------------|-----------|----------------------|-------------|------------|
| Laboratory testing | Module    | 0.028                | 4.487       | 1.086      |
|                 | Cell 1    | 0.012                | 0.672       | 0.416      |
|                 | Cell 2    | 0.012                | 0.631       | 0.422      |
|                 | Cell 3    | 0.011                | 0.632       | 0.399      |
|                 | Cell 4    | 0.014                | 0.631       | 0.484      |
|                 | Cell 5    | 0.013                | 0.632       | 0.456      |
|                 | Cell 6    | 0.012                | 0.631       | 0.432      |
|                 | Cell 7    | 0.012                | 0.631       | 0.434      |
|                 | Module    | 0.028                | 4.720       | 1.176      |
| Outdoor testing  | Cell 1    | 0.005                | 0.500       | 0.367      |
|                 | Cell 2    | 0.014                | 0.680       | 0.337      |
|                 | Cell 3    | 0.015                | 0.660       | 0.428      |
|                 | Cell 4    | 0.015                | 0.670       | 0.372      |
|                 | Cell 5    | 0.017                | 0.650       | 0.348      |
|                 | Cell 6    | 0.014                | 0.660       | 0.392      |
|                 | Cell 7    | 0.015                | 0.650       | 0.402      |
Laboratory testing were performed three times to obtain the stability of the module. Figure 5 shows the comparison of IV curve from the 1st, 2nd, and 3rd laboratory testing. First testing was immediately applied to the module before it was stored under dark condition. Meanwhile, the second and third testing was performed with 5 days interval after the module was kept in storage with uncontrolled condition. Overall the module still could manage photovoltaic effect although the tests yielded less ideal curves.

![Figure 5. I-V curve of DSSC module from 1st, 2nd, and 3rd laboratory testing.](image)

The photovoltaic parameters obtained after repeated tests are compared in Table 2. It can be seen that module performance was degraded over the storage time. The average of degradation was approximately 40% from the initial module efficiency after each testing. The degradation of the module was more likely caused by ineffective module sealing, which led to electrolyte leakage between the adjacent cells and possibly causing unwanted mass transport. Moreover, the uncontrolled condition during the storage affected the humidity and temperature of the module that can lower the module performance, in particular affecting the electrolyte reaction as it might be dried or reacted with sealant material. The degradation in the DSSC module performance indicates that more investigation on materials and more appropriate fabrication techniques are still required to improve the applicability of the DSSC modules.

Table 2. Photovoltaic parameters of DSSC module from 1st, 2nd, and 3rd laboratory testing.

| Parameter | 1st | 2nd | 3rd |
|-----------|-----|-----|-----|
| $J_{sc}$ (mA/cm$^2$) | 0.028 | 0.017 | 0.015 |
| $V_{oc}$ (V) | 4.487 | 4.589 | 4.180 |
| $\eta$ (%) | 1.086 | 0.666 | 0.398 |

4. Conclusions
DSSC module consisting of 7 active cells with Z-type series interconnection has been fabricated. The electrical measurement was conducted both in laboratory and outdoor testing and the results were
compared. Photoconversion efficiency of the module for laboratory and outdoor testing was 1.086% and 1.176%, respectively. However, the laboratory testing gave more accurate result since it provided stable light intensity during the $I - V$ measurement. This research also compared the module performance over three repeated measurements. The results suggest that stability is still problematic since the degradation of the module performance occurred after 2nd and 3rd testing, giving an approximately of 40% degradation in each testing.

References
[1] O'Regan B and Grätzel M 1991 Nature 353 pp 737–40
[2] Hagfeldt A, Boschloo G, Sun L, Kloo L and Pettersson H 2010 Chem. Rev. 110 pp 6595–663
[3] Mathew S, Yella A, Gao P, Humphry-Baker R, Curchod B F E, Ashari-Astani N, Tavernelli I, Nat. Chem 6 pp 242–7
[4] Asghar A, Emziane M, Pak H K and Oh S Y 2014 Sol. Energy Mater. Sol. Cells 128 pp 335–42
[5] Jun Y, Son J H, Sohn D and Kang M G 2008 J. Photochem. Photobiol. A Chem. 200 pp 314–7
[6] Zhang Y-D, Huang X-M, Li D-M, Luo Y-H and Meng Q-B 2012 Sol. Energy Mater. Sol. Cells 98 pp 417–23
[7] Grätzel M 2011 Photoelectrochemical cells Nature 414 pp 338–44
[8] Tzu-Chien Wei, Jo-Lin Lan, Chi-Chao Wan W-C H and Y-H C 2013 Prog. Photovolt Res. Appl. 21 pp 1625–33
[9] Han L, Fukui A, Chiba Y, Islam A, Komiya R, Fuke N, Koide N, Yamanaka R and Shimizu M 2009 Appl. Phys. Lett. 94 pp 1–4

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