Solar PV output under different wavelength of light: A Simulation Based Study

Md. Shazzadul Islam
Email-shazzadulislam89@gmail.com
Global University Bangladesh

Muhammad Fayyaz Khan
fyk@green.edu.bd
Green University Bangladesh

Md. Sahidul Islam
Email-sahid.eee1@gmail.com
Global University Bangladesh

***Abstract*— Solar PV output depends on intensity of light. This output varies with the hourly position of the sun as well as density of cloud, moisture, suspended particles in the atmosphere etc. Other than visible light waves, low and high frequency waves above and below the visible range also create energy output through solar PV. In this paper solar PV output under different wavelengths of light has been studied under P-Spice environment. It has been found that output solar PV under low frequency of light is quite appreciable and higher than normal sunlight of intensity. If such light waves are allowed to fall on solar PV through filter enhanced output from solar PV can be attained. Analytical model of PSpice is used to conduct this analysis.**

***Keywords*— Solar PV, P-Spice, Color light, Insolation, fill factor, efficiency, photon energy.**

I. INTODUCTION

Photovoltaic system refers to the technology that converts solar energy directly into electricity, through the use of Solar cells. The main parameters that are used to characterize the performance of solar cells are the short-circuit current density Jsc, the open circuit voltage Voc, the maximum power Pmax, and the fill factor FF. Sunlight is a portion of electromagnetic radiation, in particular infrared, visible, and ultraviolet light. Solar radiation incident on the Earth's atmosphere is relatively constant, the radiation at the Earth's surface varies widely due to atmospheric effects. The sun's very high temperature is due to the nuclear fusion reaction of hydrogen into helium. Every second, 6×10^{11} Kg H_2 is converted to 4×10^{3} Kg He. The difference in mass is called mass loss. It is converted into energy which, according to Einstein's relation $E=mc^2$, is equal to 4×10^{20} J. This energy is emitted as electromagnetic radiation. Its wavelength spans the ultraviolet and infrared region (0.2 to 3µm) [1] [2]. The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length [3]. The standard spectrum at the Earth's surface is called AM1.5G.The Sun emits white light includes all colors of the visible spectrum and ranges in wavelength from about 380 nm to about 750 nm. The aim of this study is to investigate the effect of different color of the sunlight on solar PV output.

II. ANALYTICAL SOLAR CELL MODEL

Photovoltaic systems (PV) are made from semi conducting materials. Most significantly, semiconductor materials are used to make the solar cell is silicon. We have used an analytical model for the currents generated by an illuminated solar cell, because a simple PSpice circuit can be written for this case, and by doing so, the main definitions of three important solar cell magnitudes and their relationships can be illustrated. These important magnitudes are: spectral short circuit current density, quantum efficiency and spectral response. The simplified equation governing the current of the solar cell is given by:

$$j = j_{sc} - j_o\left(e^{\frac{V}{V_T}} - 1\right)$$

Where J_{sc} is the short circuit current density and j_o is the saturation current [4]. The total short-circuit current generated by the solar cell is the wavelength integral of the short circuit spectral density current, as follows:

$$j_{sc} = \int_0^\infty j_{sc\lambda}\, d\lambda$$

The unit of short circuit current density is A/cm^2. Quantum efficiency is an important solar cell magnitude which is defined as the number of electrons produced in the external circuit by the solar cell for every photon in the incident spectrum. Two different quantum efficiencies can be defined, internal and external [5], as

$$\mathrm{IQE} = \frac{J_{SC\lambda}}{q\varphi_0(1-R)}$$

$$\mathrm{EQE} = \frac{J_{SC\lambda}}{q\varphi_0}$$

Where φ_0 is photon flux and R is reflection coefficient. The open circuit voltage, V_{oc} can be given by

$$V_{oc} = V_T \ln\left(1 + \frac{J_{sc}}{J_0}\right)$$

Where V_T is thermal voltage, J_0 is reverse saturation current density. The spectral response of a solar cell is defined as the ratio between the short circuit spectral current density and the spectral irradiance.

$$\mathrm{ISR} = \frac{J_{sc\lambda}}{I_\lambda(1-R)} = 0.808 \cdot (\mathrm{IQE}) \cdot \lambda$$

$$\mathrm{ESR} = \frac{J_{sc\lambda}}{I_\lambda} = 0.808 \cdot (\mathrm{EQE}) \cdot \lambda$$

Maximum power point (MPP) with the coordinates V =Vm and I= I_m. A relationship between V_m and I_m can be derived,

$$I_m = I_L - I_O\left(e^{\frac{V_m}{V_T}} - 1\right)$$

$$V_m = V_{OC} - V_T \ln\left(1 + \frac{V_m}{V_T}\right)$$

A parameter called fill factor (FF) is defined as the ratio between the maximum power P_{max} and the V_{oc} , I_{oc} product:

$$\mathrm{FF} = \frac{\mathrm{V_m I_m}}{\mathrm{V_{oc} I_{oc}}}$$

Where V_m I_m is maximum power point (MPP).The power conversion efficiency η is defined as the ratio between the solar cell output power and the solar power[6] intruding the solar cell surface P_{in}.

$$\eta = \frac{\mathrm{V_m I_m}}{P_{in}} = \mathrm{FF}\frac{\mathrm{V_{oc} I_{oc}}}{P_{in}} = \mathrm{FF}\frac{\mathrm{V_{oc} I_{oc}}}{\mathrm{G}}$$

As can be seen the power conversion efficiency of a solar cell is proportional to the value of the three main photovoltaic parameters: short circuit current density, open circuit voltage and fill factor, for a given irradiance G. The ideal solar cell model shown in figure1.

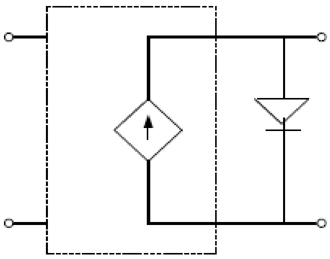

Figure 1: Ideal solar cell model

Table 1. Main parameters [8] involved in the analytical model and assumption.

Name	Value
Spectral irradiance	AM 1.5 G ($W/m^2\mu m$)
Material	silicon
Reflectance (R)	10% of all wavelength
We (emitter thickness)	0.33mm
Wb (Base thickness)	300µm
A (Area)	$126.6cm^2$
Lp (Hole diffusion length in the emitter layer)	0.43µm
Se(Emitter surface recombination velocity)	$2x10^5$ cm/s
Dp (Hole diffusion constant in the emitter layer)	3.4 cm^2/s
Ln (Electron diffusion length in the base layer)	162µm
Sb (Base surface recombination velocity)	1000 cm/s
Dn (Electron diffusion constant in the base layer)	36.33 cm^2/s

Table 2: Wavelengths of electromagnetic radiation

Color	Wavelength	Photon energy
UV	100-380 nm	3.26 - 124 eV
VISIBLE	380-750 nm	1.65 - 3.26 eV
INFRARED	750-1200 nm	0.0012 - 1.65 eV

III. RESULT AND DISCUSSION

There are different types of air mass spectrum available in the earth space. But standard air mass spectrum in the earth is AM1.5G.So for our whole analysis we used this data. In this paper we used ideal solar cell model because our main objective is to how a PV cell response for different wavelength of sunlight. All simulated result are presented by graphically and in tabular form. White light of sun in the earth space is combination of UV, VISIBLE and INFRARED wavelengths. In this paper we mainly focus on effect of PV output for different color of visible light. Visible of sun is the combination of six color and each color of light have different wavelength. So our prime concern is how PV cell affected by this six color of visible light. Different wavelengths of visible light [7] shown in table 3.

Table 3: Wavelengths of visible light

Color	Wavelength	Photon energy
Violet	380-450 nm	2.75-3.26 eV
Blue	450-495 nm	2.50-2.75 eV
Green	495-570 nm	2.17-2.50 eV
Yellow	570-590 nm	2.10-2.17 eV
Orange	590-620 nm	2.00-2.10 eV
Red	620-750 nm	1.65-2.00 eV

A. PV output for UV and INFRARED wavelength

Wavelengths of ultraviolet and infrared do not have sufficient energy to free the electrons and are absorbed as heat. Figure 2 shown in J_{SC} (short circuit current density) for UV wavelength.

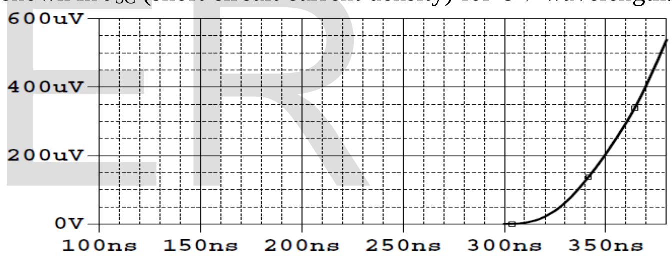

Figure 2: J_{SC} vs UV wavelength

x-axis is the wavelength in nanometer and the y-axis is the integral of the spectral short circuit current density (in mA/cm^2 units).From this figure it is clear that J_{SC} is very low for UV rays and almost zero for wavelength less than 300 nm. At shorter wavelengths and higher energies, silicon electrons will get energized and current will flow. When a photon of higher energy impacts a solar cell, energy above 1.1 eV is given off as heat. This loss is called thermalization loss.

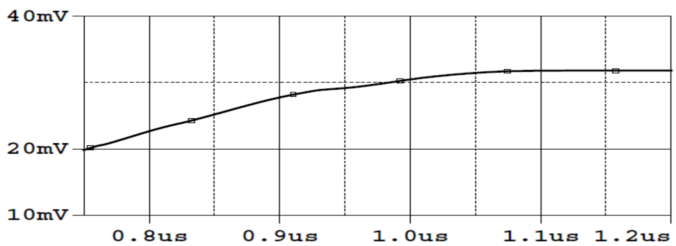

Figure 3:J_{SC} vs infrared radiation

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But for infrared radiation of sun light short circuit current density is increases (shown in figure 3) but here there is a problem occurred. Quantum efficiency and fill factor decreases with the increase of wavelength (shown in figure 4).

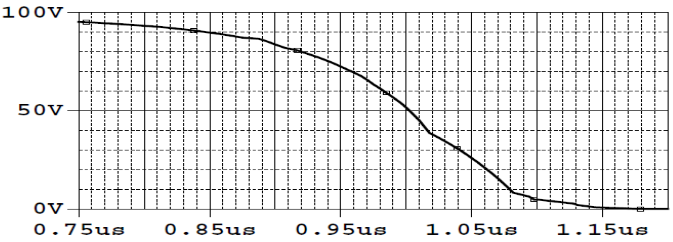


Figure 4: internal quantum efficiency

Figure 4 is a plot of internal quantum efficiency y-axis is % and x-axis is the wavelength in microns. Internal quantum efficiency decreases because photon energy of infrared wavelength is much lower than bandgap energy.

Table 4: output for UV and infrared radiation

Type	Jsc(mA/cm^2)	IQE	FF
UV	.537	0 to 70%	0.795
INFRARED	31.81	95% to 0	.521

B. PV output for Visible light

From table: 3 range of visible light is 380 to 750 nm so photon energy of this ranges varies between 1.65 - 3.2 eV. For an ideal silicon solar cell band gap is 1.11 eV, that's why visible light plays an important role on Photovoltaic Cell Electricity Generation. For a solar cell, the electrical output voltage is a function of the temperature, Intensity and color of the incident light. Now in this section we want to show that effect of six color of visible light (violet to red) on PV output.

B1. *PV output for Violet color*

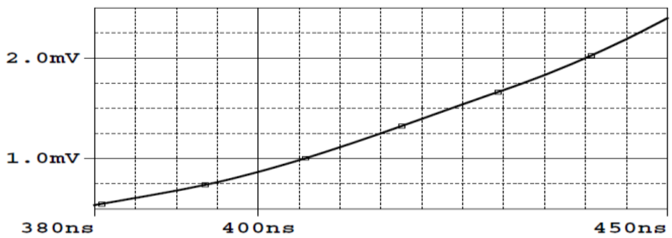


Figure 5:J_{SC} vs wavelength

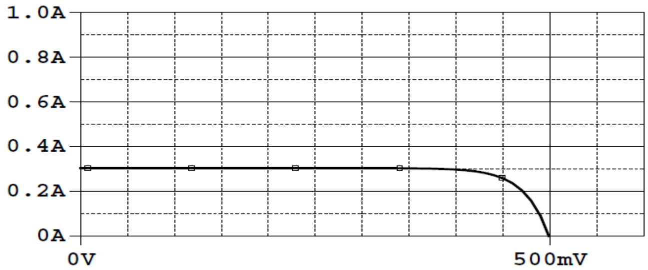


Figure 6: I (V) characteristics

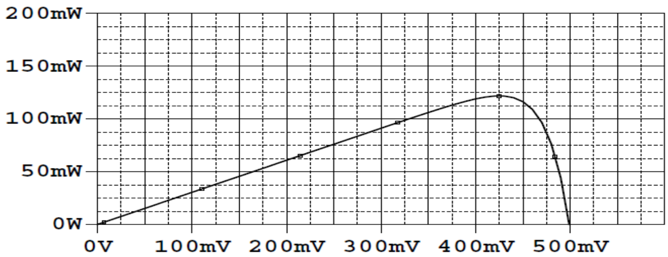


Figure 7: Power curve

Photon energy for violet color varies between 2.75 to 3.75 eV that's why excess energy transform in the form of heat, as a result J_{SC} is very low.

B2. *PV output for Blue color*

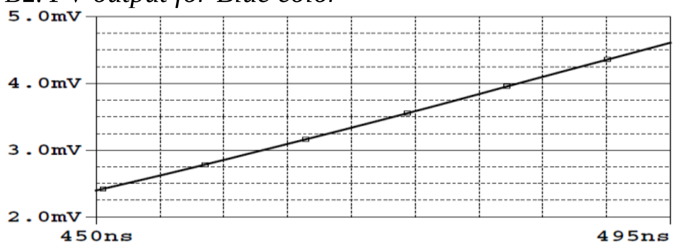


Figure 8:J_{SC} vs wavelength

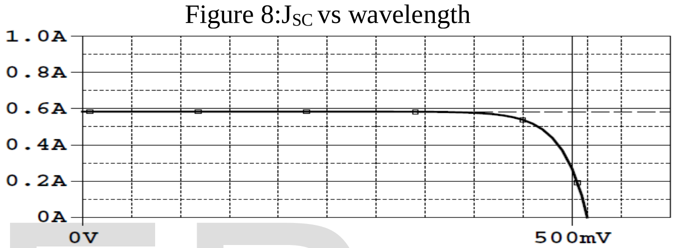


Figure 9: I (V) characteristics

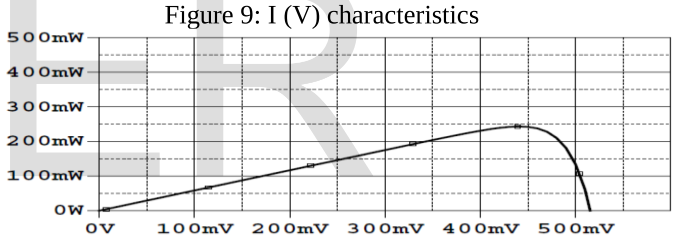


Figure 10: Power curve

For blue color J_{SC} tends to increase and also V_{OC} respectively because here photon energy is lower than blue color.

B3. *PV output for Green color*

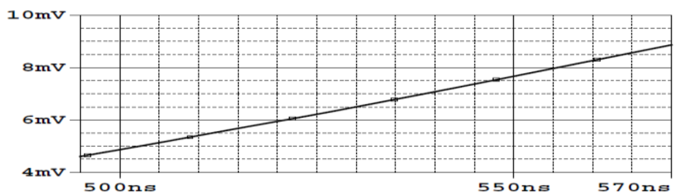


Figure 11:J_{SC} vs wavelength

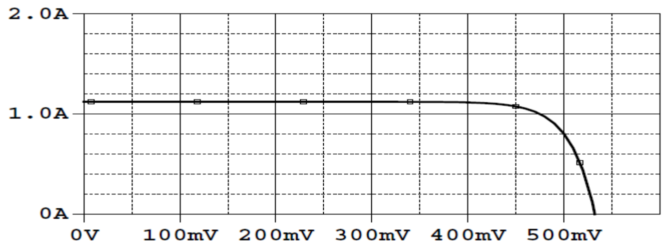


Figure 12: I (V) characteristics

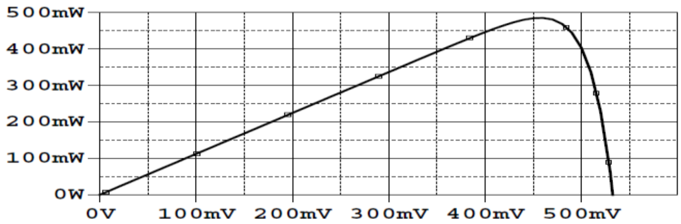


Figure 13: Power curve

From figure 11, 12, 13 we have to observe that when J_{SC} increases than V_{OC} increase slightly but power increases rapidly.

B4. *PV output for Yellow color*

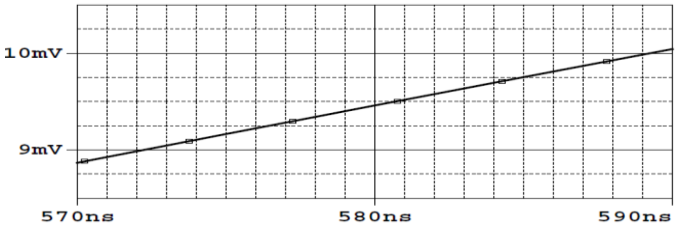


Figure 14:J_{SC} vs wavelength

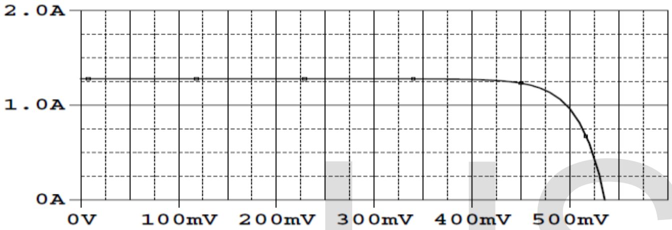


Figure 15: I (V) characteristics

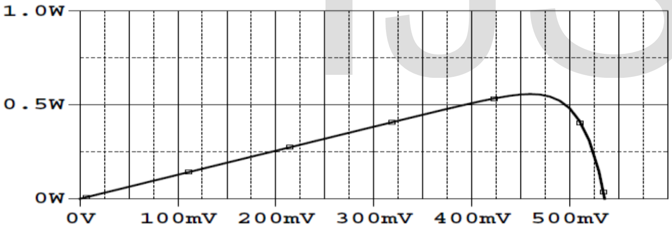


Figure 16: Power curve

In this spectrum photon energy varies between this 2.10-2.17 eV ranges so the ratio absorption of photon is increases correspondingly. There is a limitation the open circuit voltage never cross beyond the band gap of the material.

B5. *PV output for Orange color*

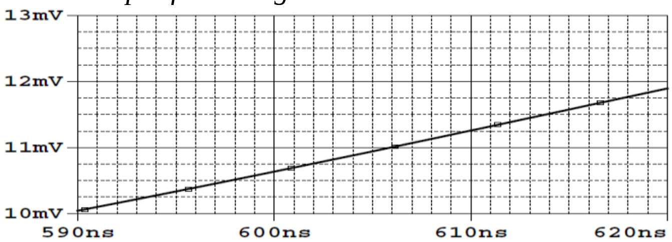
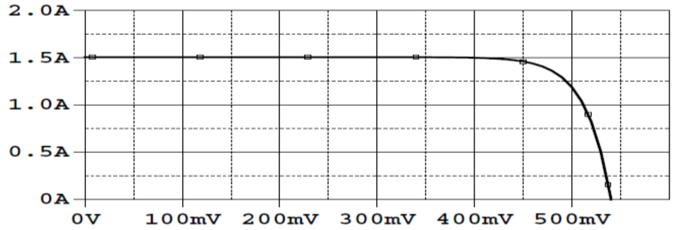


Figure 17:J_{SC} vs wavelength



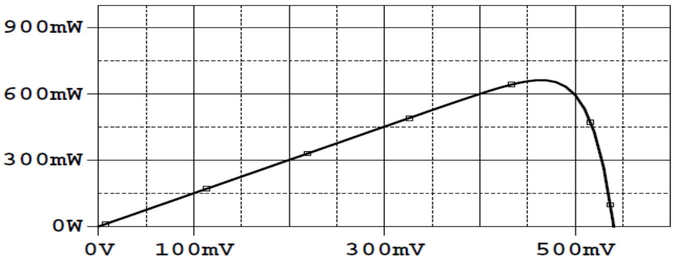


Figure 18: I (V) characteristics

Figure 19: Power curve

Form figure 17, 18, 19 we get clear information about photon absorption. For orange color photon energy range is 2.00-2.10 eV so this very close to yellow colors photon energy, that's why here overall performance is not increase much.

B6. *PV output for Red color*

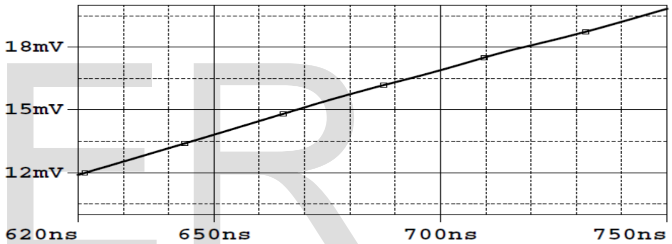


Figure 20:J_{SC} vs wavelength

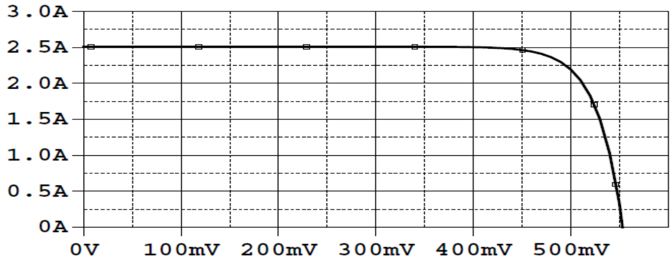


Figure 21: I (V) characteristics

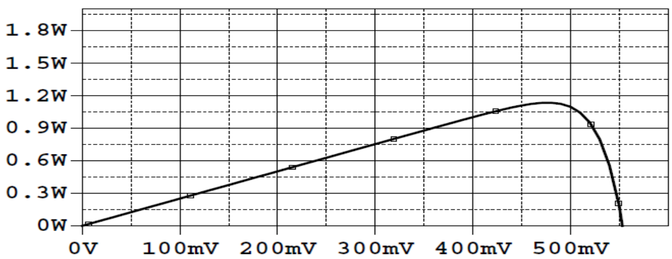


Figure 22: Power curve

Red color of the visible sun light it gives much more Output (shown in figure 20, 21, 22) than other visible color. For red color spectrum photon energy varies between 1.65-2.00 eV, so here we get less excess energy that's why creation of heat is less.

C. *PV output in tabular form*

Table 5:J_{SC} and V_{OC} of the visible light

Color	Short circuit current density J_{SC}(mA/cm^2)	Open circuit voltage V_{OC}(V)	IQE	SR(mA/W)
Violet	2.4	.500	87.27	317.85
Blue	4.61	.515	92.6	370.4
Green	8.86	.533	96	442.25
Yellow	10.1	.536	96.4	459.33
Orange	11.9	.540	96.5	483.675
Red	19.83	.553	95.1	576.22

Table 6: Maximum power point of solar cell for visible light

Color	V_m	I_m	I_{SC}(A)	P_m(w)
Violet	0.424	0.288	0.303	0.122
Blue	0.441	.551	0.584	0.243
Green	0.457	1.06	1.122	0.485
Yellow	0.460	1.21	1.28	0.557
Orange	0.469	1.41	1.51	0.662
Red	0.479	2.37	2.51	1.135

Table 7: Fill factor and efficiency of solar cell

Color	$FF=V_mI_m/V_{OC}I_{SC}$	η(%)
Violet	0.810	0.96
Blue	0.810	1.92
Green	0.810	3.83
Yellow	0.811	4.40
Orange	0.811	5.22
Red	0.817	8.99

Internal quantum efficiency for visible light varies "between" 87% to 96% (table 5 and figure 23) so it is clear that IQE is low for UV and Infrared wavelengths. Maximum IQE found from the Orange color light. For infrared wavelength IQE varies "between" 95% to 0% (shown in figure 5).

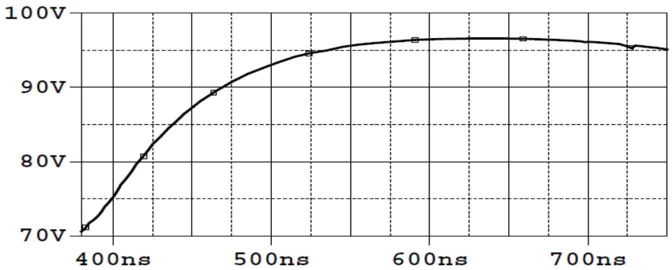


Figure 23: IQE for Visible light

Short circuit current density (J_{SC}) varies 2 mA/cm^2 to20mA/cm^2 but open circuit voltage (V_{OC}) is not changes much more shown in table 5 because open circuit voltage scales logarithmically with the short circuit current. This is also an important result indicating that the effect of the irradiance is much larger in the short circuit current than in the open circuit value. Table 6 and table 7 shows that maximum power, fill factor and efficiency. For maximum power need to calculate maximum voltage (V_m) and current (I_m). According to this results maximum efficiency of the visible light found for red color radiation. The change of fill factor for the visible light wavelengths is very low. For an ideal solar cell fill factor is 1 but practically 1 is not possible. So if the fill factor of the solar cell close to 1 than overall performance will be increase. The capacity of solar cell to taking energy is not just determined by the strength of the energy, but by the capability to detect light. If we use color filter to separate the different color from the visible wavelength spectrum, it means it is exposed to a light of specified wavelength: shorter for blue, medium for green and longer for red. After studying the data, it was resolute that the output of the solar cell in a state of sun light was significantly higher for visible light than any of the other colored light. Red had output significantly higher than others.

IV. Conclusions

Renewable energy sources will be productive insight for next generation, mainly solar energy and its products. The existing PSpice simulation results are a comprehensive study of solar cell modeling in ideal instance. The elementary equations of a solar cell are described. This paper studied a specific PV model to perceive the performance of the Photovoltaic solar cell under different wavelength of sunlight. P-Spice is very power full software to analysis the photovoltaic system. The objective of this article is to detect the wavelength and effect of color on performance of the solar cell. So after analyzing the data, it was decided that wavelength of sun light do affect the output of the solar cell. Red color produce more electricity than other. Longer wavelength of the visible light is more energetic than shorter wavelength. So we can say it efficiency of the solar cell mostly depends on visible color and also improved by exposure to red light. Future studies might research how to design solar cell for specific color of wavelength.

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