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Enhancement of Up conversion Efficiency in Solar Cells by Plasmonic Nanostructures

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ABSTRACT
In order to enhancenear infrared photon absorption by solar cells, we propose a structure including plasmonic backcontact nanogratings covered with a layer of dielectric in which an up converter material is incorporated. We show that this combination can increase up conversion efficiency by producing a strong near field in the proximity of nanowires. In this research, we employ Rigorous Coupled-Wave Analysis (RCWA) to calculate the electromagnetic fields and the enhancement of up conversion efficiency.
Keywords: *Solar cells, Plasmonic nanostructures, Surface Plasmon polariton, Up conversion, Quantum efficiency*

INTRODUCTION
Most of the world energy is provided via fossil energy. Due to the ever increasing need for energy sources and the impossibility to renew fossil fuels, renewable energy sources have attracted attention. Solar energy as a pollution free and interminable sourcehas a unique position among renewable energies. Solar cells are electronic devices that directly convert sunlight into clean electrical power. However, much of the solar energy that reaches a cell surface, particularly in the infrared region, is not absorbed by the cell and passes through it. Many solutions have been proposed for the increasing of solar cells efficiency, such asplacing anti-reflection layers on top of solar cells to reduce surface reflection [1], use of plasmonic nanogratings at the bottom of the cell [2], and using photon up conversion mechanisms to increase cell efficiency [3-4]. However, the up conversion efficiency is rather low.In this paper, with the use of periodic arrays of silver plasmonicnanogratings at the bottom of solar cells covered with an up converter material, we improve the efficiency of solar cells and the up conversion efficiency at the same time.
Study of the interaction of light with such structure, is not possible through analytic method, and numerical techniques should be used. For this purpose, we use the RCWA method to perform the calculation of electromagnetic fields inside the solar cell structure.The near filed values can be used to calculate the up conversion efficiency and compute the optimum value of effective parameters.

2- Up conversion Mechanism
Up converter materials can convert multiple infrared photons to one visible photon [4]. Several methods of up conversion mechanism exist; it involves energy transfer from an excited ion, named sensitizer, to a neighboring ion, named activator. Others are two-step absorption, being a ground state absorption followed by an excited-state absorption, and second-harmonic generation (Figure 1) [5-7].

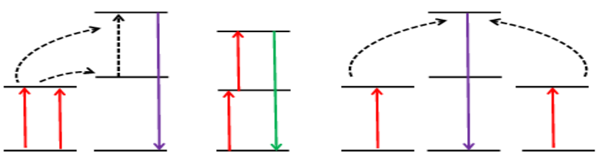


Figure (1): different mechanisms of up conversion process.

Different up converter materials with various excitation and emission wavelengths can be used to enhance solar cells efficiency. Among them, trivalent erbium is a good option for up conversion of near infrared light, where crystalline silicon solar cell is weakly absorbing, due to its ladder of nearly equally spaced energy levels that are multiples of the4I15/2 to4I13/2 transition (Figure 2).

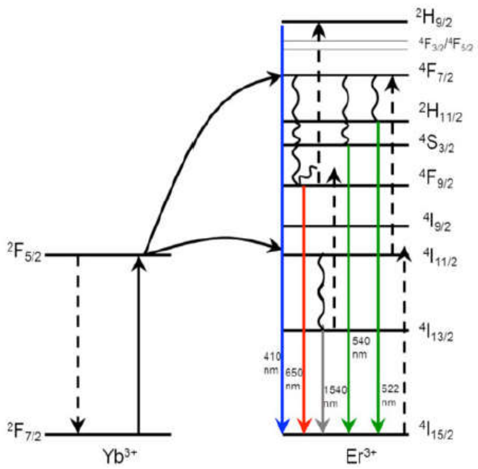


Figure (2): Up conversion in the erbium and ytterbium (Er^{+3},Yb^{+3}) couple. The dashed lines show energy transfer, the solid lines demonstrate the radiative decay, and the curly lines indicate multi-phonon relaxation processes. The main route is a two-step energy transfer after excitation around 980 nm in the Yb3+ ion that leads to excitation to the4F7/2 state of the Er3+ ion. After relaxation from this state, emission is observed from the 2H11/2 level, the 4S3/2 level, and the4F9/2 level.

The comparison of solar energy spectrum and absorption spectrum of silicon solar cells shows that the solar cell does not have a good absorption in the infrared region, and much of the infrared solar energy that's reached the cell surface, is not absorbed by the cell and passes through it. In order to enhance the cell absorption in this region, up converter layer can be used. The up converter layer is placed at the bottom of the cell and converting part of transmitted photonspassing from the cell wavelengths that can be absorbed by the cell. In fact, up conversion absorbs low energy photons and changes them into a higher energy photon, so they can be absorbed by the cell. Figure (3), shows the placement of up converter in the solar cell.

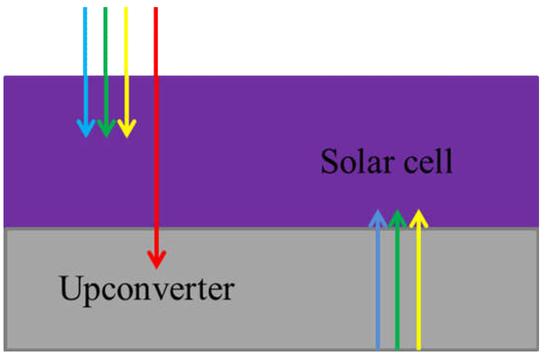


Figure (3): the placement of up conversionin the solar cell.

3- Up conversion Quantum Efficiency

By up conversion quantum efficiency, we mean the ratio of the number of emitted photons to the absorbed photons [10-11], i.e.:

$$\mu_{up} = \frac{\sum_i A_i n_i}{Abs} \quad (1)$$

where, A_i is the Einstein coefficient for spontaneous emission of the i(th) level, $n_i$is the population of the i(th) level, and Abs, the number of photons absorbed by the up converter.

The main problem with up converter layer, is it's low efficiency in the visible and infrared region.Hence, methods forenhancing of the optical absorption inside the upconverter should be searched for. The placement of silver plasmonic nanorods in the upc onverter, affects the efficiency of up conversionin a number of ways:

1- Increasing the incident photon flux: Through the creation of plasmonic models, nanorods create a strong magnetic field inside the upconversion. Since, photon flux is proportional to the square of electromagnetic fieldfor a specific wavelength, it increases. The enhance in the photon flux in the presence of plasmonic nanorods is proportional to [11]:

$$\gamma_H = \frac{|H(r)_{struct}|^2}{|H(r)_o|^2} \quad (2)$$

The "struct" index is related to the status of which, the nanorods are placed in the upconverter, and H(r), is the electromagnetic field intensity distribution in r distance from the upconverter.

2- Increasing the density of photonic modes and the probability of transition between the two energy levels: According to Fermi Golden rule, the probability of transition between two energy levels is proportional the density of photonic modes [10].

$$w_{if} = \frac{4\pi}{h}|M_{if}|\rho(r,\omega_{if}) \quad (3)$$

In this equation, $\rho(r,\omega_{if})$, is the photonic modes density and M_{if} is the transient matrix element.

By increasing photonic modes density $\rho(r,\omega_{if})$, nanorods enhance the transient probability of each mode by γ_{if}.Nanorods, affect other parameters such as the Einstein coefficient for spontaneous emission and the absorption level by the transducer [12].

$$Abs_{struct} = \gamma_{abs} Abs \quad (4)$$

$$A_{i,struct}(r) = \gamma_{if} A(r) \quad (5)$$

Therefore, by changing each parameter, the quantum efficiency of the upconverter material also changes according to equation 1. Generally, the average forenhancing of the efficiency of upconverter material is proportional to the square of the electromagnetic field intensity [8-10]. In this paper, with the use of the RCWA method, we acquire the electromagnetic field intensity distribution for two modes, one mode is with the presence of nanorods and the other is without their presence, and then in the end, we calculate the level ofenhancing theupconversion quantum efficiency.

4- The RCWA Method

Many methods have been proposed to examine the electromagnetic field distribution of periodic structures, amongst which, the RCWA method is a relatively simple and accurate method [9]. And with the use of this method, it's possible to calculate the field intensity distribution in different areas of the structure.

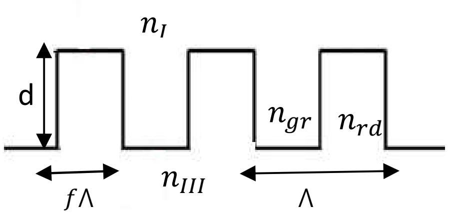


Figure (4): Schematic diagram of a periodic of silver nanorodsalong the x axis.

Figure 4, shows the period array of the proposed silver nanorod in the upconverter that includes three areas. The first area, I, is the field incident area, the second area, is the grid area (silver nanorods), and the third area III, is the transmission field. Relative electronic permittivity in the grid area (nanorods)is periodic along x and has the two values of n_{rd} and n_{gr} and is homogeneous along z. And it can be expanded into a Fourier series.

$$\varepsilon(x) = \sum_h \varepsilon_h \exp\left(j\frac{2\pi h}{\Lambda}x\right) \quad (6)$$

$$\varepsilon_h = ({n_{rd}}^2 - {n_{gr}}^2)\frac{\sin(\pi h f)}{\pi h} \quad (7)$$

In this equation, h is related to the expansion of Fourier series harmonics, and ε_h, is the h(th) component of the relative permittivity in the grid diffraction. We assume that figure 4, is radiated by TM polarized plane wave. Thewave is diffracted after radiating at the first layer boundary, and each of the diffraction components are released into the space in a specific direction. The total magnetic field in the first area includes reflection and incident fields. The magnetic field in the final area is as the outcome of transmission fields.

$$H_{I,y} = H_{inc,y} + \sum_i R_i exp[-j(k_{xi}x - k_{I,zi}z)] \quad (8)$$

$$H_{II,y} = \sum_i T_i exp\{-j[k_{xi}x + k_{II,zi}(z-d)]\} \quad (9)$$

In the above equations, R_i is the domain of the i(th) reflected wave magnetic field, and T_i is the magnetic field domain of the i(th) transmitted wave. We considerthe tangential component of the magnetic and electric fields in the diffraction grid, as Fourier expansion.

$$H_{gy} = \sum_i U_{yi}(z) \exp(-jk_{xi}x) \quad (10)$$

$$E_{gx} = j\left(\frac{\mu_0}{\varepsilon_0}\right)^{\frac{1}{2}} \sum_i S_{xi}(z) \exp(-jk_{xi}x) \quad (11)$$

In these equations, $u_{yi}(z)$ are the i(th) domains of space harmonic fields. Each of the tangential field components, hold true in the Maxwell's equation. By placing each of them in Maxwell's equation, and with a little simplification, we obtained the coupled equations bellow:

$$\begin{bmatrix} \partial U_y/\partial(z') \\ \partial S_x/\partial(z') \end{bmatrix} = \begin{bmatrix} 0 & E \\ B & 0 \end{bmatrix} \begin{bmatrix} U_y \\ S_x \end{bmatrix} \quad (12)$$

We calculate the eigenvector and eigenvalues of EB, and expand the domains based upon them:

$$U_{yi}(z) = \sum_{m=1}^{n} w_{i,m} \{c_m^+ \exp(-k_0 q_m z) + c_m^- exp[k_0 q_m (z-d)]\} \quad (13)$$

$$S_{xi}(z) = \sum_{m=1}^{n} v_{i,m} \{c_m^+ \exp(-k_0 q_m z) + c_m^- exp[k_0 q_m (z-d)]\} \quad (14)$$

Given the integrity of tangential components of electric and magnetic fields, we apply boundary conditions among different layers. The equation for the first area and the diffraction grid in point (x=0,z=0) is:

$$\begin{bmatrix} \delta_{i0} \\ j\cos\theta\, \delta_{i0}/n_I \end{bmatrix} + \begin{bmatrix} I \\ -jZ_I \end{bmatrix} [R] = \begin{bmatrix} W & WX \\ V & -VX \end{bmatrix} \begin{bmatrix} c^+ \\ c^- \end{bmatrix} \quad (15)$$

The equation between the third area and grid (x=0,z=d) is:

$$\begin{bmatrix} WX & W \\ VX & -V \end{bmatrix} \begin{bmatrix} c^+ \\ c^- \end{bmatrix} = \begin{bmatrix} I \\ jZ_{II} \end{bmatrix} [T] \quad (16)$$

In these equations, Z_I, Z_{II}, X are diagonal matrices, whose elements are $(k_{I,zi}/k_0 n_I^2)$, $(k_{II,zi}/k_0 n_{II}^2$, and $\exp(-k_0 q_m d)$. By simplifying the equations above, the domain of the reflection and transmission field will be obtained, and by calculating each coefficient, field intensity distribution for each area is calculated.

RESULTS

In order to enhance the efficiency of upconverter material, we consider a structure consisting of plasmonic nanogratings embedded in a dielectric layer which contains upconverter ions. By proper design of the nanogratings parameter, plasmonic modes can be excited and the generated strong near field can enhance the quantum efficiency of the upconversion mechanism. In the proposed structure, as shown in figure 5, we place a periodic arrays of silver nanorods with the width (w) and height (h) within the upconverter layer ($NaYF_4$: 3% Er, 17% Yb), at the bottom of the silicon solar cell with the height of (H_{si}).The structure is illuminated by a TM polarizaed light which enters from the top of the simulated space and interacts with the nanorods after passing through the cell.

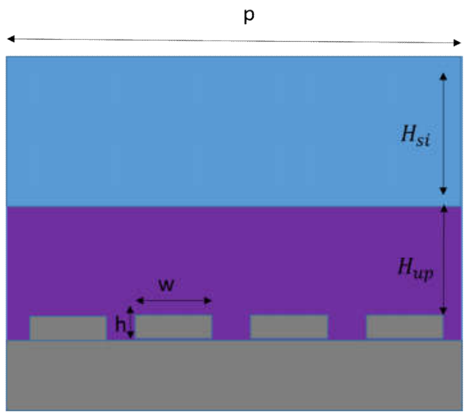


Figure (5): the proposed structure for the excitation of plasmonicmodes.

It is possible to adjust the plasmonic modes in the desired wavelength range, by changing the periodicity of nanogratings (figure 6). Since the upconverter used in this paper, is excited at the wavelength of 980 nm, the wavelength of plasmon mode should be set to 980 nm. This can be achieved with the selection of silver nanogratings periodicity of 640 nm.

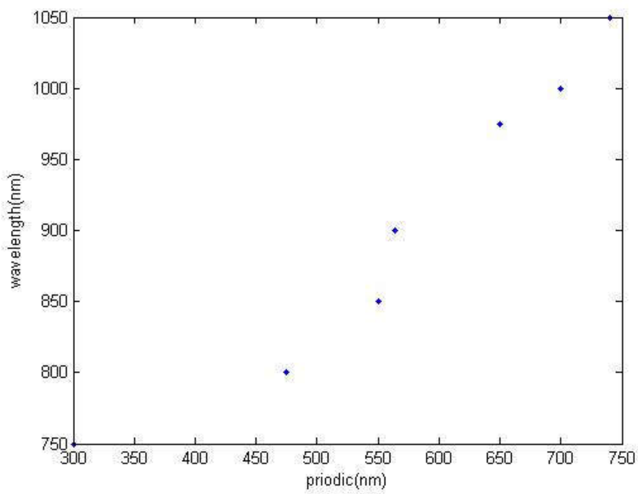
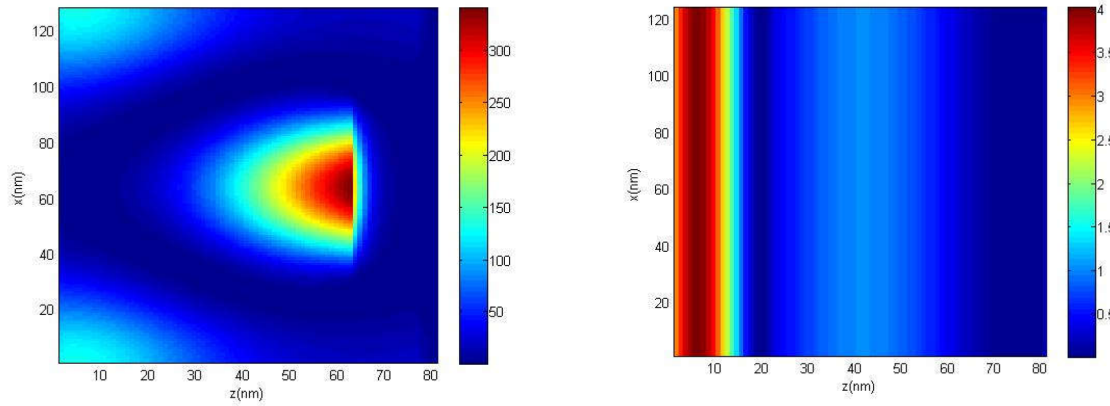


Figure (6): Displacement of SPP wavelength versus period.

In order to investigate the effect of plasmonic resonance on the upconverter efficiency, we calculate the electromagnetic field distribution density for the structure which supports SPP modes. We consider the height and thickness of nanogratings as 70 nm and 320 nm, respectively, and the thickness of the upconverter layer as 300 nm. As shown in Figure 7, it is confirmed that with this selection of parameters, a strong SPP mode is excited. In this simulation, the refractive index of upconverter host is n_{UP} = 1.50-4.6i, and silver refractive index has been considered as n_{AG} = 0.04-6.34i.



(a) (b)

Figure (7): Electromagnetic field intensity distribution in the proposed structure, a) with the presence of silver nanogratings inside the upconverter host, b) without the presence of nanogratings.

As mentioned, due to the excitation of plasmonic modes, a strong electromagnetic field is formed around the nanorods and inside the upconverter material. The comparison of figure 7 (A) and (B) shows that the electromagnetic field intensity, in all the points of the upconverter material, has increased by an average of 60 times, leading to a considerable enhancement in upconvertion efficiency. As shown in figure 8, the averaged electromagnetic field intensity in the upconverter material exhibits a strong peak around the wavelength of 980 nm. With such a large enhancement of electromagnetic field intensity in the infrared region, the upconvertionefficiency increases considerably. Consequently, the emission of photons in the visible region is increased and it enhances the performance of the solar cell in a wide spectral range.

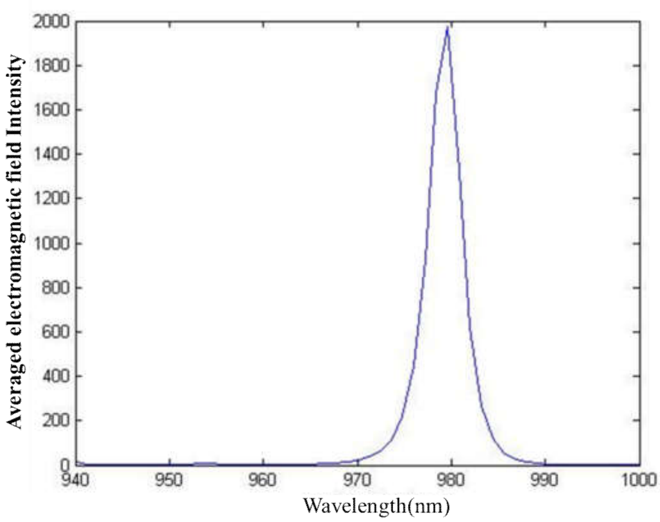


Figure (8): The averaged electromagnetic field intensity within the upconversion host.

CONCLUSIONS

We have examined the effect of plasmonic nanostructures on enhancing the efficiency of upconverter material in solar cells. We have used the RCWA method to calculate the enhancement of the electromagnetic field intensity and tune the structure parameters in order to excite SPP modes. It has been shown that by using plasmonic nanogratings the quantum efficiency of upconversion and hence the solar cell performance is considerably enhanced.

REFERENCES

1. Munday, J. N., Atwater, H. A., Large integrated absorption enhancement in Plasmonic solar cells by combining metallic gratings and antireflection coatings,Nano. Lett, 2011,11, 2195- 2201.

2. Wang, W., Reinhardt, K., Lu, Y., and Chen, Sh., Broadband light absorption enhancement in thin-film silicon solar cells, Nano. Lett, 2010 ,**10**, 2012-2018.
3. Wilfried, G. et al, Upconversion in solar cells, licensee Springer.2013.
4. Trupke, T., Shalav, A., Richards, B.S., Würfel, P. and Green, M.A., Efficiency enhancement of solar cells by luminescent up-conversion of sunlight, Solar Energy Materials & Solar Cells,2006,**90**,3327-3338.
5. Hari, P., Dachhepati, D., Bayat, Khadijeh.,Mottaghian, S., Lin, C., Smith, S.,Design,fabrication, and characterization of a Plasmonicupconversion enhancer and its prospects for photovoltaics, Journal of Photonices for Energy,2013.
6. Paudel, H. P., et al.,Enhancement of electromagnetic field intensity by metallic photonic crystal for efficient upconversion, in 35th IEEE Photovoltaic Specialists Conf.,2010,002938–002942.
7. Lin, C. et al, Highly luminescent NIR-to-visible upconversion thin films and monoliths requiring no high-temperature treatment, Chem. Mater., 2009, 21, 3406–3413.
8. Herter, B., Wolf,S., Fischer, S., Gutmann, J., et al, Increased upconversion quantum yield in photonic structures due to local field enhancement and modification of the local density ofstates– a simulation-based analysis,Optic Express, 2013.
9. Moharam, M. G., Drew, A., Grann, B.,Stable implementation of the rigorous coupled-wave analysis for surface-relief gratings:enhanced transmittance matrix approach,J. Opt. Soc. Am. A,1995.
10. Shalav, A., Richards, B.S., Green, M.A., Luminescent layers for enhanced silicon solar cell performance: Up-conversion,Solar Energy Materials and Solar cells,2007,91,829-842.
11. Herter, B., Wolf, S., Fischer, S., Peters, M., Bläsi,B., Goldschmidt, J.C., Effects of photonic structures on upconversion, Solar Energy Materials & Solar Cells, 2013.
12. Dirac, P.A.M., The Quantum Theory of the Emission and Absorption of Radiation, Proceedings of the Royal Society, 1927, **114**(243)
13. Auzel, F., Upconversion and anti-stokes processes with f and d ions in solids, Chemical Review, 2004, **104**, 139-173.