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Table of contents

Volume 53
Number 5, September 2018
‹ Previous issue   Next issue ›

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A solar simulator using a LCD projector for students' laboratory

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Abstract
A low-cost solar simulator using a LCD projector as a light source has been developed and tested successfully. The prepared simulator has an illumination spectral at the visible light region and is controllable using a computer. The prepared simulator with controllable spectral filter was used to utilize the current–voltage (*I*–*V*) measurement for solar cell testing. The *I*–*V* measurement shows that the solar cells efficiency is about 20.49% for blue illumination to 9.05% for red illumination, it is caused by the photon energy of illumination on the solar cells from high to low energy. In addition, the illumination intensity changes all the solar cells parameters, including the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the fill factor (FF). However, due to its low-cost, easy-to-use and integrated spectral filters, the solar simulator could be improved for use in a research laboratory, especially for developing countries.

Introduction

Solar energy is a potential renewable energy that can be developed as these energy sources are relatively inexpensive and abundant [1, 2]. Some application devices that utilize solar energy include solar electrical, solar fuel or solar thermal [2, 3]. Therefore, it is important to develop the characteristic measurement of these devices using a solar simulator [4, 5]. A solar simulator is an illumination source that emulates natural sunlight characteristics and is commonly used to utilize the current–voltage (*I*–*V*) measurement system for solar cell testing [6]. Quartz tungsten halogen (QTH) lamps, Metal Halide arc lamps, Xenon arc lamps or light emitting diodes (LEDs) have been used as light sources in solar simulators system [7–9]. However, recent commercial solar simulators are high cost, need specific skills to use, have a high power consumption, and need additional tools such as spectra filters [7, 10]. Therefore, the development of a low-cost, easy-to-use solar simulator with integrated spectral filters is essential. The LCD Projector device has these characteristics and can potentially be used as a light source for the solar simulator. The LCD projectors commonly have a light source derived from QTH and red LEDs [11, 12]. Thus, a LCD projector has a wide output wavelength and is available in all visible light spectral. In addition, the LCD Projector has a color spectral filter that is controllable using a computer, laptop or another device [11]. Therefore, setting the color filter electronically is expected to set the spectral illumination output accurately.

This report relates to the development of the solar simulator system using the LCD projector, as a controllable spectral illumination source. Especially, the relationship between the illumination spectra and filter settings, as well as the illumination intensity of the solar simulator, will be measured. In addition, the current–voltage (I–V) properties of the solar cell under several of the illumination color spectra will be measured and discussed.

Methods and student instructions

A solar simulator using a LCD projector suitable for testing solar cells should satisfy the following requirements:

1. The electromagnetic spectra of the light source in the visible light region from 400 nm to 720 nm, similar to the dominant sunlight spectral characteristic.
2. The solar simulator performance in generating a specific light spectral plays an important and significant role. This will be strongly influence by the LCD projectors performance to filter of the specified illumination spectra.
3. The current–voltage (I–V) measurement of the solar cells should comprehensive enough to describe the entire working area of the solar cells.
4. The whole simulator should be low-cost and easy-to-use with an integrated spectral filter.

The spectral characterization of the illumination color

The spectral characterization of the illumination color of the LCD projector was measured to understand the electromagnetic spectra characteristic for several illumination colors such as white, blue, green, yellow and red as shown in figure 1. Spectral characterization devices consist of a commercial compact spectrometer (LEYBOLD® no. 467-251, German), LCD projector (EPSON 2265U WUXGA, Japan), and computer pre-installed presentation software such as MS PowerPoint®. Firstly, a presentation slide was prepared for white, blue, green, yellow and red backgrounds with a RGB color coordinate at (255, 255, 255), (0, 176, 240), (33, 255, 44), (255, 255, 0) and (255, 0, 0), respectively. Second, presentation slide was shown using the LCD projector so that the illumination color are determined and observed. Third, the spectral measurement and analysis were performed for every illumination color using a commercial compact spectrometer. In addition, the spectral measurements were also performed for the sun illumination at 12 o'clock, and compared with the white color spectra of the LCD projector.

The current–voltage (I–V) properties measurement system

The main physical characteristics of the solar cells are electrical characteristics, which are represented by a voltage–current (I–V) properties measurement under dark or illumination. The measurement of the solar cell electrical characteristics generally uses an I–V meter device [7]. Figure 2 is a schematic of the I–V meter device consisting of the current meter, voltage gauge, load resistance, solar cells, and solar simulator using a LCD projector. Current measurements are made by assembling the current meter, solar cells and variable resistor in series. Meanwhile, the voltage meter was arranged in parallel with the solar cells or variable resistor.

The I–V measurement consists of several steps: (a) prepare the solar cells testing apparatus in front of the LCD projector, (b) measure the specified illumination color power (P_{in}), (c) measure the I_{sc} and V_{oc} value of the solar cells directly with no load, (d) measure the voltage–current (I–V) properties of the solar cells by adjusting (up/down) the variable resistor. Furthermore, (e) the calculate the voltage–power output (V–P) curve characteristic of the solar cells using equation (1), by

$$P = I \times V \tag{1}$$

and, (f) the efficiency (η) and fill factor (FF) calculation of the solar cells using equations (2) and (3).

$$\eta\,(\%) = \frac{P_{out}}{P_{in}} \times 100\%, \text{ with } P_{out} \equiv P_{max} = I_{max} \times V_{max} \tag{2}$$

$$\mathrm{FF}\,(\%) = \frac{I_{max} \times V_{max}}{I_{sc} \times V_{oc}} \times 100\% \tag{3}$$

lastly, (g) perform the above steps for different of the illumination color (RGB) and white color intensity. Variation of white illumination intensity

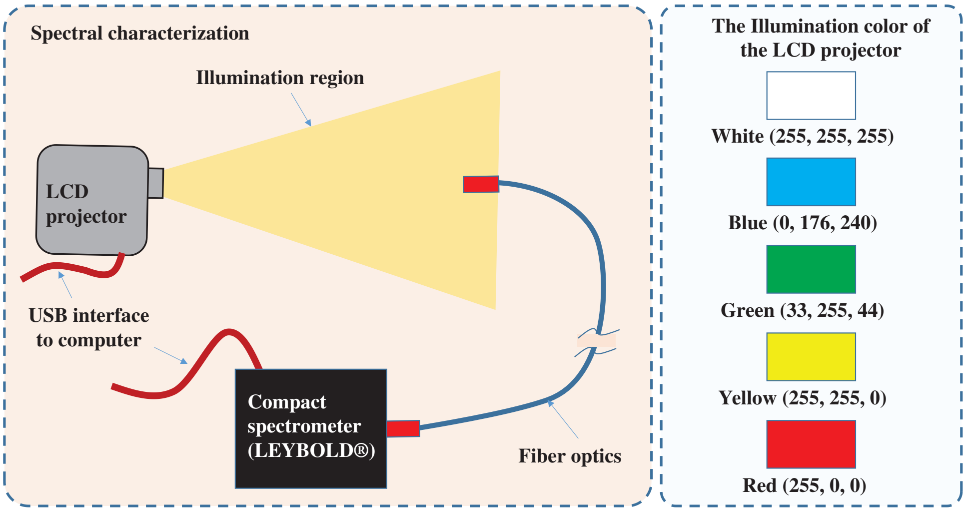

Figure 1. The spectral characterization for several of the illumination colors of the LCD projector.

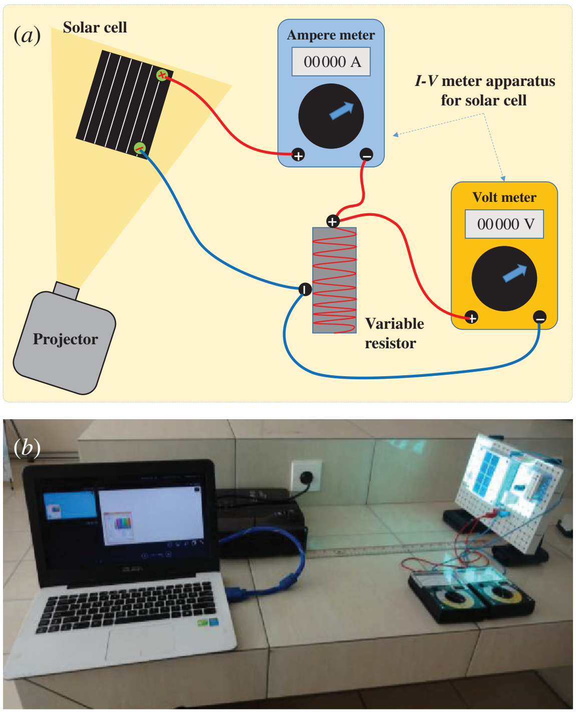

Figure 2. (a) The *I–V* measurement schematic, and (b) the *I–V* measurement prototype for solar cells tested with the LCD projector as the illumination source.

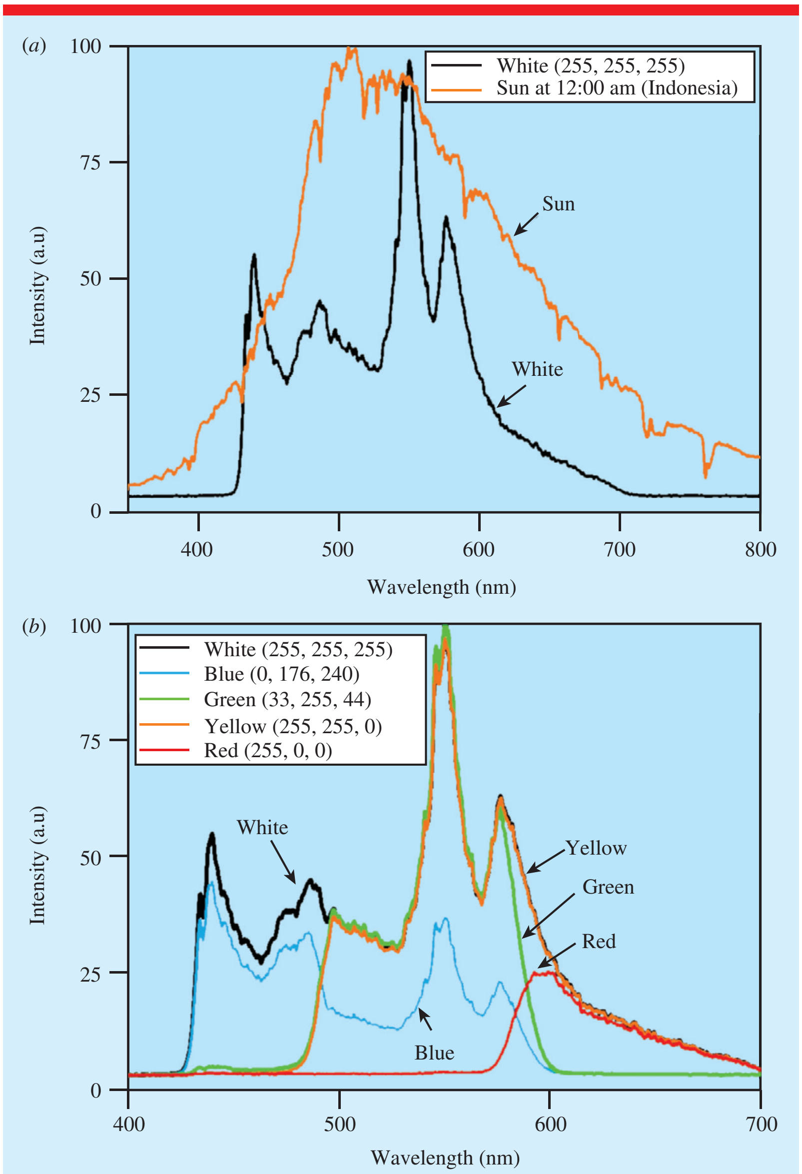

Figure 3. The spectral characteristic of (a) sun illumination at 12 am and white color, and (b) white, blue, green, yellow and red illumination color of LCD projector.

is obtained by varying the distance between the solar cell and the LCD projector.

Results and discussions

The spectral characteristic of the illumination color

Figure 3(a) is a spectral comparison analysis of the sunlight and several illumination colors from the LCD projector. The results show that sunlight has a dominant region at visible light up to the infra-red spectra from 350 nm to 1000 nm, with a peak at 531.3 nm. Meanwhile, the white illumination from the LCD projector has a spectral range in visible light ranging from 425 nm to 720 nm, with major peaks at 440.1 nm, 486.7 nm, 550.2 nm and 576.3 nm. Thus, the white-color spectral of the LCD projector is relatively similar to the visible light spectra from sunlight [11]. So, it is potentially used as a light source on solar simulators for *I–V* properties measurement of the solar cells. Figure 3(b) and table 1 are the spectral characteristic and properties for several of the illumination colors of the LCD projector. The observations show that blue spectra of illumination has a range of wavelength regions generated from 425 nm to 580 nm, with the main peak at 440 nm. The green and yellow illumination spectra have wavelength regions at 480 nm–580 nm and 480 nm–720 nm with the same peak at 550.2 nm, respectively. Meanwhile, the red illumination color spectra has a peak at 600 nm and wavelength regions at 560 nm–720 nm. These results indicate that the function of the color filter on the LCD projector was successful in filtering and controlling a specific wavelength region output.

Table 1. Spectral properties for several of the illumination colors of the LCD projectors and sunlight.

No.	Illumination color	Spectral range (nm)	Spectral peak (nm)
1	White	425–720	5502
2	Blue	425–580	4401
3	Green	480–580	5502
4	Yellow	480–720	5502
5	Red	560–720	600
6	Sunlight illumination	350–1100	5313

The current–voltage (I–V) properties of the solar cells

Figure 4 shows the *I–V* characteristics of the commercial solar cells (with an active area of 10 × 5 cm^2) for several of the illumination colors. In this work, the color illuminations of the LCD projector were varied from blue to red. The electrical characteristic of the solar cells for several of the illumination colors is summarized in table 2. The solar cells on the white illumination had an open-circuit voltage (V_{oc}) of 2.02 V, a short-circuit current (I_{sc}) of 30.4 mA, a FF of 58.15% and efficiency (η) of 18.45%. The highest solar cell efficiency was achieved by the blue illumination color of 20.49%, with a FF of 50.43%. Furthermore, the efficiency of the solar cells achieved by the green, yellow and red illumination color are 14.51%, 12.84%, and 9.05%, respectively. This result agrees with the spectral response of silicon-type solar cells [10]. In figure 5, the efficiency (η) and FF of the solar cells are designed counter to illumination color of the light source. The efficiency performance of the solar cells changes from 20.49% (blue illumination) to 9.05% (red illumination) primarily caused by changing the photon energy of the illumination on the solar cells from high to low photon energy [13, 14]. Where the high excited electrons (high V_{oc}) were generated by the blue illumination, but the low excited electron (low V_{oc}) were generated by the red illumination. As a result, the energy conversion efficiency (η) of the solar cells are determine by the illumination color. Meanwhile, the solar cells show the highest FF reaching an impressive for 58.15% under white illumination, with an average at 51% for other illumination colors. The FF value describes the value of the idealization of the solar cell to the diode characteristics; high FF values show the electrical characteristics of the solar cells are more like an ideal diode. This result shows that the difference of the solar cells performance to the illumination color is determined by matching the spectral response to the illumination spectra.

To determine the effect of photon quantity (light intensity) on electrical characteristics of the solar cells, it is necessary to measure the *I–V* characteristic of the solar cell at several of the white illumination from the LCD projector. The *I–V* characteristic and power output of the solar cells for several of the white illumination intensity is shown in figure 6. The results show that the illumination intensity changes all the solar cell parameters, including the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the FF as shown in figure 7(a) and table 3. It is because of the solar cell performance was greater affected by the series resistance at high intensity and the shunt resistance at low light intensity, respectively [13]. Meanwhile, the result shows that the efficiency of the solar cells has a linear relation with the illumination intensity, which is related to the photon quantity of the illumination

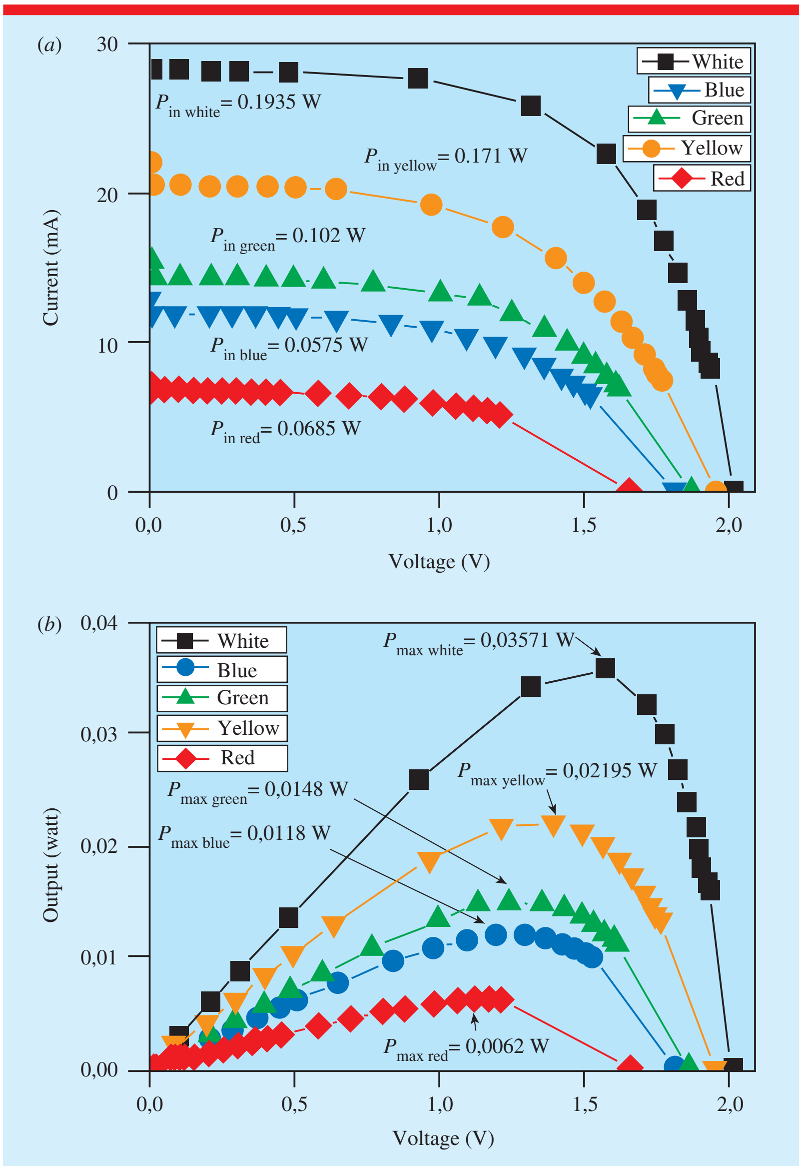

Figure 4. (a) The *I–V* curve characteristic, and (b) power output properties of the solar cells for white, blue, green, yellow and red illumination colors from the LCD projector.

(see equation (4)). The open voltage (V_{oc}) of the solar cells shows a logarithmic trend dependence on the illumination intensity and follows very closely to the basic diode model of equation (5), as shown in figure 7(b). This trend is similar to earlier reports for both *p–n* and *p–i–n* solar cells, such as polycrystalline silicon solar cells [14]. The relation of efficiency and open-circuit voltage as a function of illumination intensity describe by [13],

$$\eta \approx K_E \times E \tag{4}$$

$$V_{oc} \approx V_{ocn} + \frac{nkT}{q} \ln\left(\frac{E}{E_n}\right). \tag{5}$$

Where E_n and V_{ocn} are the illumination intensity and open circuit voltage under normal sun intensity conditions.

The electrical characteristic of the solar cells under sunlight exposure is shown in figure 8. The

Table 2. The electrical properties (current–voltage, *I*–*V*) of the solar cells for several of illumination colors.

Illumination color	I_{sc} (mA)	V_{oc} (V)	I_{max} (mA)	V_{max} (V)	P_{in} (watt)	P_{out} (watt)	η (%)	FF (%)
White	30.40	2.02	22.6	1.58	0.194	0.0357	18.45	58.15
Blue	12.84	1.82	9.82	1.2	0.058	0.0118	20.49	50.43
Green	15.45	1.87	11.84	1.25	0.102	0.0148	14.51	51.23
Yellow	22.10	1.96	15.68	1.4	0.171	0.0219	12.84	50.68
Red	7.20	1.66	5.3	1.17	0.069	0.0062	9.05	51.88
Sun	290	2.23	270	1.17	1.620	0.4312	25.4	73.89

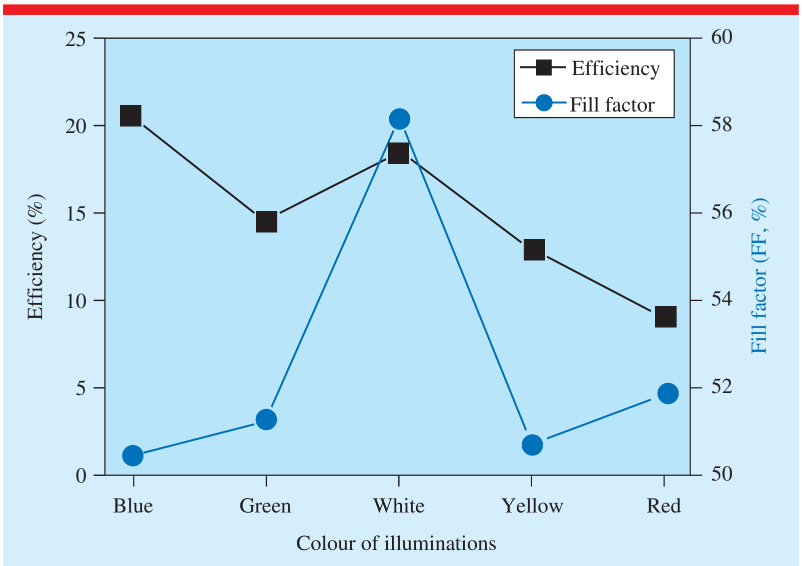

Figure 5. Solar cell properties for several illumination colors.

solar cells have an open-circuit voltage (V_{oc}) of 2.23 V, a short-circuit current (I_{sc}) of 290 mA, a FF of 73.89% and efficiency (η) of 25.4%. These results show that the solar cells under sunlight exposure have strong diode characteristics (high FF) and high conversion (η) values. This is because the sunlight has a broad and complete range of the visible light spectra, so that the conversion of photons to electrons formed is significant. In addition, the high intensity of the sunlight in solar cells causes the value of I_{sc} to increase significantly and V_{oc} is greater than when using the LCD projector as a light source. This result is in accordance with the discussion in the previous section, which

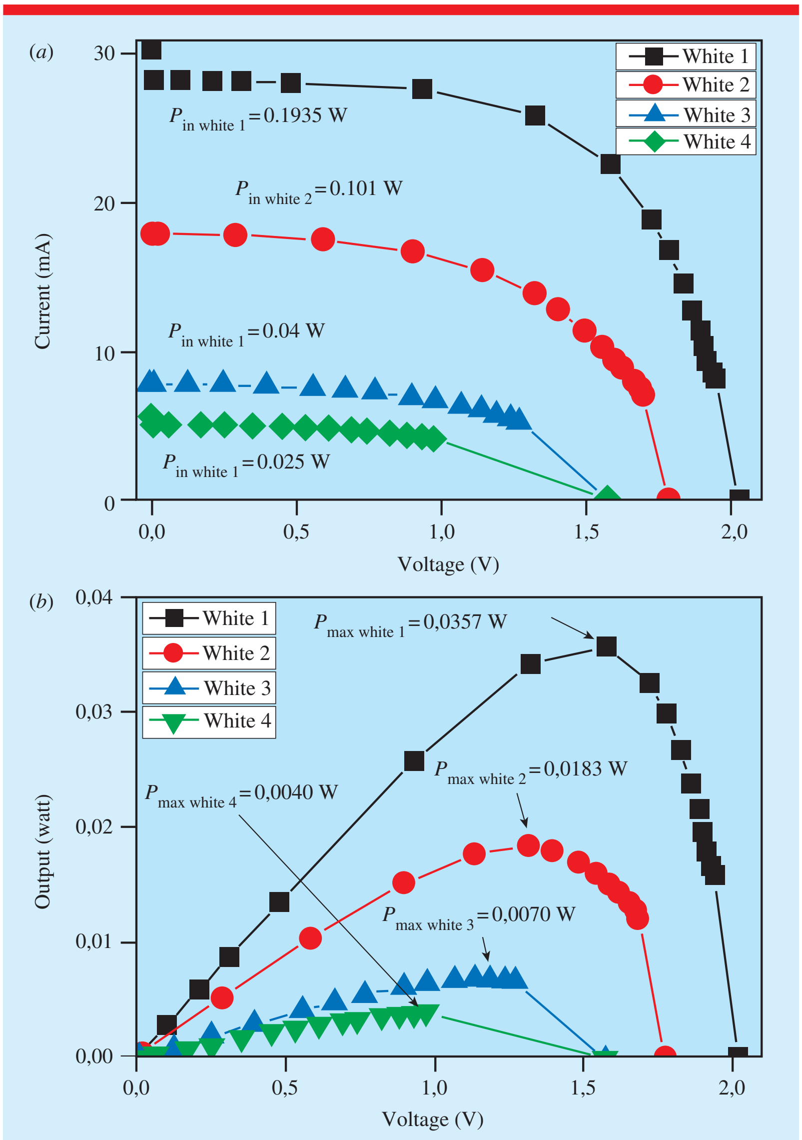

Figure 6. (a) *I–V* curve characteristic, and (b) power output properties of the solar cells for various of the illumination intensity (P_{in}) of white colors.

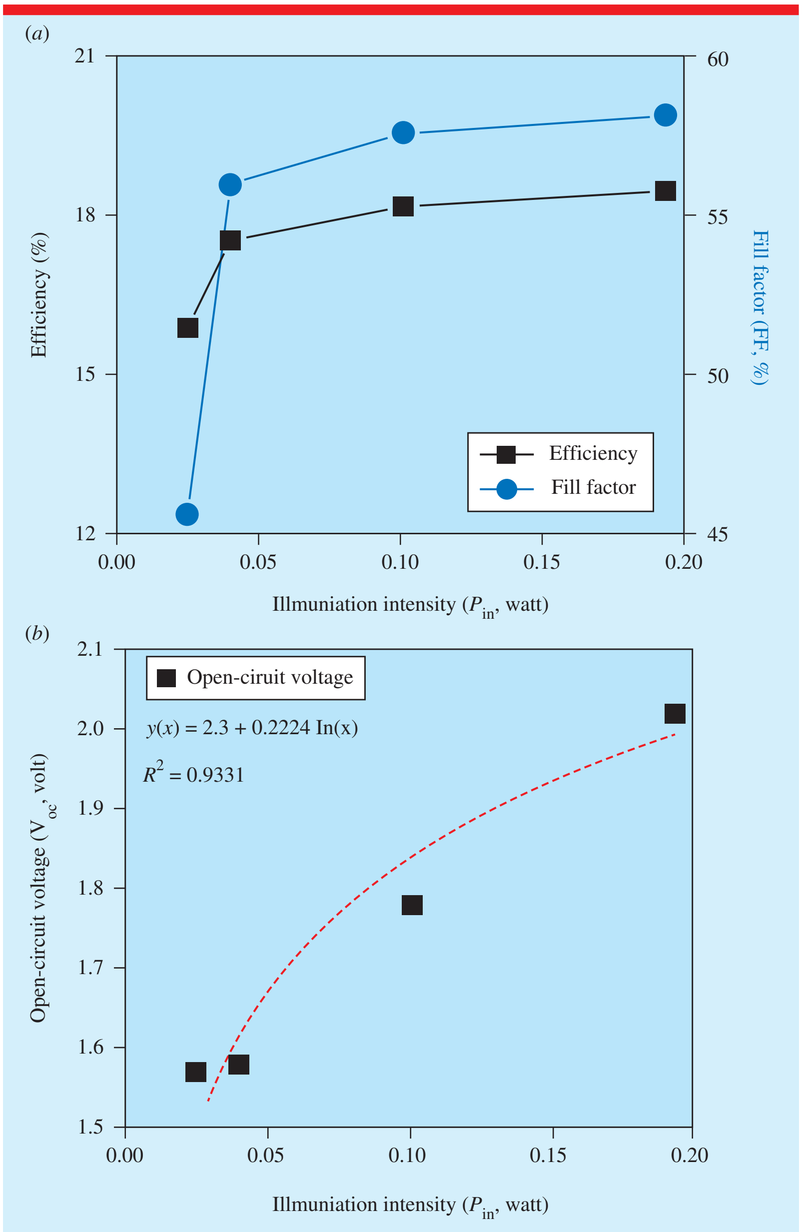

Figure 7. (a) The solar cells properties, and (b) the relation of the open-circuit voltage (V_{oc}, volt) as a function of the illumination intensity (P_{in}, watt) of the white colors.

Table 3. The electrical properties (current–voltage, I–V) of the solar cells for several of the illumination intensity (P_{in}) of white colors.

Illumination intensity	I_{sc} (mA)	V_{oc} (V)	I_{max} (mA)	V_{max} (V)	P_{in} (watt)	P_{out} (watt)	η (%)	FF (%)
White 1	30.4	2.02	22.6	1.58	0.194	0.0357	18.45	58.15
White 2	17.9	1.78	13.9	1.32	0.101	0.0183	18.17	57.59
White 3	7.93	1.58	6.15	1.14	0.04	0.0070	17.53	55.96
White 4	5.54	1.57	4.09	0.97	0.025	0.0040	15.87	45.61

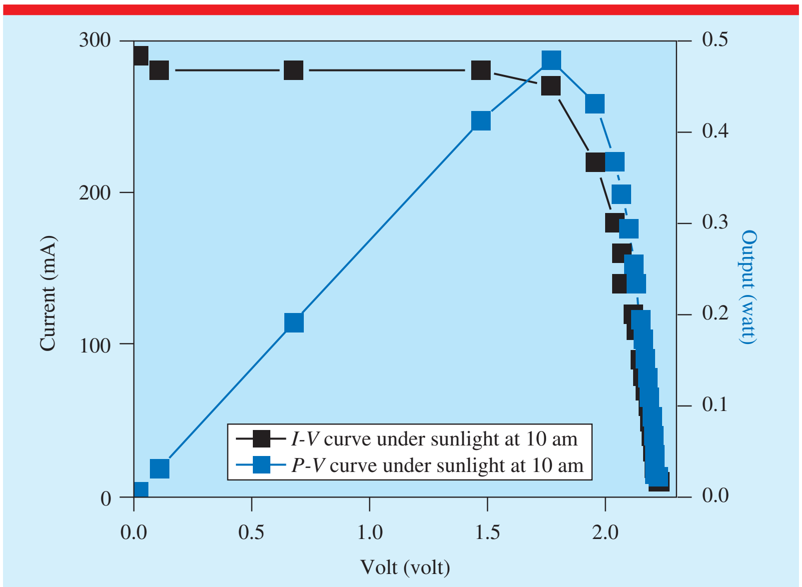

Figure 8. The *I–V* curve characteristic and power output properties of the solar cells under sunlight exposure at 10 am.

successfully showed that the spectrum and the intensity of light sources significantly affect to the electrical characteristics of solar cells.

Conclusions

A low-cost solar simulator using a LCD projector as light source has been developed and tested successfully. The relationship of the illumination spectral and filter settings, as well as the illumination intensity of the solar simulator has been measured and discussed. The prepared simulator with a controllable spectral filter was used to utilize the current–voltage (*I–V*) measurement for solar cell testing. The *I–V* measurement shows that the solar cells efficiency is about 20.49% for blue illumination to 9.05% for red illumination; it is caused by the photon energy of illumination on the solar cells from high to low energy. In addition, the illumination intensity changes all the solar cell parameters, including the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the FF.

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