Efficiency Enhancement in Dye Sensitized Solar Cell Using 1D Photonic Crystal

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Abstract
A detailed theoretical investigation of one dimensional SiO₂/TiO₂ photonic crystal based ZnO-Pt dye sensitized solar cell with N719 dye is carried out. The optical properties of the theoretically designed dye sensitized solar cell such as transmittance, absorptance and reflectance are calculated using transfer matrix method in order to calculate numerically the key parameters like open circuit voltage (V_{OC}), short circuit current (J_{sc}) and efficiency of the DSSC. The efficiency of the porous one-dimensional 1D SiO₂/TiO₂ photonic crystal coupled ZnO-Pt dye sensitized solar cell is studied for various periods of photonic crystal layers. It is found that the desired integrated system enables to maximize the absorption in the selective spectrum region (400-900 nm) and hence the maximum efficiency achieved is 4.5% for a ZnO-Pt dye sensitized solar cell having a 1D SiO₂/TiO₂ photonic crystal.

Keywords Photonic crystal · Absorber · Dye sensitized solar cell · Efficiency

1 Introduction
Dye-sensitized solar cells (DSSCs) are emerging as a technical and economical sustainable substitute to the p-n junction photovoltaic devices. The absorption of dye increases the light harvesting efficiency (LHE). The chlorophyll-form sensitized zinc oxide electrode based DSSC was synthesized in 1972 [1]. Recently developed sensitized solar cells like quantum dot sensitized solar cells and DSSCs are the potential substitutes for traditional photovoltaic systems. These systems were mainly based on materials such as silicon, cadmium telluride etc., due to their low costs and efficient production procedures [2]. Single ZnO crystals which are mostly dealt in research work deliver limited output as only about 1 % of the dye molecules’ nanostructure are capable to absorb incident light intensity [3]. In this way, the optimization of porosity of the electrode composed of refined oxide powder, improves the efficiency of DSSC.

In 1991, nano porous titanium dioxide DSSC was discovered with 7% efficiency [3]. Even if different studies have been reported, the actual efficiency of TiO₂ DSSCs is often higher than the efficiency of ZnO DSSCs [4]. This is because of the presence of the high carboxylic acid essential groups in the dyes in which the dissolution of ZnO and precipitation of dye-Zn^{2+} complexes occur. The overall power conversion efficiency have been focused on to increase the photovoltage through function of the oxide, improving the photocurrent with new dyes, and boosting stability by better encapsulation [5]. Intense research efforts extensively directed on synthesizing new organic dye molecules with higher absorptivity materials [6, 7].

Nanostructured materials, such as photonic crystal (PhC), large particle aggregation scattering layers, and plasmonic nanometals have opened to increase LHE in the third-generation solar cells [8–14]. PhCs, with periodic dielectric nanostructures, view strong ability to attain a unique level of control the light propagation and also light energy distribution in photovoltaic devices [15–17]. In these devices via several mechanisms, such as photon localization increase the red-light absorption near the red edge of a photonic bandgap, light reflection within the photonic bandgap at different angles and formation of photon resonance modes within the solar cell are used to increase the LHE [14, 15]. Hence, in photovoltaic devices integrated with PhCs, photons absorption increases which results in increased LHE with lower usage of absorbing materials. PhC coupled sensitized solar cells in 2003 has stimulated more efforts to design PhCs with different optical structural properties that permits for light management in the DSSC [18].
This work intended to explore the theoretical configuration of the porous structure of ZnO-Pt DSSC with N719 dye. Optical properties of theoretically designed DSSCs such as transmittance, reflectance and absorptance are calculated using transfer matrix method (TMM), in order to calculate numerically, the key parameters like open circuit voltage ($V_{oc}$), photo current density ($J_{ph}$), efficiency ($\eta$) etc. In addition, the efficiency of porous 1D SiO$_2$/TiO$_2$ PhC coupled ZnO-Pt DSSC is calculated and compared with ZnO-Pt DSSC without PhC. It is concluded that the presence of porous 1D SiO$_2$/TiO$_2$ PhC enhance the efficiency of DSSC.

3 Optical Properties of ZnO Working Electrode

The optical properties of the N719 loaded ZnO working electrode, are essential to evaluate the absorption of the entire structure of the ZnO DSSC with and without 1D PhC. From the recent literature of experimental research, the estimated absorbance values of the N719 loaded ZnO working electrode is found to be 34.28% for a wavelength of 534 nm having the electrode thickness of 330 nm [20]. The transmission of Dyed ZnO is calculated from the absorbance using Beer’s lambert law [21].

The reflectance is calculated from the following equation

$$R = 1 - (A + T) \quad (1)$$

where $R$ – Reflection, $A$ – Absorptance and $T$ - Transmission

The refractive index of N719 loaded ZnO working electrode is calculated from the following equation [22].

$$n = \frac{1 + R + \sqrt{R}}{1 - R} \quad (2)$$

The refractive index of N719 loaded ZnO working electrode is calculated and is found to be comparable with various experimental work [23]. The calculated value and values of refractive index of other components from the literature is listed in the Table 1.

DSSC consists of multiple thin layers with distinct optical properties. A classical interaction exists between the electromagnetic radiation and a finite one-dimensional non-periodic multilayer, where the corresponding maxwell’s equations are solved using TMM formalism. This interaction system fulfills the conditions proposed by the reflection, transmission and absorption, within the layers, and optical interference between incoming and outgoing optical electric fields [23, 24].

The effective index of refraction which may be expressed as

$$\gamma_j(\lambda) = \gamma_j(\lambda) + ik_j(\lambda) = \gamma_j(\lambda) + i\lambda_0(\lambda)/4\pi$$

Table 1 Refractive indices and thickness of different layers of ZnO-Pt DSSC device with 1D PhC [20].

| Layers | Components | Refractive index | Thickness |
|--------|------------|-----------------|-----------|
| 1      | Substrate(glass) | 1.5             | 3 mm      |
| 2      | FTO        | 1.81            | 400 nm    |
| 3      | Dyed ZnO   | 1.94            | 15μm      |
| 4      | Dye/SiO$_2$/KI | 1.43           | 95 nm     |
| 5      | Dye/TiO$_2$/KI | 1.81           | 88 nm     |
| 6      | Electrolyte(KI) | 1.42          | 50 μm     |
| 7      | Platinum   | 2.32            | 2 nm      |
| 8      | FTO        | 1.81            | 400 nm    |
| 9      | Substrate(glass) | 1.5            | 3 mm      |
thickness $d_j$ for each layer $j$. Here $\gamma_j$ is the real refractive index, $k_j$ is the imaginary refractive index, and $\alpha_j$ is the absorption coefficient $j = 1, 2...n$. Figure 1 shows the theoretically designed DSSC with actual parameters of different layers. Light of intensity $I_0$ is assumed to be incident normal to the substrate for a centre wavelength of 550 nm ($\lambda_0$) and multiple reflections at the air/substrate and substrate/multilayer interfaces are taken into account for the study of transmission spectra of DSSC [25].

### 4 Integration of 1D Photonic Crystal in DSSC

Photonic crystal with multilayers having different lattice parameters is fabricated which can increase the photogenerated current for the whole spectral region in which the dye absorbs. Hence the presence of photonic crystal inside the ZnO-Pt DSSC enhances the light harvesting efficiency. In this section, we numerically analyse the integrated system of the ZnO-Pt DSSC with 1D porous SiO$_2$/TiO$_2$ photonic crystals shown in Fig. 2. Initially the optical properties of ZnO-Pt DSSC structure are analyzed using TMM method. Secondly the optical properties of 1D porous SiO$_2$/TiO$_2$ photonic crystals coupled ZnO-Pt DSSC are calculated. The PhC structure consist of alternative porous SiO$_2$ and TiO$_2$ dielectric layers, whose optical parameters are taken from the literature [26, 27]. The thickness of SiO$_2$/TiO$_2$ layers are taken as $d_{SiO2} = 95$ nm and $d_{TiO2} =$ 80 nm. The Fig. 2 shows that the porous 1D SiO$_2$/TiO$_2$ PhC coupled DSSC.

The matrices are formed for the intersection between two layers and wave propagation through each layer. The product of all the transfer matrices forms the actual transfer-matrix of solar cell. The photon absorption of these two solar cell designs (with and without PhC) has been favorably compared with the state-of-art solar cell designs. The combination of sub cell layers has yielded very high photon absorption through the entire solar radiation spectrum. The layers can represent in a matrix form in which the product of the individual layers are matrices. Finally, this method involves the system converting the matrix into reflection, transmission and absorption coefficient [7].

A common mathematical approach, transfer-matrix method is used to compute the spectral properties of 1D multilayered photonic structures, which is tailored for the analysis of the optical characteristics of DSSCs that incorporate a porous 1D PhC absorber layer. The model showed excellent quantitative agreement with angle-dependent spectral transmission measurements recorded from complete DSSCs, allowing detailed analysis of the LHE by the dye from the 1D PhC [28].

According to TMM, each single layer has a transfer matrix the $M$ is given by [7, 29].

$$M_{total} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos\delta & i\gamma \sin\delta \\ i\gamma \sin\delta & \cos\delta \end{bmatrix}$$

The phase difference is $\delta = \left( \frac{2\pi}{\lambda_0} \right) \times \gamma \times t \times \cos(\theta)$

$\lambda_0$ - Centre wavelength, $t$ - Thickness of incident layer, $\gamma$ - Refractive index of layer

The product of each intermediate layer starting with air layer, the resulting products describes entire stack in the order in which lights encounter them. Since each layer associated with its own transfer matrix, for our theoretically designed photonic crystal based DSSC system, the matrix describing the number of layers between the air and substrate according to Macleod et.al is given by italic

$$M_{total} = M_1 * M_2 * M_3 * M_4 * M_5 * (M_H * M_L)^N * M_6 * M_7 * M_8$$

Where $M_1, M_2, M_3, M_4, M_5, M_6, M_7, M_8$ are the matrix corresponding to glass substrate, FTO, ZnO, Dye, electrolyte, platinum, FTO and glass substrate respectively.

$M_H$ and $M_L$ are the corresponding components of the porous SiO$_2$/TiO$_2$ photonic crystal and $N$ is the period of photonic crystal.

$$\begin{bmatrix} \cos\delta_H & \frac{i}{\gamma_H} \sin\delta_H \\ \frac{i}{\gamma_H} \sin\delta_H & \cos\delta_H \end{bmatrix} \times \begin{bmatrix} \cos\delta_L & \frac{i}{\gamma_L} \sin\delta_L \\ \frac{i}{\gamma_L} \sin\delta_L & \cos\delta_L \end{bmatrix}^N$$

For the entire structure of photonic crystal based DSSC, the total transfer matrix is given by

$$M_{total} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$$

where the matrix elements can be calculated in terms of the elements of the single-period matrix.
From the total matrix, the reflection coefficient $\rho$, reflectivity $R$, transmission coefficient $\tau$, transmittivity $T$, and absorptivity $A$ can be found.

The reflection coefficient
\[
\rho = \frac{\gamma_1 m_{11} + \gamma_1 \gamma_s m_{12} - m_{21} - \gamma_s m_{22}}{\gamma_1 m_{11} + \gamma_1 \gamma_s m_{12} + m_{21} + \gamma_s m_{22}}
\]  
(7)

The reflectivity is
\[
R = \rho \times \rho^*
\]  
(8)

where the asterisk denotes the complex conjugate.

The transmission coefficient $\tau$
\[
\tau = \frac{2\gamma_1}{\gamma_1 m_{11} + \gamma_1 \gamma_s m_{12} + m_{21} + \gamma_s m_{22}}
\]  
(9)

The transmittivity is given by
\[
T = \text{Re} \left( \frac{\gamma_s}{\gamma_1} \right)^\tau^*\tau
\]  
(10)

The absorptivity is calculated from
\[
A = 1 - (R + T)
\]  
(11)

By substituting $R$ and $T$ from the Eqs. (8) and (10) in Eq. (11), the equation for absorptivity is given by
\[
A = \frac{4\gamma_1 (m_{11} + m_{12} \gamma_s)(m_{21} + m_{22} \gamma_s) - \gamma_s^2}{\gamma_1 m_{11} + \gamma_1 \gamma_s m_{12} + m_{21} + \gamma_s m_{22}}
\]  
(12)

where $\gamma_1$ and $\gamma_s$ - Refracted indices of first and last layer of the DSSC structure.

5 Photovoltaic Properties of ZnO-Pt DSSC with 1D SiO$_2$/TiO$_2$ PhC

In this work, the photocurrent density ($J_{ph}$), open circuit voltage ($V_{oc}$), saturation current ($J_0$), quantum efficiency and power conversion efficiency of ZnO-Pt DSSC are theoretically calculated. It is compared with corresponding numerical calculations carried out through 1D SiO$_2$/TiO$_2$ PhC coupled ZnO-Pt DSSC.

The photocurrent density is calculated from the following equation [30].
\[
J_{ph} = e \int_{\lambda_{min}}^{\lambda_{max}} A^* \varphi_T(\lambda) d\lambda
\]  
(13)

where $e$–electron charge, $A$–Total absorption of ZnO–Pt DSSC calculated from (12).

The photoflux is given by
\[
\varphi_T = \frac{P_{in}}{h \times f_g} = 1.96 \times 10^{21} \text{m}^{-2} \text{s}^{-1}
\]

where $P_{in}$ - incident flux at solar spectrum A.M 1.5 is 1000 W/m$^2$.

The saturation current is given by
\[
J_0 = -2\pi \int_0^{\lambda_g} 2 \frac{h c}{\lambda} \left[ \exp \left( \frac{hc}{\lambda K_B T} \right) - 1 \right]^{-1} d\lambda
\]  
(14)

$h$ - Planck's constant, $c$ - velocity of light, $K_B$-Boltzmann constant, $T=300K$.

The open circuit voltage is given by
\[
V_{oc} = \frac{K_B T}{e} \ln \left( \frac{J_{ph}}{J_0} + 1 \right)
\]  
(15)

$J_{ph}$ and $J_0$ are calculated from Eqs. (13) and (14).

The fill factor can be calculated using the following equation [28].
\[
FF = \frac{v_{oc} \ln(v_{oc} + 0.72)}{v_{oc} + 1}
\]  
(16)

where $v_{oc} = e V_{oc}/k_B T$ is a normalised voltage.

Fig. 3 The reflectance, absorptance and transmittance profile of ZnO-Pt DSSC coupled with and without 1D SiO$_2$/TiO$_2$ PhC
The efficiencies of the theoretical designed DSSC with and without PhC are calculated using the equation

\[ \eta = \frac{J_{ph} \cdot V_{oc} \cdot FF}{P_{in}} \]  

(17)

6 Results and Discussions

The optical parameters such as transmittance, absorptance and reflectance of the DSSC with and without PhC can be calculated using TMM method, by solving the Eqs. (7) to (12) with MATLAB software.

Figure 3 shows the optical characteristics of ZnO-Pt DSSC with 1D SiO₂ / TiO₂ PhC coupled layers (n = 0, 2, 3). The effect is more pronounced in the range of 500 nm – 800 nm. In Table 1, the absorptivity without PhC result indicates that the photo electrode does not consume incident light in a single pass owing to the low light scattering of the multilayer non-periodic structure. But the presence of 1D SiO₂/TiO₂ PhC coupled inside the working electrode can form the scattering centres and strengthen the scattering process by its periodic structure. Light scattering is employed in dye-sensitized solar cells to improve the optical absorption of the incident light [31–34].

From the absorption graph it is understood that more absorption takes place when DSSC is coupled with PhC. It gets maximum absorption of light in DSSC with PhC having period \( n = 2 \) compared with PhC having period \( n = 3 \).It may due to the refractive index contrast make a disorder in the interface of PhC layers. The optimized periods of layers can increase the path length as well as diffused or multiple scattered/reflected and localized the incident light at longer time. As a result, significant optical absorption amplification in a broad spectral range is achieved by 1D photonic crystal and a multi-layer non-periodically structured absorbing material.

The photo current density, open circuit voltage for 1D SiO₂/TiO₂ PhC integrated ZnO-Pt DSSC are analysed using Eqs. (13) & (14). The effect is maximum when the DSSC coupled with 1D PhC with period \( n = 2 \). The effect of photo current density with number of period of PhC layers is studied and is shown in the Fig. 4. The short-circuit current increases and attains the maximum value with number of periods \( n = 2 \) at the wavelength of 700 nm.

Because of the increase of optical absorption by multiple reflection / scattering in the interface of PhC structure, it can localize the maximum number of photons on the electrode therefore the short-circuit current is increased in the DSSC. The 1D PhC acts as absorber or bottom reflector can trap the incident light. It reduces the group velocity of the photons which can prevent recombination of the exciton for a longer time, hence it leads to the higher rate of photoelectron generation. The lowering of short-circuit current after \( n = 2 \) is due to the maximum reflection in the forbidden bandgap of PhC. By analysing all the optical parameters and substituted in Eq. (13), the efficiency of DSSC may be investigated. The calculated \( J_{sc}, V_{oc}, FF \) and \( \eta \) for various number of periods in the PhC are shown in the Table 2. It is concluded that the DSSC having PhC with period of \( n = 2 \) get a maximum value of 4.5%.

The theoretical results revealed the porous 1D SiO₂/TiO₂ PhC as absorbing layer and act as a potential couple layer to improve the efficiency by trapping the photons and initiate the photons drive gradually back through the absorbing electrode in the selective spectrum range 400 nm -900 nm.

| Table 2 | Photovoltaic parameters of ZnO-Pt DSSC coupled with and without 1D SiO₂/TiO₂ PhC |
|---------|---------------------------------|
| ZnO-Pt DSSC | Number of periods (n) | \( J_{sc}(\mu A \ cm^{-2}) \) | \( V_{oc}(V) \) | FF | \( \eta(\%) \) |
| SiO₂/TiO₂ (PhC) | 0 | 85.71 | 0.37 | 0.75 | 2.3 |
|  | 2 | 152 | 0.39 | 0.72 | 4.5 |
|  | 3 | 127 | 0.38 | 0.76 | 3.7 |
7 Conclusion

The photovoltaic parameters of ZnO-Pt with N719 dye based DSSC are calculated. ZnO-Pt DSSC coupled with porous 1D SiO₂/TiO₂ PhC is theoretically designed. The absorptance of the integrated system of ZnO-Pt DSSC with and without 1D SiO₂/TiO₂ PhC are calculated using TMM method. It is found that the desired integrated system enable to maximize the absorption in the selective spectrum region (400-900 nm). The solar cell parameters are studied for various periods of PhC in the integrated system. The short circuit current ($J_{sc}$), open circuit Voltage ($V_{oc}$), fill factor (FF) and hence the efficiency($\eta$), are calculated theoretically at 700 nm wavelength. The optical design of 1D SiO₂/TiO₂ PhC absorbing layer enhance the cell efficiency without affecting kinetic balance between charge separation and recombination. The maximum short circuit current ($J_{sc}$) is found to be 440 $\mu$A cm⁻² which leads to a maximum efficiency of 4.5%. for a DSSC having 1D SiO₂/TiO₂ PhC.

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Author Contributions

There are variety of methods available to increase the efficiency of DSSC. The propagation of light inside the DSSC can be increased as possible to trap the light and hence to increase the efficiency of the solar cell.

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Data Availability

The [data type “Photonic structure parameters”] data that support the findings of this study are available in [http://www.tandfonline.com/loi/tmop20."

Declarations

The submitted work should be original and should not have been published elsewhere in any form.

Consent to Participate

Not Applicable.

Conflict of Interest

The authors declare that they do not have a conflict of interest.

The Problem Being Addressed

1D SiO₂/TiO₂ photonic crystal based ZnO-Pt DSSC with N719 dye is theoretically designed. The optical properties of theoretically designed DSSC such as transmittance, absorptance and reflectance are calculated. The use of 1D SiO₂/TiO₂ photonic crystal light trapping structures in DSSCs demonstrates the ability to increase the performance of solar to electrical conversion.

References

1. Tributsch H, Calvin M (1971) Electrochemistry of excited molecules: photo-electrochemical reactions of chlorophylls. Photochem Photobiol 14:95–112
2. Tsubomura H, Matsumura M, Nomura Y, Amamiya T (1976) Semiconductor based photoelectrochemical cells for solar energy conversion. Nature. 261:402–403
3. O’Regan B, Grätzel M (1991) A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films. Nature 353:737–740
4. Quintana M, Edvinsson T, Hagfeld G, Boschlo O (2007) Comparison of dye-sensitized ZnO and TiO2 solar cells: studies of charge transport and carrier lifetime. J Phys Chem C 111:1035–1041
5. Kroon J et al (2007) Nanocrystalline dye-sensitized solar cells having maximum performance. Prog Photovolt 15:1–18
6. Ding IK, Tetreault N, Brillet J, Hardin BE, Smith EH et al (1999) Large area hole transporter deposition in efficient solid-state dye-sensitized solar cell mini-modules. Opt Express 4:183105-1–4
7. Deepak TG, Anjusree GS, Sara Thomas TA, Arun SV, Nairand A, Nair S (2014) A review on materials for light scattering in dye-sensitized solar cells. RSC Adv 4(34):17615–17638
8. Hore S, Vetter C, Kern R, Smit H, Hinsch A (2006) A. sol. Energy Mater. Sol Cells 90:1176–1188
9. Ferber J, Luther J (2001) Modeling of Photovoltaic and photocurrent in dye-sensitized titanium dioxide solar cells. J Phys Chem B 105:4895–4903
10. Mallick SB, Sergeant NP, Agrawal M, Lee JY, Peumans P (2011) Coherent light trapping in thin-film photovoltaics. MRS Bull 36:453–460
11. Vynck K, Burrusi M, Ribolfi F, Wiersma DS (2012) Photon management in two-dimensional disordered media. Nat Mater 11:1017–1022
12. Hou W, Pavaskar P, Liu Z, Thess J, Ayyol M, Cronin SB (2011) Plasmon resonant enhancement of dye sensitized solar cells. Energy Environ Sci 4:4650–4655
13. Yu ET, van de Lagemaat J (2012) Photon management for photovoltaics. MRS Bull 36:424–28(2012)
14. Green MA, (2009). Prog. Photovoltaics: Res. Applications 17: 183–189
15. Kranz L, Buecheler S, Tiwari AN (2013) TiO₂ as intermediate buffer layer in Cu(In,Ga)Se₂ solar cells. Sol Energy Mater Sol Cells 119:278–280
16. Nishimura S, Abrams N, Lewis BA, Halaoui LI, Mallouk TE, Benkstein KD, Van de Lagemaat J, Frank AJ (2003) Standing Wave Enhancement of Red Absorbance and Photocurrent in Dye-Sensitized Titanium Dioxide Photoelectrodes Coupled to Photonic Crystals. J Am Chem Soc 125(20):6306–6310
17. Anta JA, Guélien E, Tena-Zaera FU (2012) ZnO-based dye-sensitized solar cell. Phys Chem C 116:11413–11425
18. Singh A, Mohan D, Ablawat DS, Richa (2017) Processing and performances of spun coated silver doped ZnO photoanode based dye sensitized solar cell. Appl Ceram 11(3):213–219
19. Qiao F, Dang L, Lu Q, Gao F (2014) High-performance dye-sensitized solar cells based on ag-doped SnS2 counter electrodes. J Phys Chem C 118:16856–16862
20. Mayhofer TG, Popp J (2019) Molecular and biomolecular spectroscopy. Systematic ab initio gradient calculation of molecular geometries, force constants, and dipole moment derivatives. Acta Crystals. J Am Chem Soc 125(20):6306–6310
21. Anta JA, Guélien E, Tena-Zaera FU (2012) ZnO-based dye-sensitized solar cell. Phys Chem C 116:11413–11425
22. Singh A, Mohan D, Ablawat DS, Richa (2017) Processing and performances of spun coated silver doped ZnO photoanode based dye sensitized solar cell. Appl Ceram 11(3):213–219
23. Qiao F, Dang L, Lu Q, Gao F (2014) High-performance dye-sensitized solar cells based on ag-doped SnS2 counter electrodes. J Phys Chem C 118:16856–16862
24. Mayhofer TG, Popp J (2019) Molecular and biomolecular spectroscopy. Systematic ab initio gradient calculation of molecular geometries, force constants, and dipole moment derivatives. Acta Crystals. J Am Chem Soc 125(20):6306–6310
25. Anta JA, Guélien E, Tena-Zaera FU (2012) ZnO-based dye-sensitized solar cell. Phys Chem C 116:11413–11425
26. Luque-Raigon JM, Halme J, Miguez H (2014) Angular optical behavior of photonic-crystal-based dye-sensitized solar cells. J Quant Spectrosc Radiat Transf 134:9–20
27. Yeh P (2005) Optical waves in layered media. Wiley Publication, Hoboken [chapter 6]. ISBN: 978-0-471-73192-4
28. Clarke TM, Durrant JR (2010). Charge photogeneration in organic solar cells. Am Chem Society 110(11):6736–6767
29. Huang DM, Snaith HJ, Grätzel M, Meierholz K, Moul AJ (2009) Optical description of solid-state dye-sensitized solar cells. II. Device optical modeling with implications for improving efficiency J Appl Phys 106: 073112 1–6
25. Luque-Raigón JM, Halme J, Carmen L-LJ (2019) Angular optical behavior of photonic-crystal-based dye-sensitized solar cells. Photon. Energy 9(2):025501–025519
26. El-Khozondar HJ, El-Khozondar RJ, Shabat MM (2009) Metamaterial-dielectric photonics crystal waveguide structure. Mod Phys Lett B 23(28):4675-4683
27. Margulis GY, Hardin BE, Ding IK, Hoke ET, McGehee MD (2013) Parasitic absorption and internal quantum efficiency measurements of solid-state dye sensitized solar cells. Adv Energy Mater 3:959–966
28. Mohammed ZH (2019) The fresnel coefficient of thin film multilayer using transfer matrix method TMM. IOP Conf Ser Mater Sci Eng 518:032026-1-10
29. Wang J, Yang L, Lin D, Luo Y, Li D, Menga Q (2005) Optical studies of random disorder of colloidal photonic crystals and its evolution in evaporation induced self-assembly. J Chem Phys 137:2341111–2341112
30. Deepak TG, Anjusree GS, Thomas S, Arun Shantikumar TA, Nair V, Sreekumaran A (2014) A review on materials for light scattering in dye-sensitized solar cells. RSC Adv 4:17514-1-34
31. Jäger K, Isabella O, Smets AHM, van Swaaij René ACMM, Zeman M (2014) Solar energy fundamentals, technology, and Systems Delft University of Technology
32. Mihi A, Miguez HJ (2005) Origin of light-harvesting enhancement in colloidal-photonic-crystal-based dye-sensitized solar cells. J Phys Chem B 109:15968–15976
33. Barkat O, Mamri B (2018) Numerical method for a one-dimensional defective photonic crystal selective filter. Electric Electron Tech 2(2):9–13
34. Cinà L, Taheri B, Reale A, Di Carlo A (2014) Diffusion length mapping for dye-sensitized solar cells. Energies 9:686-1-14

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