

ANALYSES OF ONE-DIMENSIONAL GRATINGS ON THE PERFORMANCE OF SOLAR CELLS

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This study presents a simple technique for improving the power conversion efficiency of a solar cell. In the proposed approach, a reflective-type diffraction optical grating is fabricated on the surface of the solar cell in order to redirect the incident light reflected from the solar cell back onto the solar cell surface. The experimental results show that the addition of the optical grating increases the open circuit voltage, V_{oc} , from 2.62V to 3.62V and improves the maximum output voltage, V_m , from 2.5V to 3.5V. As a consequence, the power conversion efficiency of the solar cell increases from 27% to 37.8%, corresponding to an improvement of around 40%.

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1. Introduction

As natural resources of coal, gas and oil dwindle and become increasingly inaccessible and expensive to obtain, the use of solar energy as a sustainable power source has become increasingly attractive. Scientists have estimated that the sunlight incident on the surface of the Earth over a period of 1 hour is of the order of 1.2×10^{12} KW and is sufficient to meet the energy requirements of the entire human race for around 1 year. Thus, solar energy represents an ideal solution for meeting the energy requirements of both developed and developing nations in an environmentally friendly manner. When developing solar power systems, three issues are of primary concern, namely improving the power conversion efficiency, reducing the production and operational costs, and ensuring the system reliability. Of these three issues, improving the power conversion efficiency in a simple and cost-effective manner has attracted particular attention in the literature [1-4]. In general, the energy efficiency of a solar cell can be improved in one of two different ways, namely by choosing an appropriate semiconductor material and dopant with which to fabricate the solar cell, or by increasing the intensity of the incident light. In the former approach, the solar cells are fabricated using materials with specifically chosen energy gap characteristics designed to absorb photons of different wavelengths so as to reduce the energy loss in the carrier energy gap zone. Whilst undeniably effective, this approach has the disadvantage that a detailed knowledge of the physical properties of semiconductor elements is required in order to obtain the optimal results [5-8]. In the second approach, a Fresnel lens is used to increase the intensity of the sunlight focused on the surface of the solar cell. This method is also highly effective in improving the power conversion efficiency of the solar cell, but requires the use of a sophisticated sun tracking system and therefore tends to be too expensive for practical applications

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[9-10].

This study presents a novel method for improving the power conversion efficiency of a solar cell in a straight forward and low cost manner. In the proposed approach, conventional holographic optical interference lithography techniques and standard micro-electro-mechanical systems (MEMS) methods are used to fabricate an enhanced solar cell chip in which a polymer-based reflective-type diffraction optical grating is fabricated on the surface of the solar cell (see Fig.1). As shown in Fig.1, when the solar cell is exposed to sunlight, the incident light reflected from the solar cell (reflectivity r_1) is redirected by the optical grating (reflectivity r_2) such that it is re-incident upon the solar cell surface, thereby increasing the net amount of solar energy absorbed by the cell.

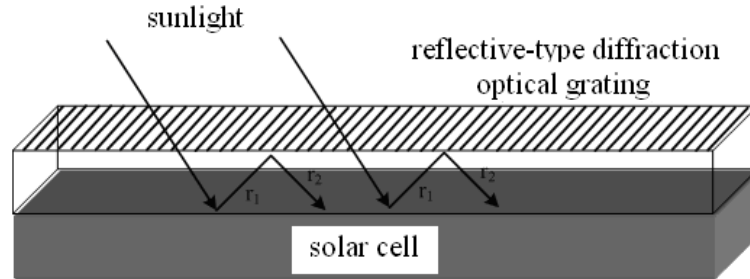


Fig.1. Schematic illustration of solar cell with reflective-type diffraction optical gratings. Re-focusing of reflected incident light by diffraction optical gratings.

2. Manufacture and theoretical principles of enhanced solar cell with optical gratings

2.1 Manufacturing procedure

The enhanced solar cell proposed in this study was fabricated using conventional photolithography and MEMS-based techniques. The basic steps in the fabrication procedure are summarized in the paragraphs below.

Step 1: Fabrication of optical grating mold

As shown in Fig.2, the mold for the reflective-type diffraction optical grating was manufactured by spin coating a thin layer of Ultra123 positive photoresist (PR) on a glass substrate and then patterning the PR layer using a holographic interference lithography technique [6,11].

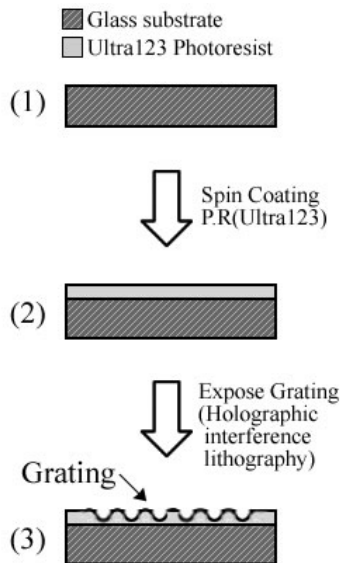


Fig.2. Overview of optical grating mold fabrication process.

The structure of the holographic interference lithography system used to pattern the PR mold is shown schematically in Fig.3. In this experimental setup, the light source was provided by a He-Cd laser with a central wavelength of 325 nm and an output power of 60mW. After passing through the beam splitter, the laser beam was separated into two plane waves with an equal light intensity. The plane waves were reflected by two planar-type mirrors and were then incident upon the surface of the PR-coated glass substrate mounted in the sample holder. As shown in Fig.3, the interference of the two beams on the PR layer results in the formation of a periodic grating structure. The relationship between the spacing of the optical grating (T), the wavelength of the laser light source (λ), and the incident angles of the two laser beams (θ_1 and θ_2 , respectively) is given by

$$T = \frac{\lambda}{\sin \theta_1 + \sin \theta_2} . \quad (1)$$

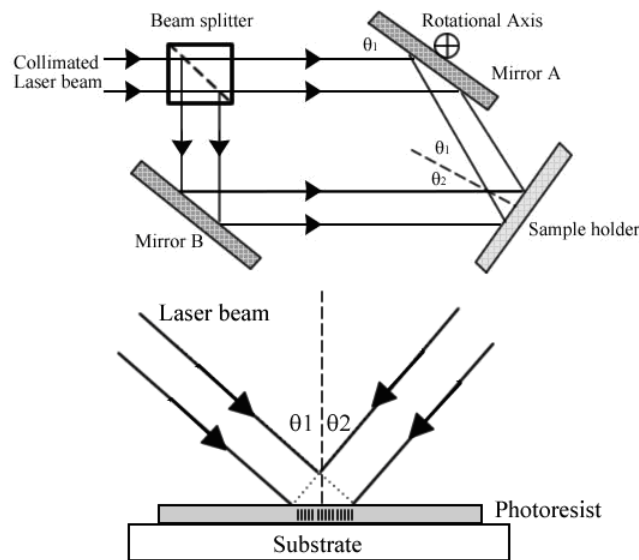


Fig.3. Schematic illustrations of holographic interference lithography system and showing patterning of PR layer to form periodic grating structure.

Step 2: Fabrication of optical grating and enhanced solar cell

The diffraction optical grating was manufactured by spin coating a thin layer of polydimethylsiloxane (PDMS) on the PR mold (see Step 1 in Fig.4). Following the curing process, the PDMS grating was simply peeled off the PR mold (see Step 2 in Fig.4) and then attached to a glass substrate. Spacers of an appropriate height were fixed on either side of the glass substrate. A solar cell (also attached to a glass substrate) was then positioned on top of the spacers, thereby forming a cavity between the solar cell and the PDMS grating. Liquid OG polymer was introduced into the cavity via capillary forces (see Step 3 in Fig.4) and was cured using UV light (see Step 4 in Fig.4). Finally, the PDMS grating was removed to leave the final OG grating / solar cell structure (see Step 5 in Fig.4).

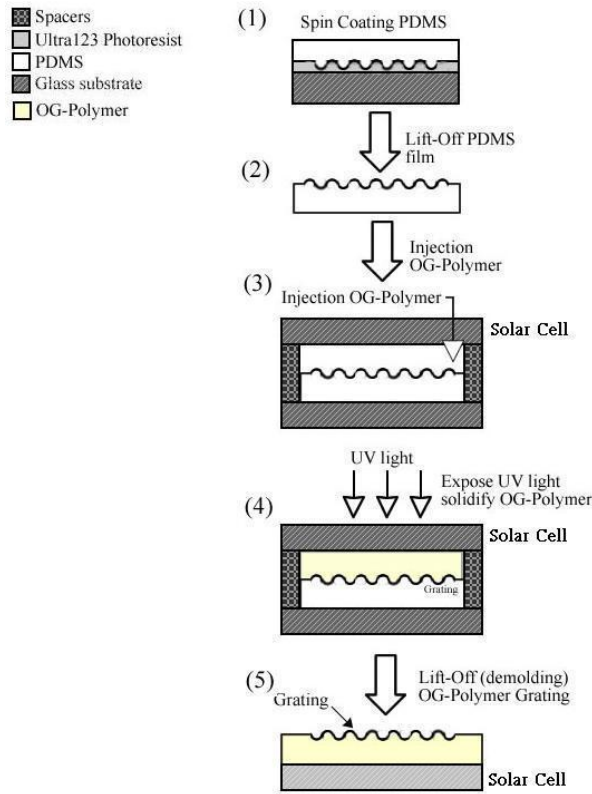


Fig.4. Schematic illustration showing fabrication of optical grating / solar cell structure.

2.2 Correlation between reflectivity, open circuit voltage and short circuit current of enhanced solar cell

The I-V characteristic curve of a solar energy cell is given by [12-15]

$$I_d = I_o \left[e^{\frac{V}{nV_T}} - 1 \right]. \quad (2)$$

In an open circuit scenario, the I-V characteristic curve can be expressed as

$$I = -I_{ph} + I_o \left[e^{\frac{V_{oc}}{nV_T}} - 1 \right] = 0 \quad (3)$$

Therefore, the open circuit voltage, V_{oc} , is given by

$$V_{oc} = V_T \ln \left(\frac{I_{ph}}{I_o} \right) \quad (4)$$

In Eq.(4), the current is determined by the intensity of the incident light (I), i.e. $I_{ph} = rKI$, where r is the reflectivity of the solar cell and K is a constant. Therefore, in the case shown in Fig.1 where the incident light reflected from the solar cell is re-directed by the optical grating such that it is incident once again upon the surface of the solar cell, the open circuit voltage, V_{oc} , is given as

$$V_{oc2} = V_{oc1} + V_T \ln\left(\frac{I_{ph2}}{I_{ph1}}\right) = V_{oc1} + V_T \ln\left(\frac{r_1 r_2 KI}{KI}\right) = V_{oc1} + V_T \ln(r_1 r_2). \quad (5)$$

Thus, the average open circuit voltage of the solar energy can be derived as

$$V_{ocav} = \sqrt{V_{oc1}^2 + V_{oc2}^2}. \quad (6)$$

The short circuit current of the enhanced solar cell varies with the intensity of the incident light in accordance with

$$I_{sc2} = I_{sc1} \left(\frac{r_1 r_2 KI}{KI}\right) = I_{sc1} r_1 r_2. \quad (7)$$

Therefore, the average short circuit current of the solar cell is given by

$$I_{scav} = \sqrt{I_{sc1}^2 + I_{sc2}^2}. \quad (8)$$

2.3. Fill factor (FF) and power conversion efficiency of solar cell

In theory, the output power generated by a solar cell is given by $P_{out} = I'V'$ and is equivalent to the trapezoidal area under the characteristic I-V curve. The output power of the solar cell increases as the intensity of the incident light increases and attains its maximum value at an output current of $I' = I_m$ and an output voltage of $V' = V_m$. In practice, however, the maximum current attainable from the solar cell is equal to I_{sc} while the maximum voltage is equal to V_{oc} . Thus, the actual output power generated by the solar cell is given by $I_{sc}V_{oc}$. The ratio of the maximum power point to the product of the short circuit current and the open circuit voltage is known as the fill factor (FF), and is defined as

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}. \quad (9)$$

Essentially, FF measures the extent to which the I-V characteristic curve of a practical solar cell approaches the ideal trapezoidal form. In an ideal world, FF has a value of 1. However, in practice, the p-n junction characteristics of the solar cell limit the output power, and thus FF usually has a value of around 70~80%, depending on the particular materials used to construct the solar cell device.

The power conversion efficiency of a solar cell is defined as the ratio of the maximum output power, P_m , to the power of the incident light, i.e.

$$\eta = \frac{P_m}{P_{in}} = \frac{I_m V_m}{P_{in}} \times 100\% = \frac{FF \cdot I_{sc} V_{oc}}{P_{in}} \times 100\%. \quad (10)$$

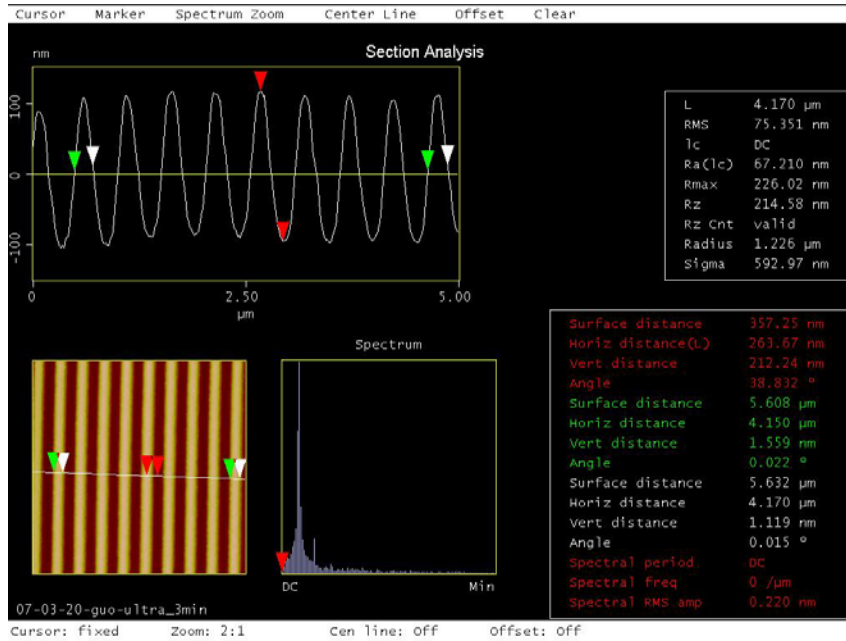
3. Experimental Characterization of Enhanced Solar Cell

3.1 Surface measurement of polymer diffraction optical grating

Next, we present a series of photographs of the enhanced solar cell fabricated in the current study. The surface characteristics of the OG-polymer diffraction grating were

examined using an atomic force microscope (AFM, Veeco/DI-3100), an optical microscope (OM), respectively.

Figures 5(a) presents 2D AFM image of the enhanced solar cell. From inspection, the spacing of the optical gratings is found to be $0.52 \mu\text{m}$, while the optical grating depth is 212.24 nm . Figures 5(b) presents OM image of the diffraction gratings.



(a)



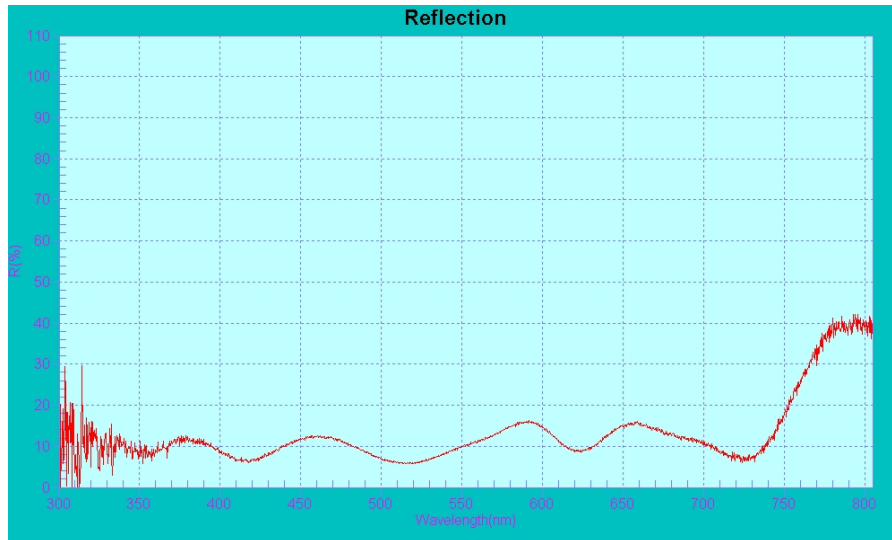
(b)

Fig. 5. (a) 2D surface measurement results obtained using AFM. (b) OM image of diffraction optical grating.

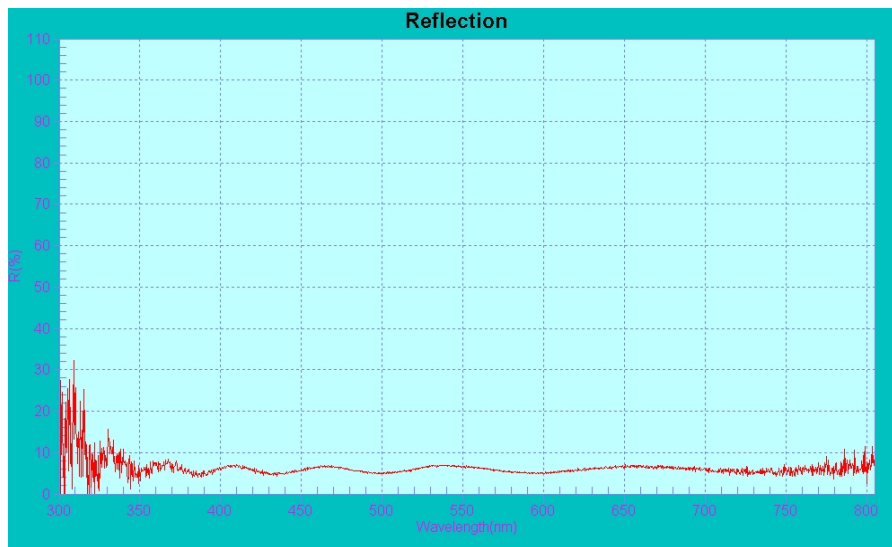
3.2 Measurement of reflectivity characteristics of enhanced solar cell

To quantify the effect of the diffraction optical grating on the power conversion efficiency, η , of the solar cell, experiments were performed to measure the reflectivities of a conventional solar cell and the optical grating, respectively, as a function of the wavelength of the incident light. The corresponding results are presented in the form of PL spectrographs in Figs. 6(a) and (b), respectively. The measured values of the reflectivity parameters r_1 (solar cell) and r_2 (optical grating) are indicated in Table 1. The value of 5.9% shown in Table 1 for the

reflectivity of the diffraction optical grating indicates that most of the incident light reflected from the solar cell is reflected by the optical grating and re-focused upon the solar cell surface, thereby improving the power conversion efficiency, η .



(a)



(b)

Fig.6. (a) Variation of reflectivity of conventional solar cell with incident light wavelength. (b) Variation of reflectivity of optical grating with incident light wavelength.

Table 1 Measured values of reflectivity parameters

	Reflectivity
Solar cell (r_1)	13.7%
Reflective-type diffraction optical grating (r_2)	5.9%

4. Results and Discussion

4.1 Conventional solar cell with no diffraction optical grating

Table 2 summarizes the experimental results obtained for the open circuit voltage, V_{oc} , short circuit current, I_{sc} , maximum output voltage, V_m , maximum output current, I_m , fill factor, FF , and power conversion efficiency, η , of the conventional solar cell when testing was performed under an air mass of 1 (AM1) with an input power, P_{in} , of $1000mW/m^2$.

Table 2 Parameter values of conventional solar cell

Parameters	Values
Open circuit voltage (V_{oc})	2.62 V
Short circuit current (I_{sc})	109.1 mA
Maximum output voltage (V_m)	2.5 V
Maximum output current (I_m)	108 mA
Fill factor (FF)	94 %
Power conversion efficiency (η)	27 %

4.2 Enhanced solar cell with diffraction optical grating

4.2.1 Open circuit voltage, V_{oc}

From Eq.(5), the open circuit voltage, V_{oc2} , of the enhanced solar cell with the diffraction optical grating was determined to be 2.5V. Therefore, the average open circuit voltage, V_{ocav} , was found from Eq.(6) to be 3.62V. Finally, the maximum output voltage, V_m , was determined from Eq.(11) to be 3.5V, i.e.

$$V_m = V_{oc} - V_T \ln \left(1 + \frac{V_m}{V_T} \right). \quad (11)$$

Fig. 7 plots the simulation results obtained using MATLAB software for the relationship between the open circuit voltage of the enhanced solar cell and the reflectivity of

the diffraction optical grating.

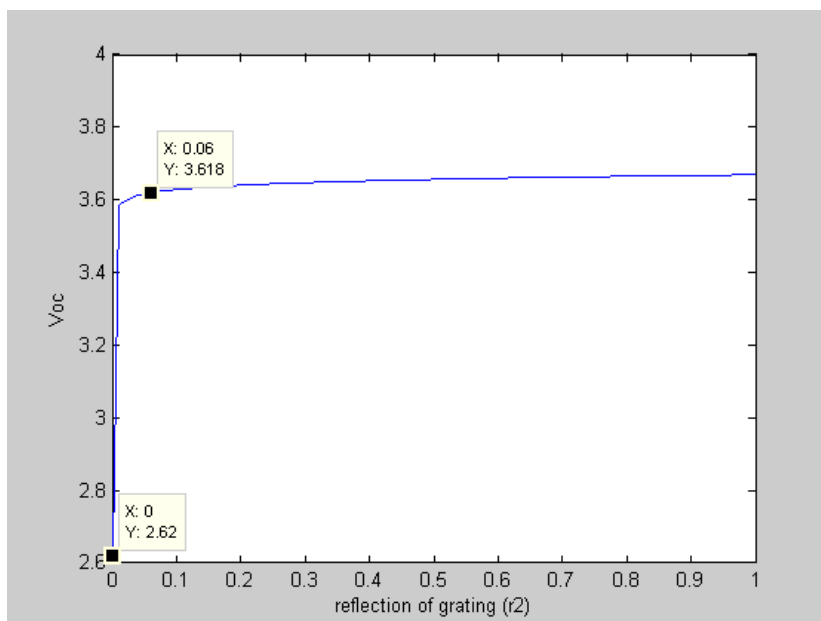


Fig.7. Variation of open circuit voltage, V_{oc} with reflectivity of gratings.

4.2.2 Short circuit current, I_{sc}

From Eq.(7), the short circuit current, I_{sc2} , of the enhanced solar cell was found to be 0.88mA. Thus, the average short circuit current, I_{scav} , was determined from Eq.(8) to be 109.1mA. Finally, from Eq.(12), the maximum output current, I_m , was found to have a value of 108mA, i.e.

$$I_m = I_{sc} \left(1 + \frac{V_T}{V_m} \right). \quad (12)$$

The relationship between the short circuit current and the reflectivity of the optical grating was simulated using MATLAB software, as shown in Fig.8.

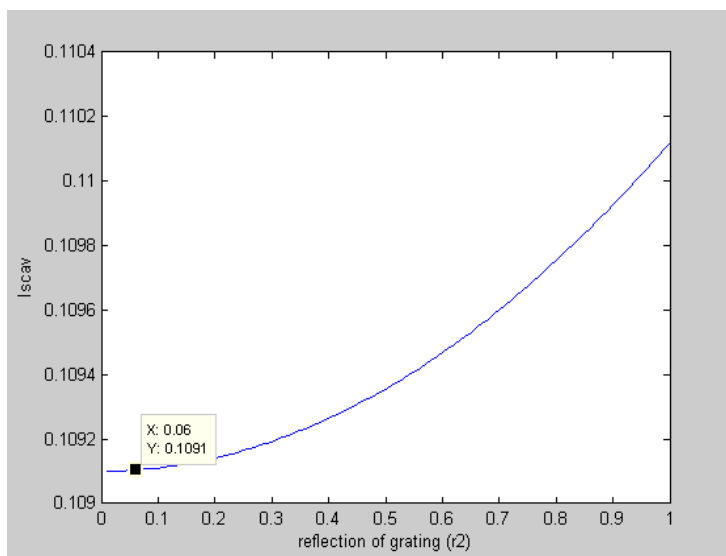


Fig.8. Variation of short circuit current, I_{sc} with reflectivity of gratings .

4.2.3 Fill factor and power conversion efficiency, η

In accordance with the values of the open circuit voltage, V_{oc} , short circuit current, I_{sc} , maximum output voltage, V_m , and maximum output current, I_m , presented above, the fill factor (FF) was determined to be 95.7%, while the power conversion efficiency, η , was found from Eq.(10) to have a value of 37.8%. Table 3 summarizes the experimental results obtained for the parameter values of the enhanced solar cell. Meanwhile, Fig.9 illustrates the MATLAB results for the variation of the power conversion efficiency, η , of the enhanced solar cell with the reflectivity of the grating.

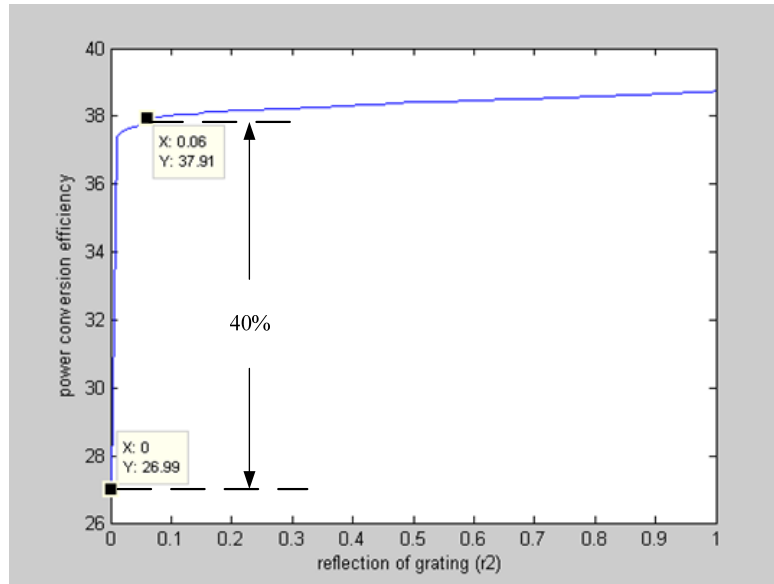


Fig.9. Variation of power conversion efficiency, η with reflectivity of gratings.

Table 3 Parameter values of enhanced solar cell

Parameters	Values
Open circuit voltage (V_{oc})	3.62V
Short circuit current (I_{sc})	109.1mA
Maximum output voltage (V_m)	3.5V
Maximum output current (I_m)	108mA
Fill factor (FF)	95.7%
Power conversion efficiency (η)	37.8%

Comparing Tables 2 and 3, it is found that the OG polymer diffraction optical grating with a reflectivity of 5.9% increases the open circuit voltage, V_{oc} , from 2.62 V to 3.62V,

improves the maximum output voltage, V_m , from 2.5V to 3.5V, and increases the power conversion efficiency, η , from 27% to 37.8%. Therefore, the effectiveness of the optical grating in improving the performance of the conventional solar cell is confirmed.

Figure 10 illustrates the variation of the reflectivity of the enhanced solar cell with an optical grating as a function of the wavelength of the incident light. From inspection, the average reflectivity is found to be 9.9 %. In other words, the addition of the reflective-type diffraction optical grating reduces the reflectivity of the conventional solar cell (see Table 1). Thus, it can be inferred that an increase is obtained in the net amount of light energy absorbed by the solar cell.

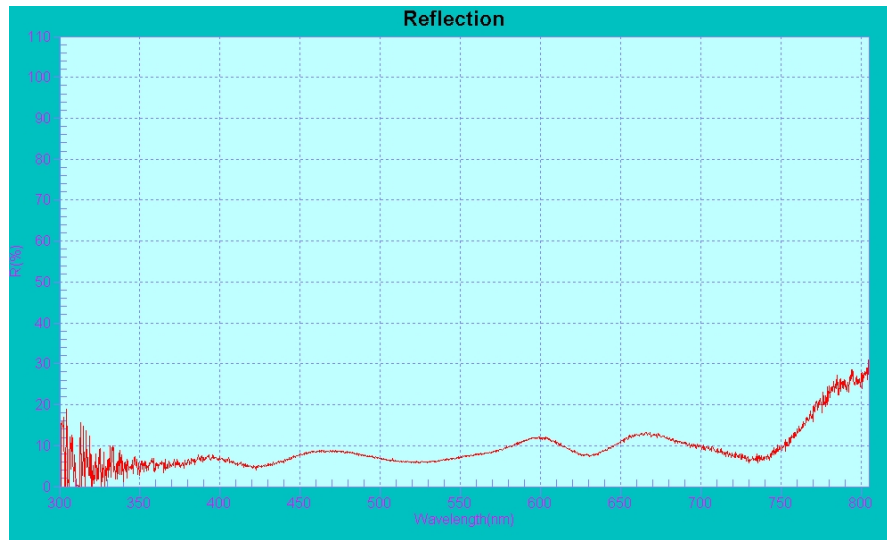


Fig.10. Variation of reflectivity of enhanced solar cell with diffraction optical gratings.

5. Conclusion

This study has presented a simple, low cost technique for improving the energy conversion efficiency of a solar cell. In the proposed approach, the incident light reflected from the solar cell is re-directed by a reflective-type diffraction optical grating such that it is refocused upon the surface of the solar cell. The experimental results have shown that the diffraction grating increases the open circuit voltage, V_{oc} , of the solar cell from 2.62V to 3.62V and improves the maximum output voltage, V_m , from 2.5V to 3.5V. As a result, the energy conversion efficiency of the solar cell, η , increases from 27%, to 37.8%, representing an improvement of approximately 40%.

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