Converting effects for increasing solar cell efficiency

Giovanni Cittadino

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Summary

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Sources of energy:

- Fossil energy
- Renewable energy
  - wind energy
  - biomass energy
  - hydroelectric energy
  - geothermal energy
  - solar energy

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Solar Spectrum

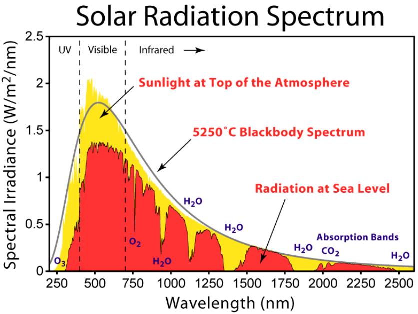


Figure: Solar Spectrum out the atmosphere(yellow), black body and at seaside level(red)

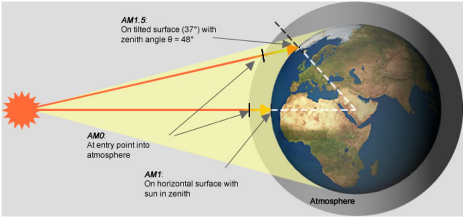


Figure: Definition of AM

Spectrum

AM (Air Mass)coefficient$\simeq \frac{1}{cos\theta}$

working principles of a single junction cell

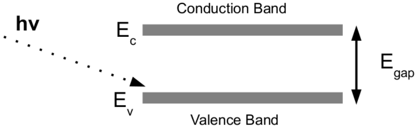


Figure: valence and conduction band

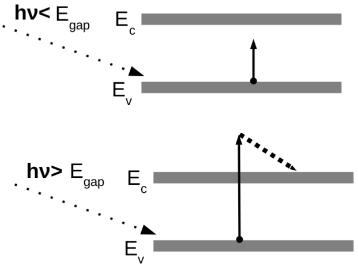


Figure: Loss due to not absorption and thermalization

- Creation of a electron-hole pair with $E_{ph} \geq E_g$
- Employment of a pn junction for avoiding the recombination

- 60% of Solar Spectrum is lost using mono-crystal silicon solar cell
- the conversion efficiency is equal 25%(NREL data)

Mono-crystal silicon solar cell and solar radiation recover

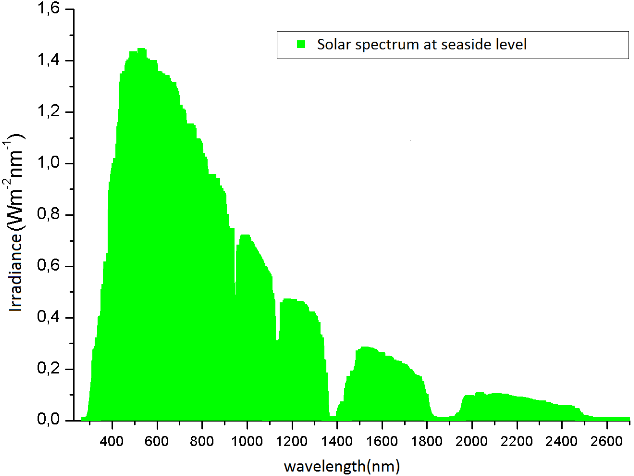


Figure: Solar spectra at seaside level

Mono-crystal silicon solar cell and solar radiation recover

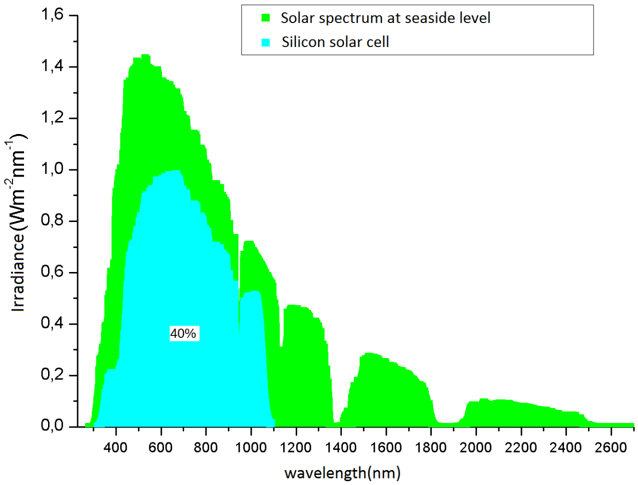


Figure: Fraction of solar spectrum using by a silicon mono-crystal solar cell

Mono-crystal silicon solar cell and solar radiation recover

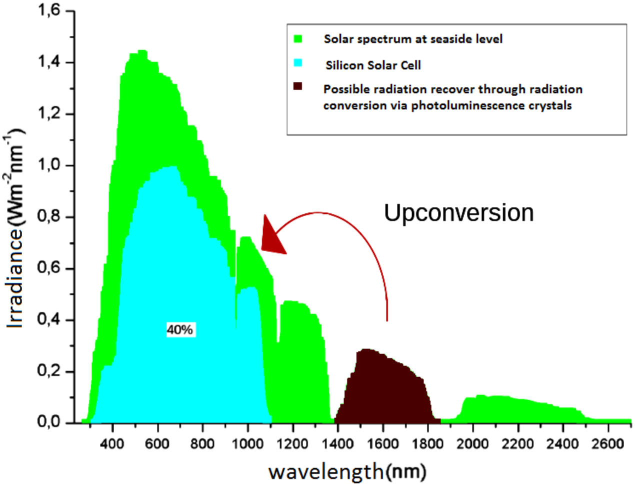
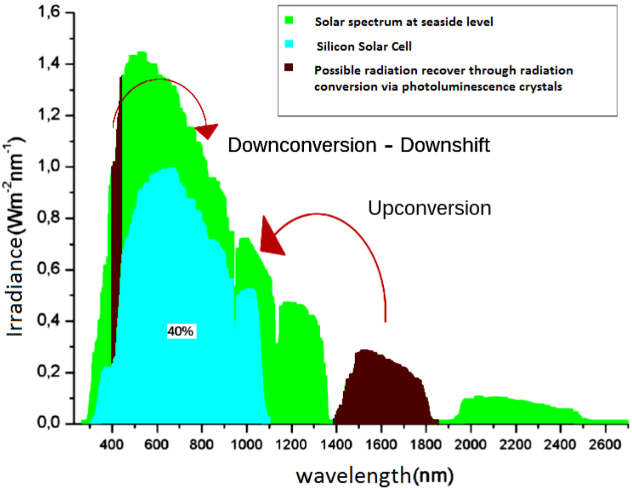


Figure: Fraction of solar spectrum might be used with conversion phenomenon of the radiation

Mono-crystal silicon solar cell and solar radiation recover



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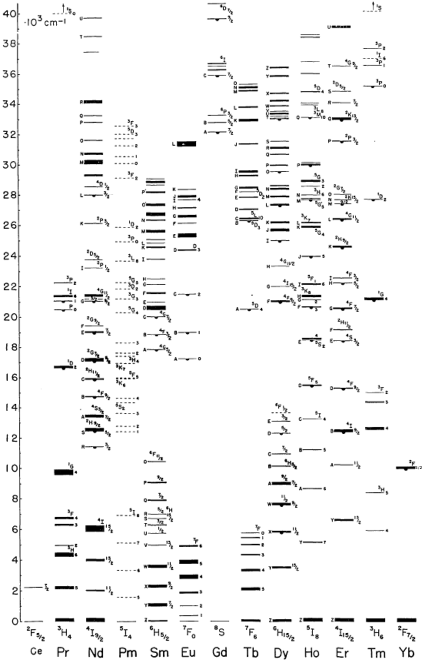


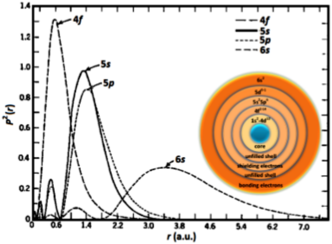
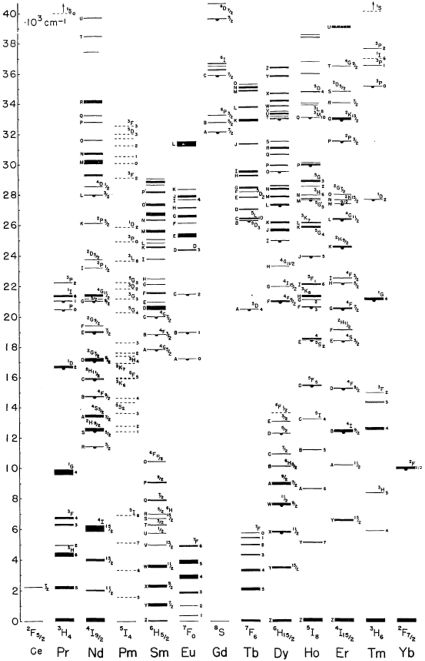


Figure: Shell distribution for an ion Gd^{+}

- Valence electrons are not those outer
- Outer Orbitals shield the electrons that are located at the shell 4f
- The existence of a crystal field allows the transition $4f \rightarrow 4f$



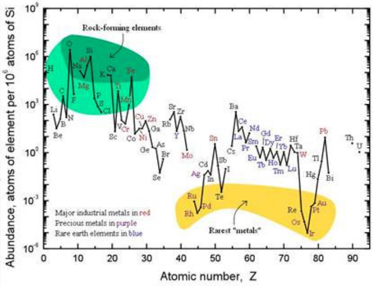


Figure: Element abundance belonging to the Rare Earth on our planet

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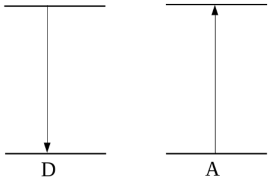
- Outer Orbitals shield the electrons that are located at the shell 4f
- The existence of a crystal field allows the transition $4f \rightarrow 4f$

Mechanisms of energy transfer

- Resonant energy transfer(Energy Migration)
- No-resonant energy transfer
- Cross-relaxation
- Upconversion



D=donor ion A= acceptor ion

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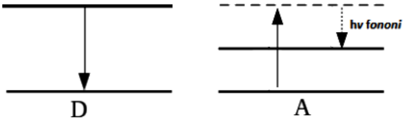

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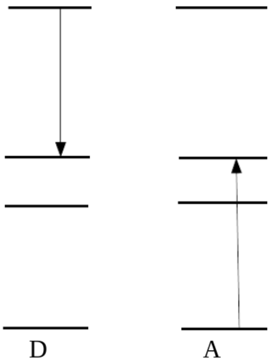

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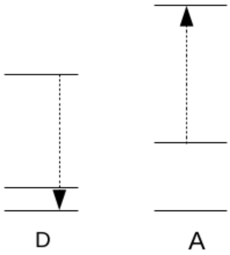
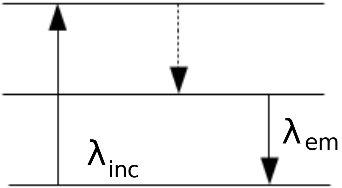


Conversion phenomenon of the radiation

- Downshift
- Downconversion
- Upconversion



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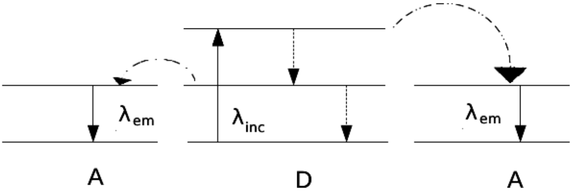

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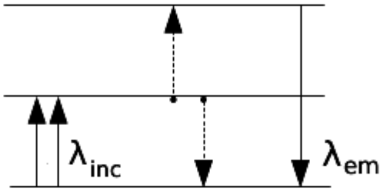
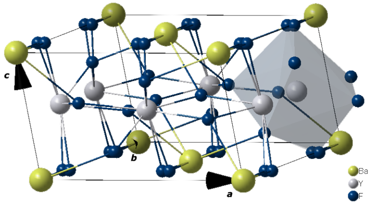


BaY_2F_8 crystal structure



Lattice constant

a = 6.972 Å	$\alpha = 90°$
b =10.505 Å	$\beta = 90°$
c =4.260 Å	$\gamma = 99.76°$

- monoclinic structure
- low phonon energy($\sim$ 400 cm^{-1})
- $1.28 \cdot 10^{22} \frac{\text{ioni } Y^{3+}}{cm^3}$

Crystal Growth

Crystal grown in our laboratory with Czochralski method

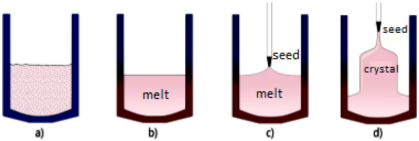


Figure: Grow scheme of a crystal

a) Preparation of the powder mixture
b) Fusion
c) Seed dipping
d) Pull and Crystallization

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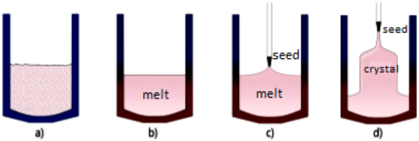

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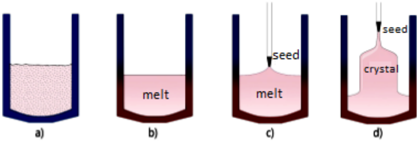

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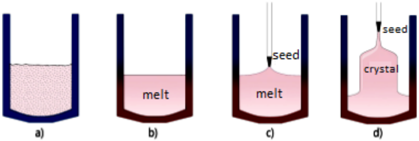

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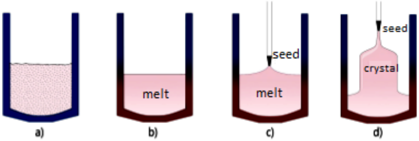

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a) Preparation of the powder mixture
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Samples made:

- BaY_2F_8:Pr^{3+}
- BaY_2F_8:Yb^{3+}-Pr^{3+}
- BaY_2F_8:Er^{3+}

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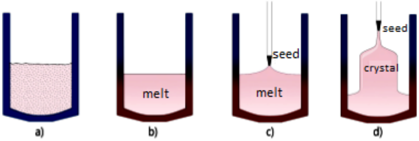

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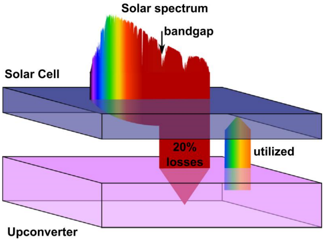


Samples made:

- $BaY_2F_8{:}Pr^{3+}$
- $BaY_2F_8{:}Yb^{3+}$-Pr^{3+}
- $BaY_2F_8{:}Er^{3+}$

At the present we focus on only Upconversion phenomenon

$BaY_2F_8:Er^{3+}$ Absorption (Upconversion)

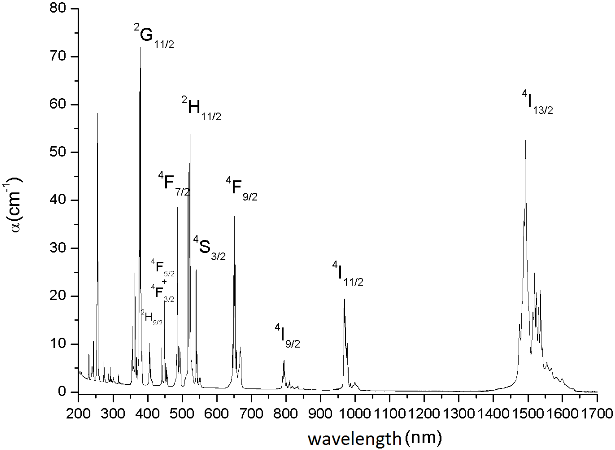
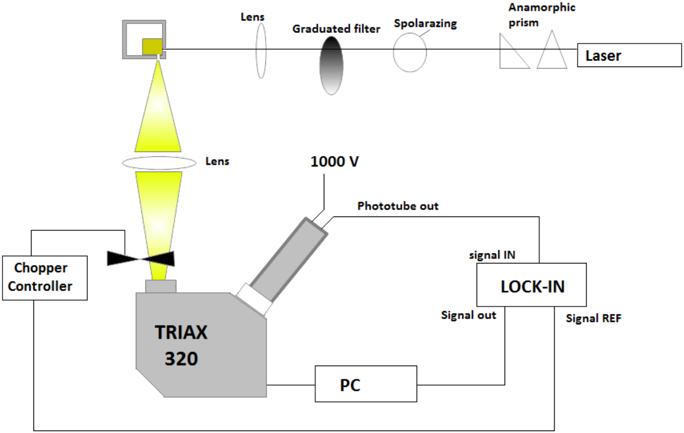


Figure: Absorption of the sample: BaY_2F_8:30%Er^{3+}

Experimental apparatus for fluorescence measurement



$BaY_2F_8:Er^{3+}$ Fluorescence (Upconversion)

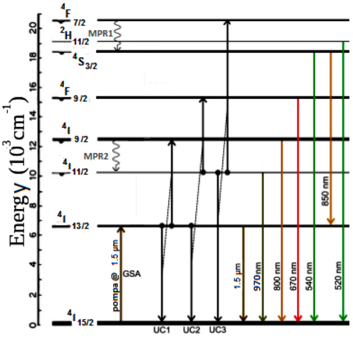


Figure: Pump scheme for the ion Er^{3+}

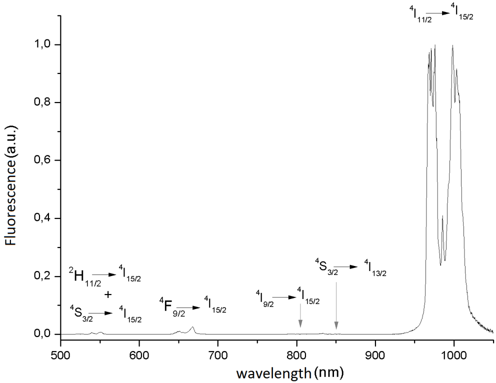


Figure: fluorescence of the sample BaY_2F_8:30%Er^{3+}

98% of the radiation up-converted is around 1 μm where there is the maximum silicon cell efficiency

EQE

External **Q**uantum **E**fficiency is defined as:

$$EQE = \frac{\#\text{electron per unit of time}}{\#\text{photon per unit of time}}$$

then leading to:

$$EQE = \frac{hc}{e} \frac{I_{sc}(\lambda)}{P_{inc}(\lambda) \cdot \lambda}$$

$$I_{sc} = \int_{E_g}^{\infty} EQE(E)\Phi_{inc}(E)dE \qquad \eta = \frac{max\,|(I_{sc} - I_d(V))V|}{P_{inc}}$$

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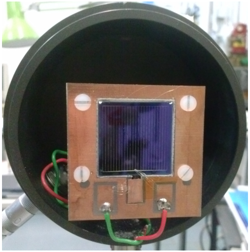


Figure: Bi-facial cell used for Upconversion phenomenon

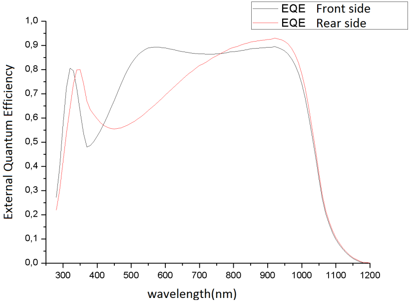
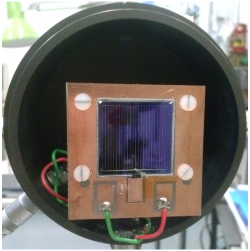


Figure: External Quantum Efficiency



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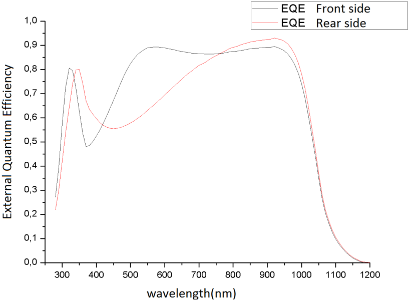

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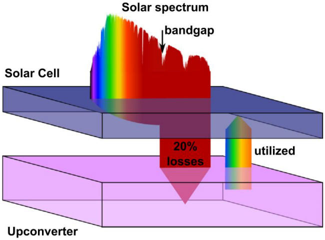
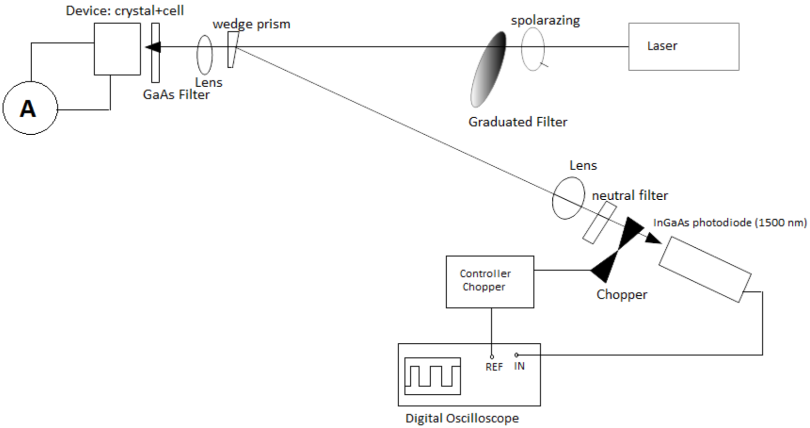


Experiment set-up for EQE measurement



EQE at 1.5 µm using mono-crystal

EQE with laser pump tuned at 1558 nm

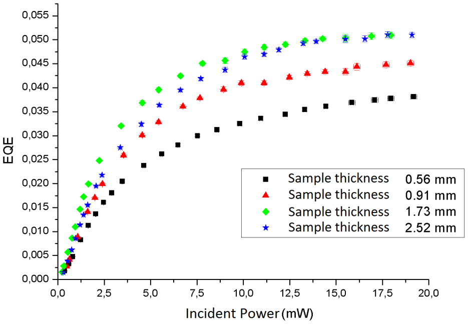
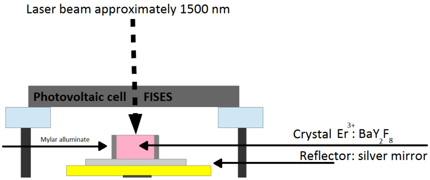


Figure: EQE configuration 1



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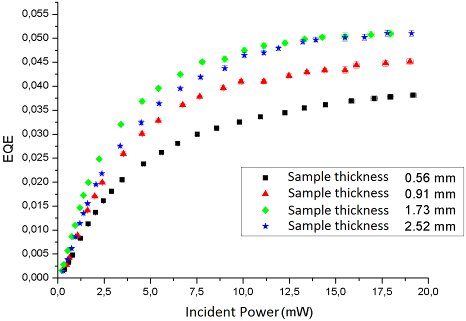

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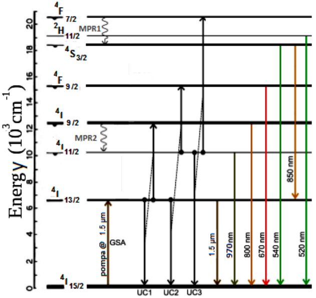
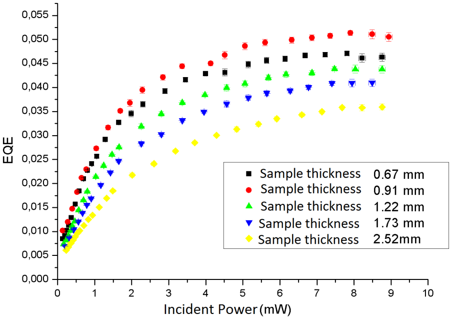


Figure: Pump scheme of the ion Er^{3+}

EQE at 1.5 μm using mono-crystal

EQE using laser pump tuned at 1485 nm



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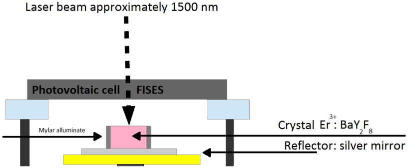

Figure: configurazione 1

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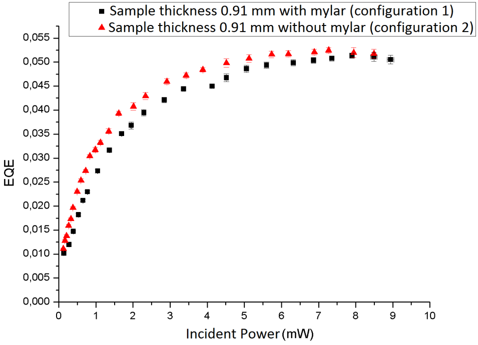
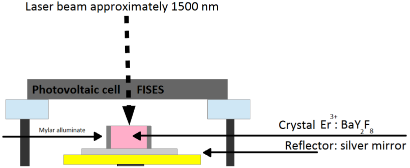


Figure: EQE configuration 1 e 2



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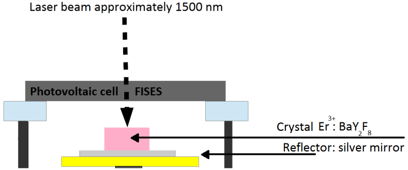


Figure: configuration 2

EQE at 1.5 µm with mono-crystal

EQE using laser pump tuned at 1485 nm

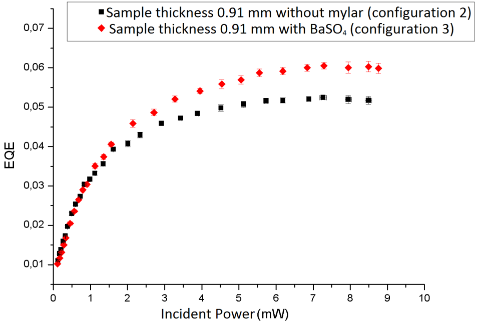
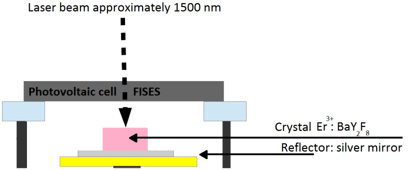


Figure: EQE configuration 2 e 3



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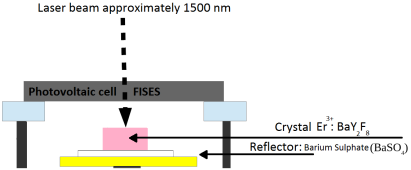

Figure: configuration 3

EQE at 1.5 μm with mono-crystal

EQE with laser pump tuned at 1494 nm

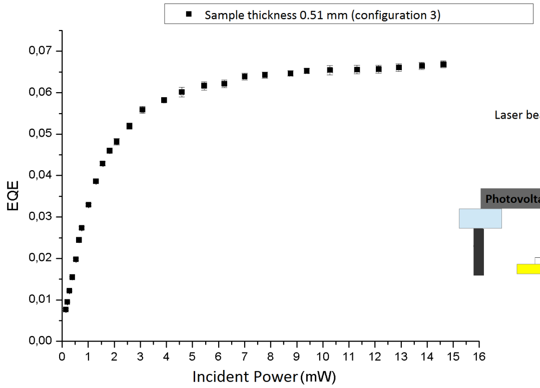

Figure: EQE with the configuration 3

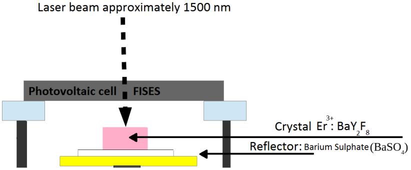

Figure: configuration 3

Sun concentration

$$C = \frac{\int \alpha(\lambda) T_{cell}(\lambda) \Phi_{laser}(\lambda) d\lambda}{\int \alpha(\lambda) T_{cell}(\lambda) \Phi_{AM1.5}(\lambda) d\lambda}$$

where:
$T_{cell}(\lambda)$ is the solar cell trasmittance
$\alpha(\lambda)$ is the absorption coefficient of the converter crystal
$\Phi_{AM1.5}(\lambda)$ is the flux of photon of the AM1.5 spectrum
$\Phi_{laser}(\lambda)$ is the laser flux
schematise as:

$$\Phi_{laser}(\lambda) = \frac{\lambda}{hc} I(\lambda) \delta(\lambda - \lambda_0)$$

in which λ_0 is our pump wavelength

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Conclusion

Result obtained

- The best result is EQE=6.7±0.2% using mono-crystal and it is given with $C=16\cdot10^3$ and $(1.10\pm0.12)\cdot10^5$ W m^{-2} at 1494 nm
- Thanks to collaboration with Fraunhofer Institute it was able to carry out measurements both with laser at 1522 nm getting EQE=8.0±0.2% with 4530 ± 240 W m^{-2} and with solar simulator. At the moment the mono-crystal shows a $\Delta J_{SC,UC}=17.27\pm3.0$ mA cm^{-2} [1] at an illumination with $C=94\pm17$, equivalent to a record relative enhancement of the $I_{sc}=0.55\pm0.14\%$.
- The previous best value, using β–$NaYF_4$:25% Er^{3+}, was $I_{sc}=0.19\pm0.04\%$ but with $C=207\pm86$ [2],at the same solar concentration factor C the new record is nearly tripling the previously highest value reported in lecture.

Possible improvements

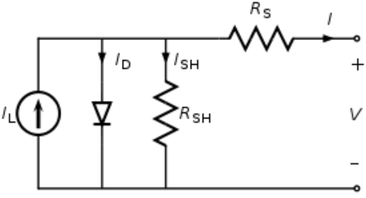
- Employment of other Rare Earth ions for taking advantages of different conversion region
- Possible research about new host crystal like $LiYF_4$, KY_3F_{10} o $LiLuF_4$

[1] Solar Energy & Materials Solar Cells 136(2015) 127–134

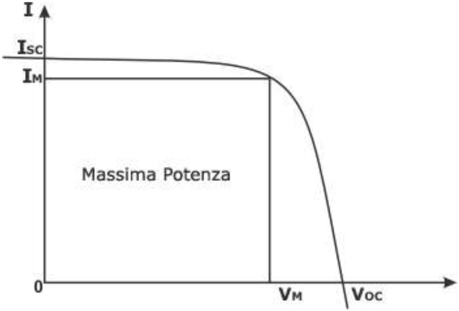
[2] IEEE J. Photovolt. 4 (2014)183–189.

Scheme of photovoltaic cell

A photovoltaic cell can be schematised in this way:



$$I = I_L - I_D - \frac{V + IR_S}{R_{SH}}$$

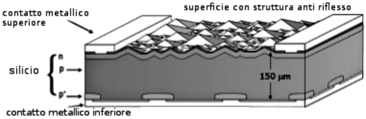


$$\eta = \frac{I_{max} \cdot V_{max}}{P_{inc}}$$

modern generation of solar cell

- First generation(conversion efficiency equal to 25%*)
- Second generation(conversion efficiency equal to 20%*)
- Third generation(conversion efficiency equal to 44%*)

* Measures carried out in laboratory and reported by NREL (National Renewable Energy Laboratory)



- junction p-n of c-Si o m-Si
- thickness included between 150-250 µm

modern generation of solar cell

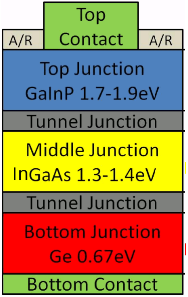
- First generation(conversion efficiency equal to 25%*)
- Second generation(conversion efficiency equal to 20%*)
- Third generation(conversion efficiency equal to 44%*)

* Measures carried out in laboratory and reported by NREL (National Renewable Energy Laboratory)

- thin film junction with thickness included between 1-10 μm
- p-n junction with new material as a-Si, CdTe o CIGS

modern generation of solar cell

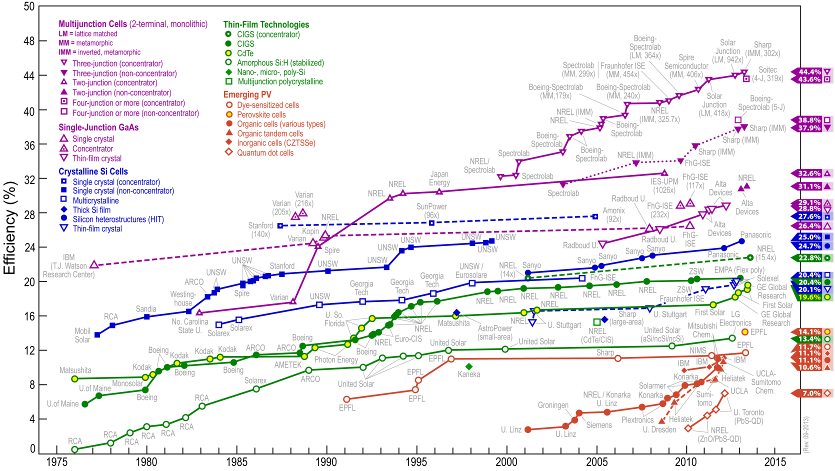
- First generation(conversion efficiency equal to 25%*)
- Second generation(conversion efficiency equal to 20%*)
- Third generation(conversion efficiency equal to 44%*)



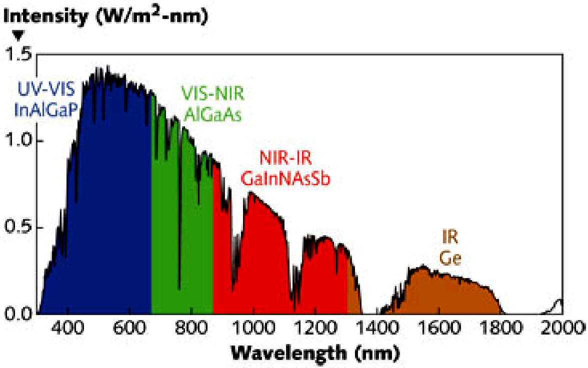
* Measures carried out in laboratory and reported by NREL (National Renewable Energy Laboratory)

- research of maximum efficiency using material with several gaps with tandem configuration

Best Research-Cell Efficiencies



Back to Rare Earth



▸ Back to Rare Earth

Upconversion

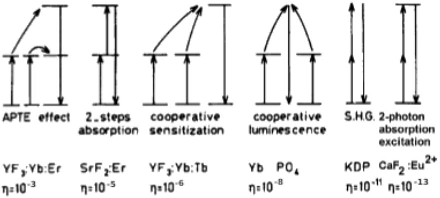


Figure: all kind of upconversion with relative efficiency

back to phenomenon of conversion

ETU(Energy Transfer Upconversion)

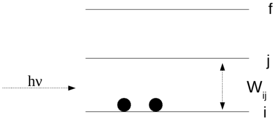


Figure: Absorption first photon

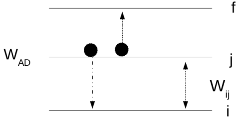


Figure: ETU(Energy Transfer Upconversion)

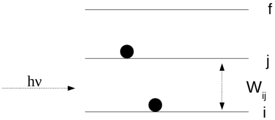


Figure: Absorption second photon

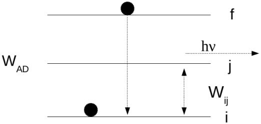


Figure: Emission of one photon

$$W_{if} = N_{Er} * W_{ij}^2 * W_{AD} \propto I^2$$
$$W_{ij} \propto I$$

▸ back to EQE at 1.5 μm

Dependence of the EQE on incident power

$$EQE = \frac{hc}{e} \frac{I_{sc}(\lambda)}{P_{inc}(\lambda) \cdot \lambda}$$

Downconversion/Downshift $I_{sc} \propto P_{inc} \rightarrow EQE \propto Cost$

Upconversion $I_{sc} \propto P_{inc}^2 \rightarrow EQE \propto P_{inc}$

back to EQE at 444 nm

back to EQE at 1.5 µm

Cell plus converter in device configuration for EQE at 1.5 µm

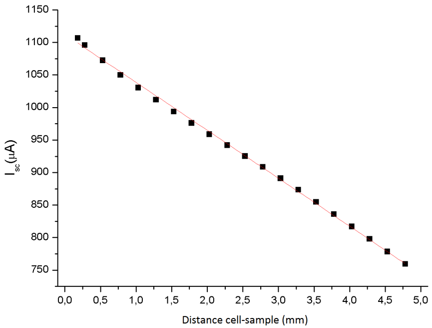


Figure: Current supply as function of the cell converter distance

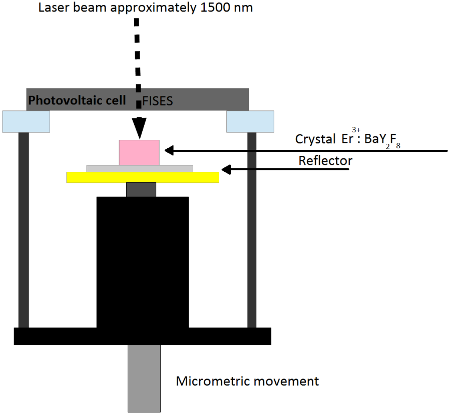


Figure: General configuration of cell+crystal converter

Cell plus converter in device configuration for EQE at 1.5 μm

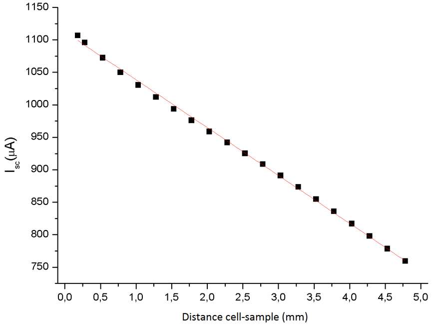


Figure: Current supply as function of the cell converter distance

Figure: General configuration of cell+crystal converter