Study of Submerged Mono-and Poly-Crystalline Silicon Solar Cells with Split Spectral Ranges Using Optical Filters

To cite this article: Prasanth K. Enaganti and Sanket Goel 2020 ECS J. Solid State Sci. Technol. 9 075005

View the article online for updates and enhancements.
Submerged solar photovoltaic systems are one of the emerging technologies in underwater power systems. The development of submerged solar photovoltaics allows an environmentally-friendly design and delivery of a modern power generation system for marine electronic devices, navigation, defense purposes, and autonomous vehicles, etc. The prediction of the performance of a solar panel for a particular oceanic environment will be a challenge a priori. However, their studies demonstrate the ability of the solar photovoltaics in submerged power systems. The prospect of utilizing photovoltaic modules immersed in water or protected by a layer of water indicates the natural supply of green energy resources incorporated in swimming pools or decorating fountains and ponds.

In earlier work, it was found that single-crystalline silicon solar cells show increased efficiency at shallow depths. Also, the single-crystalline PV panels have been investigated in two different on-site locations with varying water depths as the performance of the solar panels depends upon the time of the day, solar radiation, and other environmental variations. While going deeper into waters, the solar spectrum itself alters and becomes narrower with increasing water depths. The solar spectrum transmitted by the air-water interface, the intensity gets slightly reduced in the short wavelength portion of the solar spectrum. At shallow depths, the longer wavelengths, a specific part of shorter wavelengths, gets modified, and the visible region remains the same. A study has been carried out to link the bandgap energy of the material with light intensity and its distribution by filtering the solar spectrum and reducing the solar radiation using a water flow lens. The spectra at low/low light intensities are predominant over the light intensity itself, and the water flow lens system shows a gradual increase in the photovoltaic response, which can further increase the performance of the solar cell.

A dye-sensitized solar cell was examined with different light intensities, such as the xenon, tungsten, and halogen lamp, and it was demonstrated that high efficiency was achieved at low intensity by maintaining the same light source and altering the intensity. In a recent finding, it has been demonstrated that organic solar cells are incredibly resilient and also work even in underwater conditions without encapsulation by selective removal of the electron acceptors from the top of the electrode. The high bandgap energy materials and an organic photovoltaic cell with multi-junction architecture consist of two absorber layers with a similar spectral response that can allow the sufficient transmission of the narrowed underwater spectrum.

In the recent study, it has been analyzed that both organic and inorganic wide bandgap semiconductors can be utilized as the absorbers to achieve high efficiency for solar cells in underwater applications. A case study at Petrolina city and the mathematical model with optical filters for the monocrystalline silicon module observed a 16% difference in the power output using the optical filter compared to the standard solar spectrum depending upon the environmental factors. Also, an optical filter reflecting higher than 1000 nm wavelengths showed between 1.1% and 6.8% gain in the energy generation from the monocrystalline silicon solar module. The first attempt made in splitting the spectrum with filters was on thermophotovoltaic systems to reduce the thermal losses in photovoltaic cells. Moreover, the spectrum splitting techniques provide a better spectral match between the source of light and solar cells and also to optimize the performance of the different solar cells from the selection of the solar spectrum. The evaluation of splitting the spectrum with various filters demonstrated the improvement in the performance of PV modules with ideal and experimental designs. Moreover, in underwater conditions, the spectral ranges get narrower, and the specific wavelengths in the spectrum contribute significantly to power generation from solar cells. In our study, we have split the spectral ranges using optical filters from the solar simulator to study the performance of the solar cells in underwater settings.

In exploring the usage of solar photovoltaics in marine environments, the recent findings from our group have explored the underwater solar photovoltaic cells by changing the water environments with pure water (deionized water) and with water impurities at shallow water depths up to 20 cm. Also, rigorous analysed with real seawater conditions and natural lake water have also been accomplished. Moreover, the studies were carried out with three different commercially available solar cells like the amorphous, mono- and poly-crystalline solar cells. However, based on our studies, we concluded that the solar cells in underwater conditions have enormous potential, especially for water monitoring and sensing applications. Besides, we believe that it can also be used for high-power applications because the decrease in power
Figure 1. (a) Overall experimental setup with solar simulator, (b) Submersible Pyranometer in water, (c) Submerged solar cell (d) with Short pass filter (SPF) (e) with Long pass filter (LPF) and (f) with a Bandpass filter (BPF).

Figure 2. Spectral irradiance of the (a) without filter, with (b) short pass filter (c) long pass filter (d) bandpass filter.
output with varying water depths can be improved by boosting the voltages with current technologies using advanced power electronic converters. In the present study, we have studied underwater mono- and poly-crystalline silicon solar cells with varying spectral ranges like the near UV, Vis, and IR regions from the Standard AM 1.5 solar simulator using optical colour glass filters. The obtained results manifest that with the limited spectral ranges also the mono- and poly-crystalline silicon solar cells showed better performance in underwater conditions.

Underwater Experimental System

The underwater experimental system was realized with a customized tank similar to our previous work, as shown in

![Figure 3](image-url)  
(a) Irradiation and (b) percentage decrease in irradiation with reference to the depth of the water using short pass filter.

![Figure 4](image-url)  
JV curves (a) Mono- (c) Poly-crystalline and PV curves (b) Mono- (d) Poly-crystalline using SPF.
Polydimethylsiloxane (PDMS) has been used for encapsulation to effectively protect solar cells in underwater conditions due to its hydrophobic nature and other advantages.\textsuperscript{20}

Characterization.—A solar simulator (from Photo Emission Tech., Inc. of model no SS50AAA with Class AAA Xenon Short arc lamp of 150 W, Airmass AM1.5 G) was used to analyze the solar cells in water. The experimental tests were performed using commercially purchased mono- and poly-crystalline silicon solar cells with ratings of 5.01 V, 44.6 mA from IXYS, South Korea, and 3 V, 100 mA from Kitronik Ltd, China. In order to characterize these solar cells in different spectral regions, three different types of

- Short circuit current density ($J_{sc}$) (a) Mono- (c) Poly-crystalline and Maximum power density ($P_{max}$) (b) Mono- (d) Poly-crystalline with respect to depth using SPF.

- Irradiation and (b) Percentage decrease in irradiation with reference to the depth of the water using long pass filter.

Fig. 1. Polydimethylsiloxane (PDMS) has been used for encapsulation to effectively protect solar cells in underwater conditions due to its hydrophobic nature and other advantages.\textsuperscript{20}
colour glass filters, such as the short pass filter (KG-3), long pass filter (RG-610), and bandpass filter (BG-38) obtained from Optics & Allied Engg. Pvt. Ltd, India. The filters show the more than 90% transmittance in the spectral ranges depending upon the type of filter. Also, a submersible pyranometer was used to determine the variations in underwater solar radiation with depth in three different spectral regions. The spectral ranges of the filters were measured using the spectroradiometer (Ocean Insight company of model no FLAME-S-XR1-ES) at the water surface (0 cm). In addition to that, a precision/accuracy source meter was used to obtain the JV (Current-Voltage) and PV (Power-Voltage) characteristics of the solar cells. Figures 1d–1f show the underwater experimental characterization of solar cells with different colour filters.

Results and Discussion

In this section, the variation of solar radiation, the performance of the mono- and polycrystalline silicon solar cells in three unique spectral ranges with the change in water depths have been discussed. These spectral ranges include Short Pass Filter (SPF), Long Pass Filter (LPF), and Band Pass Filter (BPF) as shown in the Fig. 2 from the standard solar simulator.

Short pass filter (SPF).—The SPF blocks the IR portion of the light from the solar simulator and allows to transmit the light from near UV to Vis- spectrum region in the wavelengths range 350 to 650 nm. Figure 3 shows solar radiation and its changes with water depth using an SPF. The solar radiation at the surface (considered as 0 cm) is decreased in the case of using an SPF due to the filtration of the IR portion of the solar spectrum. It was witnessed that the rate of decrease in solar radiation underwater was 56.93% at 20 cm in case of SPF, which allowed transmitting the light effectively in the wavelength range 350 nm to 650 nm.

Also, Fig. 4 shows the JV and PV characteristics of Mono- and Poly-crystalline silicon solar cells up to 20 cm of water depth. Due to the drop in the solar radiation, it shows that the JV and PV characteristics decrease relatively with the water depths. Further, Fig. 5 shows the short circuit current density (Jsc) and maximum power output density (Pmax) with the water depth. The Jsc also decreases with water depth, which is proportional to the incoming solar radiation falling on the Mono- and Polycrystalline solar cells in water. Moreover, the obtained JV and PV characteristics reflect the Pmax of the solar cells, which also reduced with the increase in water depth. Although the Pmax decreases with depth using the SPF, it shows better performance in both mono- and poly-crystalline, especially in underwater conditions. Also, when compared with our previous studies without using any filter, in this study the SPF shows good response in underwater conditions.

Long pass filter (LPF).—Subsequently, the UV–vis portion was filtered, and the IR portion of the light (from 600 nm–1100 nm) was
allowed to transmit from the solar simulator to analyze the performance of Mono- and Poly-crystalline silicon solar cells in water. Figure 6 shows the solar radiation and its transmission in water with depth using the IR portion of light. The 80% of the transmission of IR portion of light was absorbed by the water at 20 cm depth as shown in the Fig. 6b.

As we go deep into the water, the light intensity gets reduced, which also reduces the amount of solar radiation passing through.
water. Figure 7 shows that the JV and PV features of mono- and poly-crystalline silicon solar cells also reduce with an increase in water depth, which is similar to the SPF. Still, the rate of decrease in Solar radiation in the IR portion is high. This is due to the absorption of the IR portion of light in waters with an increase in depth. Moreover, this will further reduce the maximum power output $P_{\text{max}}$ and the $J_{sc}$ also of the solar cells, as shown in Fig. 8. This is due to the decrease in the underwater solar radiation with water depths.

**Band pass filter (BPF).**—The BPF transmits the blue-green portion of light effectively in the window of 400 nm to 550 nm from the solar simulator by filtering the other wavelengths of light. Figure 9 shows the transmission of the filtered solar radiation in underwater conditions. As can be seen, with BPF, there was less absorption by the water and the light transmitted effectively in underwater conditions. As shown in the Fig. 9b, the rate of decrease in solar radiation in BPF showed only 49% decrease in solar radiation at 20 cm which is very less compared to the SPF and the LPF.

In our previous studies without using any filter, the solar radiation was 100 mW cm$^{-2}$ at the surface. In contrast, in the present study at the surface (0 cm depth), the solar radiation showed 20.28 mW cm$^{-2}$ using the BPF. Although the intensity of solar radiation was very less using BPF at the surface, but the rate of decrease in solar radiation underwater conditions in was even lesser in comparison to the SPF and the LPF. Further, it reflects the performance of JV and PV characteristics, as shown in Fig. 10. In addition to that, the $P_{\text{max}}$ and $J_{sc}$, as shown in Fig. 11, also reduces with water depth but the rate of decrease in underwater conditions using BPF showed a better performance compared to SPF and LPF.

**Comparative study of with and without filters.**—The solar irradiation in water and $P_{\text{max}}$ of the mono- and poly-crystalline silicon solar cells, up to 20 cm, have been compared without using the filter and reported in our previous studies. In the present work, the solar radiation and the performance of mono- and poly-crystalline silicon solar cells in underwater conditions have been analysed with SPF, LPF and BPF filters. Further, a comparative study has been carried out for mono- and poly-crystalline silicon solar cells with filters and without filters. Figure 12a shows the solar irradiation transfer in water with filters and without filters. It was observed that at the surface (0 cm) without using any filter, the solar radiation was 100 mW cm$^{-2}$ as mentioned in our previous studies. However, using the SPF, LPF, and BPF filters, the solar radiation gets reduced at the surface because the spectrum from the solar simulator is filtered depending on the filter type used.

Further, at the surface using the LPF filter, the solar radiation showed high compared to the SPF and BPF because it filtered the shorter wavelengths of light and allowed effectively to transmit the IR portion of the light and longer wavelengths of light from the solar simulator. Moreover, in underwater conditions, as the IR portion of the light was more absorbed by water, its intensity reduced with depth. Such a reduction in intensity was observed to be more in LPF compared to the SPF and BPF. The BPF transmits the solar radiation

![Figure 10. JV curves (a) Mono- (c) Poly-crystalline and PV curves (b) Mono- (d) Poly-crystalline using BPF.](image-url)
effectively compared to the SPF and LPF because of the blue-green portion of the light, which can be more suitable in underwater conditions.

Figures 12b, 12c shows the $P_{max}$ of the mono- and poly-crystalline silicon solar cells with filters and its comparison without filter based on our previous studies. Although, as the solar radiation got attenuated using the filters at the surface itself, but the obtained results manifest that the performance of the solar cells was improved in underwater conditions using the BPF as the blue portion of the light was more suitable for the solar cells in underwater conditions. Also, the percentage (%) decrease in $P_{max}$ with depth in Fig. 12d showed very less in BPF compared to the SPF, LPF, and even without the filter. Further, the investigations with the SPF, LPF, and BPF showed the importance of the different regions of the solar spectrum and its effects on the behaviour of solar cells in submerged conditions. Moreover, these studies also specify to explore other influences of various solar spectral regions for the utilization of solar cells proportional to the water depth in submerged conditions.

Conclusions

In this work, the performance of submerged mono- and poly-crystalline silicon solar cells has been analysed with different spectral regions from the solar simulator. Also, the same has been compared with our earlier studies without the filter. The outcomes of this work determined that the importance of the regions of the spectral ranges on the performance of the solar cells underwater, which declines with the depth. The obtained results manifest that the blue-green light portion of light using the bandpass filter shows a significant effect on the behaviour of the solar cells in specifically underwater conditions compared to the Visible and IR portions. The percentage (%) decrease in $P_{max}$ of solar cells in underwater conditions was 44.8% and 39.4% for mono- and poly-crystalline silicon solar cells, respectively, using the BPF. Whereas, in LPF, it shows a higher decrement of 76.81% and 72.92%, respectively. Also, the SPF shows decrements of 50.53% and 49.54% for mono- and poly-crystalline silicon solar cells, respectively. From our previous work, without filters, the decrement was 63.06% and 60.72% for mono- and poly-crystalline silicon solar cells respectively. Based on these investigations, it has been observed that different portions of spectral ranges from solar simulator have a substantial impact on the performance of the solar cells in underwater settings. Therefore, it is essential to study the various spectral ranges for the solar cells and its influence in underwater conditions. Although there are many challenges, by exploring in different ways and its limitations, there will be a vast potential for the solar cells to utilize in underwater conditions, especially in the future, for marine-based environments for solving the long-term power necessities.
Figure 12. Comparison of irradiance (a), Pmax for monocrystalline (b), poly-crystalline (c) and (d) Percentage (%) decrease in Pmax at 20 cm and its comparison.

References

1. J. D. Stachiw, “Performance of photovoltaic cells in an undersea environment.” J. Eng. Ind., 102, 51 (2011).
2. P. Jenkins, S. Messenger, K. Trautz, S. Maximenko, D. Goldstein, D. Scheiman, and Walters, “High band gap solar cells for underwater photovoltaic applications.” 38th IEEE Photovoltaic Specialists Conference, p. 2061 (2012).
3. M. Rosa, P. Rosa-clot, and G. Marco, “Science direct science direct submerged PV solar panel for swimming pools: SP3.” Energy Procedia, 134, 567 (2017).
4. M. Rosa-Clot, P. Rosa-Clot, M. G. Tira, and P. F. Scandura, “Submerged photovoltaic solar panel: SP2.” Renew. Energy, 35, 1862 (2010).
5. M. Rosa-clot, P. Rosa-clot, R. Lanzafame, S. Nachtmann, M. Rosa-clot, P. Rosa-clot, P. F. Scandura, S. Taddei, and G. M. Tina, “Field experience with performances evaluation of a single-crystalline photovoltaic panel in an underwater environment.” IEEE Transactions on Industrial Electronics, 57, 2492 (2010).
6. J. A. Muaddi and M. A. Jamal, “Solar spectrum at depth in water.” Renewable Energy, 1, 31 (1991).
7. M. A. Jamal and J. A. Muaddi, “Solar energy at various depths below a water surface.” J. Energy Res., 14, 859 (1990).
8. S. A. Maclean, P. Jenkins, R. Hoheisel, R. J. Walters, K. M. Trautz, D. Goldstein, S. I. Maximenko, and D. Scheiman, “High-bandgap solar cells for underwater photovoltaic applications.” IEEE J. Photovoltaics, 4, 202 (2014).
9. J. A. Röhr, J. Lipton, J. Kong, S. A. Maclean, and A. D. Taylor, “Efficiency limits of underwater solar cells.” Joule, 4, 840 (2020).
10. R. B. Heideier, A. L. V. Gimenes, M. E. M. Udaeta, and M. A. Saidel, “Optical filter design applied to photovoltaic modules to maximize energy production.” Sol. Energy, 159, 908 (2018).
11. S. A. Maclean, P. Jenkins, R. Hoheisel, R. J. Walters, K. M. Trautz, D. Goldstein, and D. Scheiman, “High-bandgap solar cells for underwater photovoltaic applications.” IEEE J. Photovoltaics, 9, 492 (2019).
12. J. Kong et al., “Underwater organic solar cells via selective removal of electron acceptors near the top electrode.” ACS Energy Lett., 4, 1034 (2019).
13. J. A. Muaddi and M. A. Jamal, “Spectral beam splitting technology for increased- conversion efficiency in solar concentrating systems.” Sol. Energy Mater. Sol. Cells, 84, 19 (2004).
14. J. M. Russo, D. Zhang, M. Gordon, S. Vorndran, Y. Wu, and R. K. Kostak, “Spectrum splitting metrics and effect of filter characteristics on photovoltaic system performance.” Opt. Express, 22, A528 (2014).
15. P. K. Enganiti, S. Nambi, H. K. Bebera, P. K. Dwivedi, S. Konda, M. Imamuddin, A. K. Srivastava, and S. Goel, “Performance analysis of submerged polycrystalline photovoltaic cell in varying water conditions”, Photovoltaics.” IEEE J. Photovoltaics, 10, 531 (2020).
16. P. K. Enganiti, P. K. Dwivedi, A. K. Srivastava, and S. Goel, “Analyzing consequence of solar irradiance on amorphous silicon solar cell in variable underwater environments.” Int. J. Energy Res., 44, p. 4493 (2020), no. October 2019.

ORCID

Sanket Goel @ https://orcid.org/0000-0002-9739-4178
21. P. K. Enaganti, P. K. Dwivedi, R. Sudha, A. K. Srivastava, and S. Goel, “Underwater characterization and monitoring of amorphous and monocrystalline solar cells in diverse water settings,” IEEE Sens. J., 20, 2730 (2020).
22. P. K. Enaganti, P. K. Dwivedi, A. K. Srivastava, and S. Goel, “Study of solar irradiance and performance analysis of submerged monocrystalline and polycrystalline solar cells.” Prog. Photovoltics Res. Appl., 28, 725 (2020).
23. C. Resistance, “Data Sheet BG38,” p. 2013 (2014).
24. C. Resistance, “Data Sheet KG3,” no. December, p. 2 (2004).
25. C. Resistance, “Data Sheet RG610,” p. 1 (2014).