Improving the efficiency of a dye-sensitized solar cell with a reflex condenser system

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Abstract: Dye-sensitized solar cells (DSSCs) are inexpensive to manufacture and easy to process in comparison with silicone solar cells, but they are difficult to commercialize due to their low efficiency. Accordingly, the aim of this study was to improve the efficiency of a DSSC via an aluminum film reflective plate, reusing discarded light after it was absorbed. We found that the factor having the most dominant influence on DSSC efficiency was the amount of radiation reacting with the dye. For a reflective plate with ϴ = 30° and h = 15 mm, DSSC efficiency was increased about three times.

OCIS codes: (350.6050) Solar energy; (000.4930) Other topics of general interest.

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1. Introduction

Silicone-based solar cells provide high efficiency, but are hampered by a number of serious disadvantages, such as high cost; toxic waste byproducts; lengthy, complicated, processing, and lowered efficiency depending on the angle of incidence. In order to overcome their disadvantages of these cells, numerous studies of dye-sensitized solar cells (DSSCs) have been conducted. DSSCs offer advantages such as low manufacturing cost (less than 20% of the cost of a silicone solar cell), simple processing, transparency, low toxicity, and flexibility.

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However, there are still many issues that must be resolved to pave the way for commercialization, including improved efficiency, enlarged surface, and electrolyte-sealing technology [1–3].

Currently, the efficiency, of a DSSC is around 11%, beyond which further improvement is not possible, due to limits on material development [4–6]. For the commercialization, more than 20% efficiency is required, and hence the effect of material development must be enhanced by a method for improving cell efficiency through the use of an external component, such as condensing, reflector or condensing lens [7–11].

In this study, we attempt to improve the efficiency of a solar cell by rerouting the light with a reflector, reusing discarded light after it is absorbed.

2. Purpose of the experiment

The objectives of this study were to improve the efficiency of a DSSC by designing a reflex condenser system, and to derive its most suitable conditions. The unused light transmitted through a DSSC can be transformed into an electric flow via a reflex condenser system. This is the advantage of the system, and the means by which cell efficiency is expected to be improved.

Assuming that the light was direct sunlight, incident perpendicular to the ground, a light simulation was conducted using the light tool program. Based on the simulation results, an actual reflective plate was designed and manufactured, and the efficiency of the resulting DSSC was measured. Changes in DSSC efficiency were predicted to occur in response to three variables. The first of these was the sunlight incident on the reflector; in other words, it was assumed that the efficiency changed according to the area of the incident sunlight. Secondly, it was assumed that the efficiency changed according to the reflective area (the area required to reflect the sunlight). Finally, it was assumed that the efficiency changed according to the reaction with the dye. The purpose of this research was to identify the design factors, such as the angle and height of the reflex condenser system, and then determine the dominant effect of the aforementioned three variables on the efficiency of the DSSC, as well as the highest photoelectric conversion efficiency.

3. Experimental method

3.1 Fabrication of the DSSC

A transparent conducting oxide (TCO) was used for the electrodes, which were made from fluorine tin oxide (FTO)-coated glass with a thickness of 2.1 mm and a sheet resistivity of 7 Ω. TiO_2 sol-gel dye paste was used, with N719 dye and An50 electrolyte. A thermoplastic sealant sheet (Dye-sol, Surlyn®), 60-μm thick, was used to seal the device.

The manufacturing process was as follows. First, organic matter was removed by sonicating in acetone for 30 minutes. The acetone was removed by washing in ethanol for 30 minutes, and the ethanol was removed by washing with distilled water for 30 minutes. The TiO_2 paste (Dye-sol, P50) was applied twice, using a silk screen, and baked in a furnace at 450°C for 3 – 4 hours. It was then soaked in N719 for 12 hours. Finally, it was sealed via the thermoplastic sealant sheet, assembled into cells, and injected with An50 electrolyte.

3.2 Structure of the reflective condenser system

A reflected sunlight collection system using aluminum film was designed with due consideration to the angle against a normal line to the ground, the area of the incident sunlight, and the reflective area, as shown in Fig. 1.

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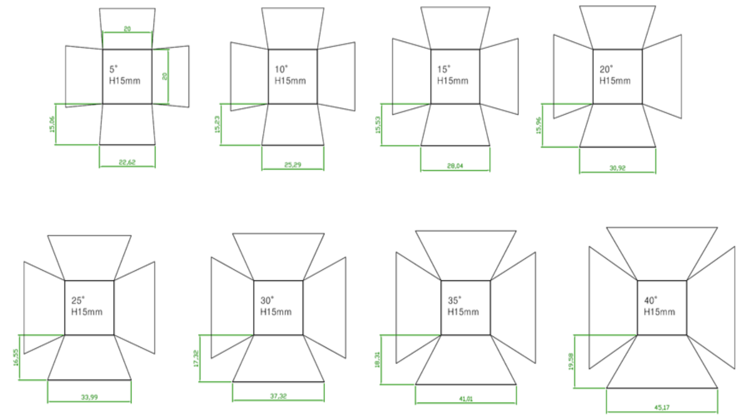

Fig. 1. Reflective condenser plate design.

The area of the reflector floor was 20 mm × 20 mm, considering the size of the dye-sensitized solar cell (17 mm × 17 mm). When the area of the incident sunlight was fixed, the design angles of the reflectors against a normal line to the ground were 5°, 30°, 35°, and 45°, and when the vertical height of the reflectors was fixed (at 15 mm), the design angles were 5°, 10°, 15°, 20°, 25°, 30°, 35°, and 40°, as shown in Fig. 2.

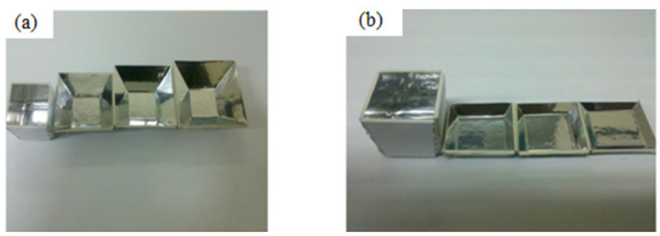

Fig. 2. (a) Manufactured reflectors with a fixed area of incident light. (b) Manufactured reflectors with various of incident light.

Figure 3(a) shows the test apparatus used to measure the characteristics of a DSSC. The tests were conducted under a standard light source with an air mass (AM) of 1.5 (1 sun, 100 mW/cm2) using a solar simulator. I_{SC}, V_{OC}, and the current–voltage curves of the DSSC were scanned using a 1-sun light source and a xenon (Xe) lamp with a Keithley 2400 source meter at 10 point/s. Figure 3(b) shows a fabricated DSSC.

In this test, the reference efficiency of a single DSSC was measured. A reflector was then installed on the cell, and the change in efficiency was observed.

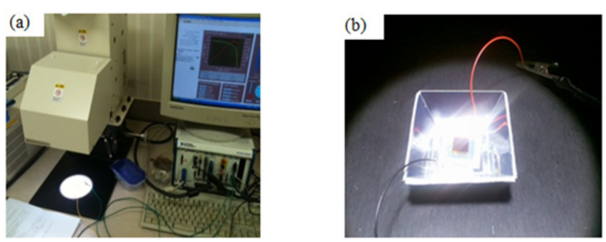

Fig. 3. (a) Test apparatus used to measure characteristics of dye-sensitized solar cell. (b) Fabricated DSSC.

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4. Results

4.1 Fixed area of incident sunlight

The light simulations were conducted using the Light Tool program, and the light was assumed to be direct incident sunlight perpendicular to the ground. The results are shown in Fig. 4. The blue lines represent the incident and reflective path of the sunlight, and the black lines indicate the reflector housing. The turquoise area at the center of the reflector housing represents the DSSC dye (7 mm × 7 mm). What is noteworthy in these optical simulations is how many blue lines enter the turquoise area. The results indicate that the greatest amount of light impacted the dye when ϴ was 35°. When ϴ exceeded 45°, the sunlight was not incident on the floor reflector, but was reflected from the sides and dissipated into the air.

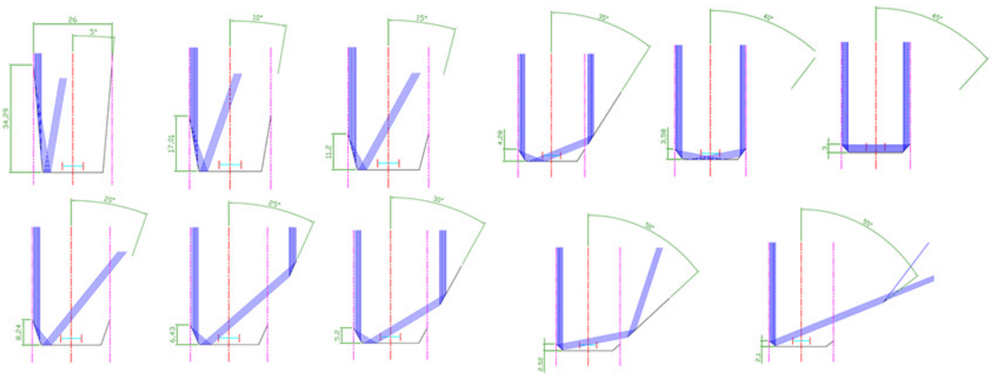


Fig. 4. Light simulation result for a fixed area of incident sunlight.

An experimental schematic is shown in Fig. 5(a) for a fixed area of incident sunlight. The incident area in this case was 26 mm × 26 mm (the same as in the simulations), and the DSSC efficiencies were measured for ϴ = 5°, 30°, 35°, and 45°.

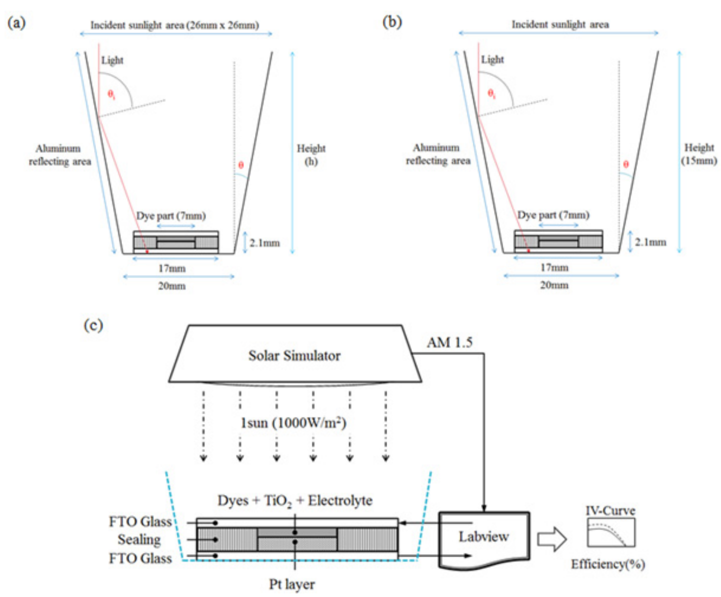


Fig. 5. (a) Experimental schematic for a fixed area of incident light. (b) Experimental schematic for varying areas of incident light. (c) Concept of test apparatus used to measure characteristics of a DSSC.

The reference DSSC efficiency was 3.485% when 1000 W/m^2 of sunlight was input. The efficiencies measured after the reflectors were installed are listed in Table 1.

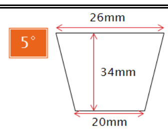
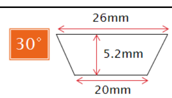
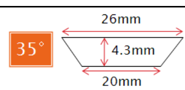
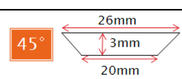
Table 1. Efficiency of DSSC with a fixed area of incident sunlight

Intensity [W/m^2]	Area of cell [mm^2]	Temperature [°C]
1000	49	25

Θ [°]	Θ$_i$ [°]	Height [mm]	P_{max} [mW]	V_{mp} [V]	I_{mp} [mA]	Efficiency [%]
5	85	34	2.49	0.52	4.79	5.081
30	60	5.2	2.31	0.52	4.45	4.714
35	55	4.3	2.14	0.52	4.13	4.367
45	45	3	2.10	0.52	4.05	4.285

The light simulations indicated a maximum amount of sunlight reacting with the dye when Θ was 35°, but according to the test results, the efficiency was highest when Θ was 5°. This discrepancy was attributed to the differences in the vertical height. When Θ is 5°, the vertical height is 34 mm, which is approximately 8 times larger than when Θ is 35°. Accordingly, the reflective area differs, and more sunlight reaches the dye due to scattering or spread reflection in the air. It can be shown that when the same amount of sunlight is incident on the reflector, the reflective area does not have a dominant impact on the DSSC efficiency. The efficiencies for different reflective areas, expressed by values of Θ, are listed in Table 2. The resulting relationship between the DSSC efficiency and the reflective area of the reflector is shown in Fig. 6.

Table 2. Efficiency of DSSC according to the reflective area

Schematic of reflective area	Θ$_i$ [°]	Reflective area [mm^2]	Efficiency [%]
	85	3128	5.081
	60	478.4	4.714
	55	395.6	4.367
	45	276	4.285

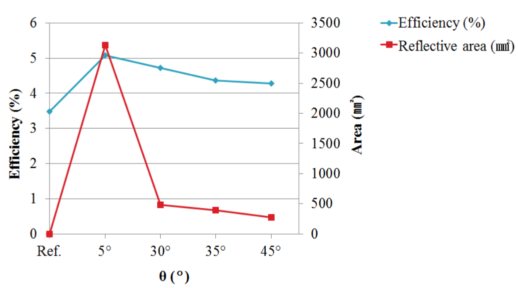


Fig. 6. Efficiency-curves of DSSC with respect to the reflective area

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4.2 Varying area of the incident light

In Section 4.1, the vertical height of the reflector was changed along with Θ in order to maintain a fixed area of incident sunlight. However, the purpose of this research was to find a relationship between the area of incident sunlight and DSSC efficiency. Therefore, in this test, the vertical height of the reflector was fixed at 15 mm while Θ was increased.

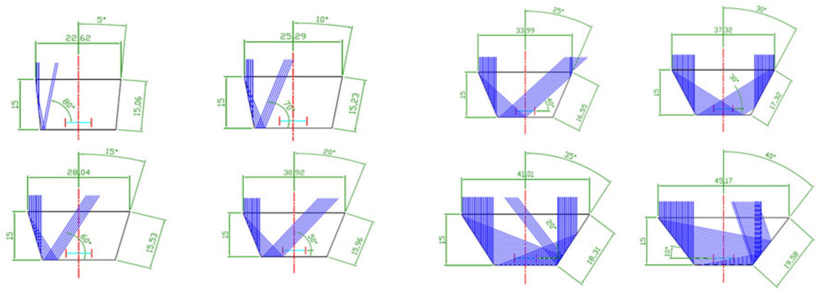

Fig. 7. Light simulations for a fixed vertical height of the reflector.

An experimental schematic is shown in Fig. 7 for a fixed vertical height of the reflector. Under the same conditions as the simulations, the vertical height was fixed at 15 mm, and the DSSC efficiencies were measured for Θ = 5°, 10°, 15°, 20°, 25°, 30°, 35°, and 40°. The reference DSSC efficiency was 3.485% when 1000 W/m^2 of light was input. The efficiencies measured after the reflector was installed are listed in Table 3.

Table 3. Efficiency of DSSC with varying areas of incident sunlight

Θ [°]	$Θ_i$ [°]	Height [mm]	P_{max} [mW]	V_{mp} [V]	I_{mp} [mA]	Efficiency [%]
5	85	15	1.71	0.52	3.29	3.48
10	80	15	1.85	0.52	3.57	3.77
15	75	15	2.15	0.52	4.15	4.38
20	70	15	2.64	0.51	5.19	5.38
25	65	15	3.42	0.52	6.58	6.97
30	60	15	4.85	0.51	9.51	9.89
35	55	15	4.56	0.51	8.95	9.30
40	50	15	3.13	0.52	6.02	6.38

The light simulations indicated a maximum amount of sunlight reacting with the dye when Θ was 30° and 35°. The actual DSSC efficiencies obtained from the test results were also highest for these values, 9.89% and 9.30%, respectively.

The incident light areas were calculated [Table 4] in order to determine their relationship with the DSSC efficiency. In this test, as Θ increased, the incident light area gradually increased, and the hypothesis that changes in the incident light area are related to changes in DSSC efficiency was verified. Proportionality between the incident light area and the DSSC efficiency was demonstrated in the range of Θ values from 5° to 30°. However, the DSSC efficiency decreased with increasing incident light area when Θ was greater than 30°. This means the relationship between the incident light area and the DSSC efficiency is not always proportional, and changes in Θ seem to have a dominant impact on DSSC efficiency. The relationship between the DSSC efficiency and the incident light area is shown in Fig. 8.

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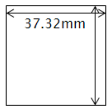
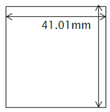
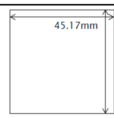
Table 4. Schematics of the incident sunlight area and the efficiency of DSSC

Schematics of incident sunlight area	Θ [°]	Area of incident sunlight [mm^2]	Efficiency [%]
	30	1392.8	9.89
	35	1681.8	9.30
	40	2040.3	6.38

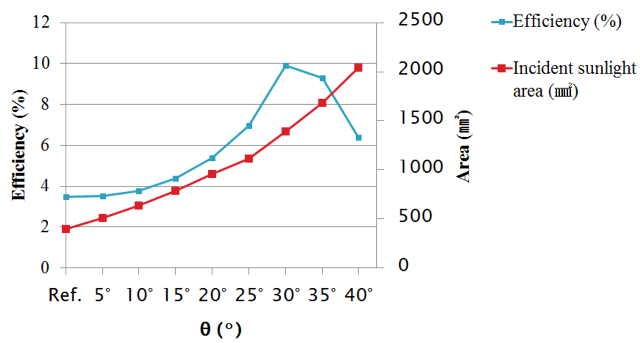


Fig. 8. Efficiency-curves of the DSSC with respect to the incident sunlight area.

According to the test results of [4.1] and [4.2], the incident light area and reflective light area cannot greatly impact the DSSC efficiency. The reason the efficiency was highest when Θ was 30° and 35° is that the amount of sunlight reacting with the dye of the DSSC was greatest. Therefore, it is necessary to calculate the amount of sunlight that reached the dye through the reflector; these values are listed in Table 5.

Table 5. Efficiency of DSSC according to the amount of sunlight reacting with the dye

Θ [°]	Amount of reactive sunlight with the dye from vertical direction + reflected by beside + reflected by bottom [W]	Efficiency [%]
20	(7x7 + 0 + 1.76x7x4)mm^2 x 1000W/m^2 = 0.098W	5.38
30	(7x7 + 7x7x4 + 7x7x4)mm^2 x 1000W/m^2 = 0.441W	9.89
40	(7x7 + 7x7x4 + 0)mm^2 x 1000W/m^2 = 0.245W	6.38

The calculated amount of sunlight reacting with the dye of the DSSC was highest (0.441 W) when Θ was 30°. The proportionality of the DSSC efficiency is shown in Fig. 9. The amount of sunlight reacting with the dye was the factor having a decisive impact on the DSSC efficiency.

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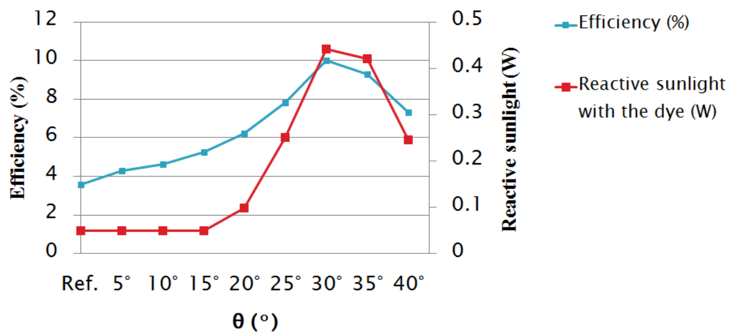

Fig. 9. Efficiency-curves of the DSSC with respect to the amount of sunlight reacting the dye.

5. Conclusion

A reflector was employed to increase the efficiency of a DSSC by using discarded light, and the influential factors in the reflector design were determined. The factors expected to impact the DSSC efficiency were the reflective area of the reflector, the area of the incident sunlight, and the actual amount of sunlight reaching the dye in terms of Θ.

The changes in the efficiency of a DSSC were insignificant relative to changes in the area of the optical reflection (about 0.4%) or the area of the optical incidence. The area of the optical incidence was not proportional to the DSSC efficiency. A value of Θ that produces a maximum efficiency was shown to exist.

The amount of sunlight reacting with the dye of a DSSC had a dominant impact on the efficiency.

Throughout these tests, the optimum Θ value was selected as the most important design factor of a reflector used in a highly efficient DSSC. In order to develop DSSC modules for future commercial release, the material and geometric characteristics of the reflector must also be simulated and studied.

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