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Luminescent solar concentrator

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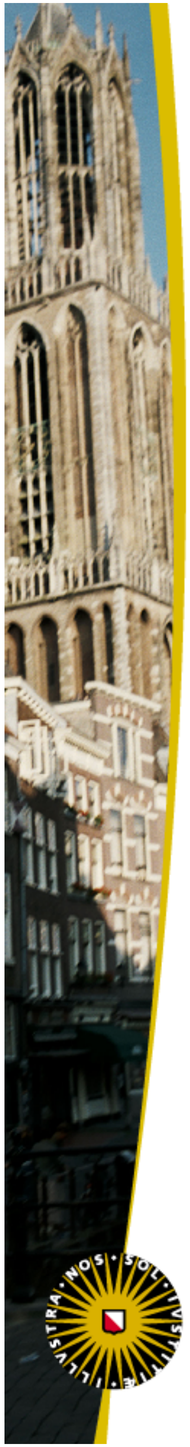

Luminescent solar concentrator

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Winter College on Optics and Energy
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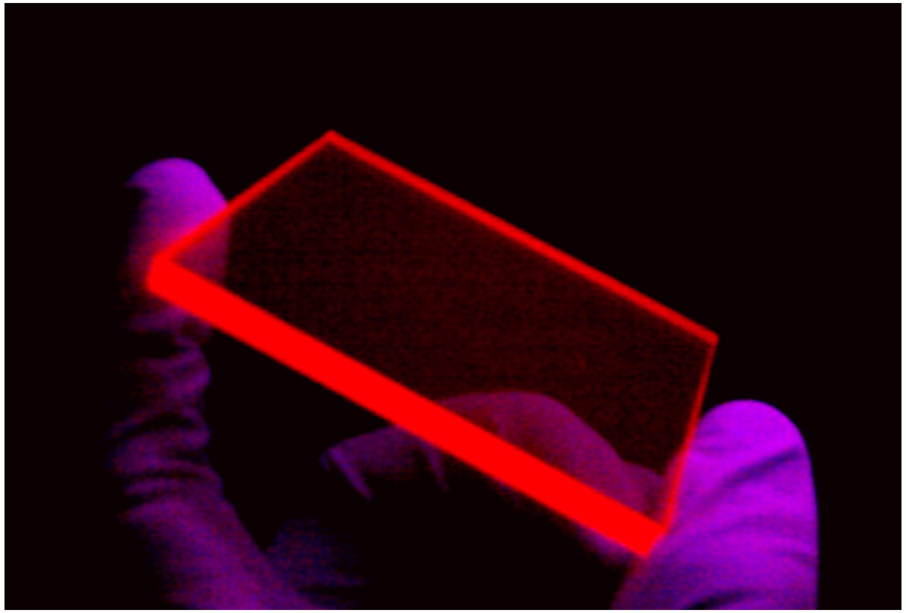

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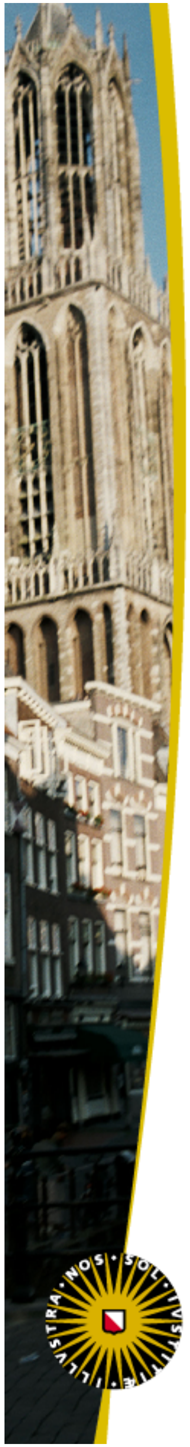
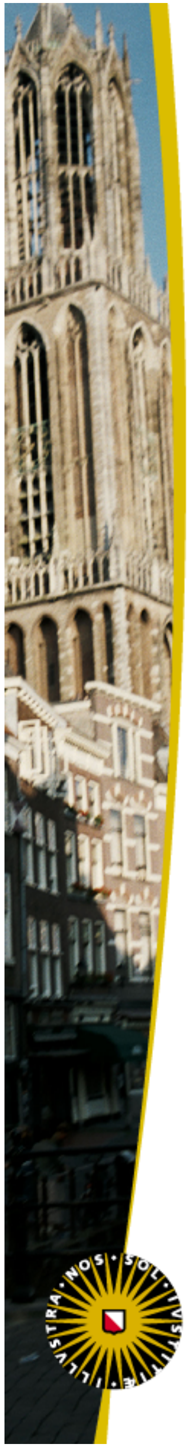
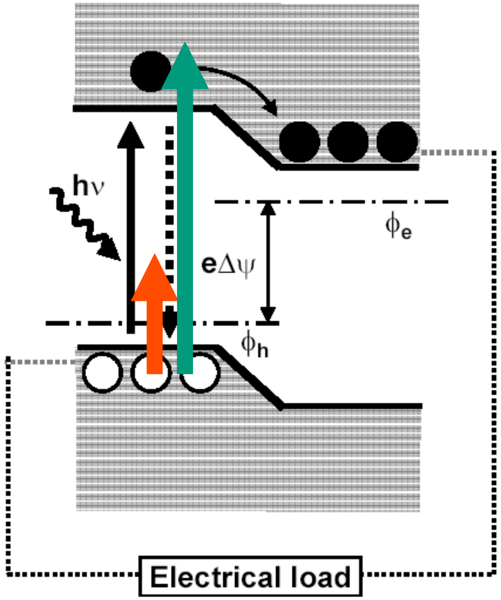


Introduction



Introduction

- Solar cell efficiency limited to 30% on thermodynamic grounds
  - pn junction optimal for monochromatic light
- Fundamental loss terms (Si)
  - **Spectral** (50% loss)
    - No absorption for $E_{ph} < E_g$
    - Partial use of energy when $E_{ph} > E_g$
- Practical limit presently ~15% (mc-Si)
- Challenge: use **complete** solar spectrum



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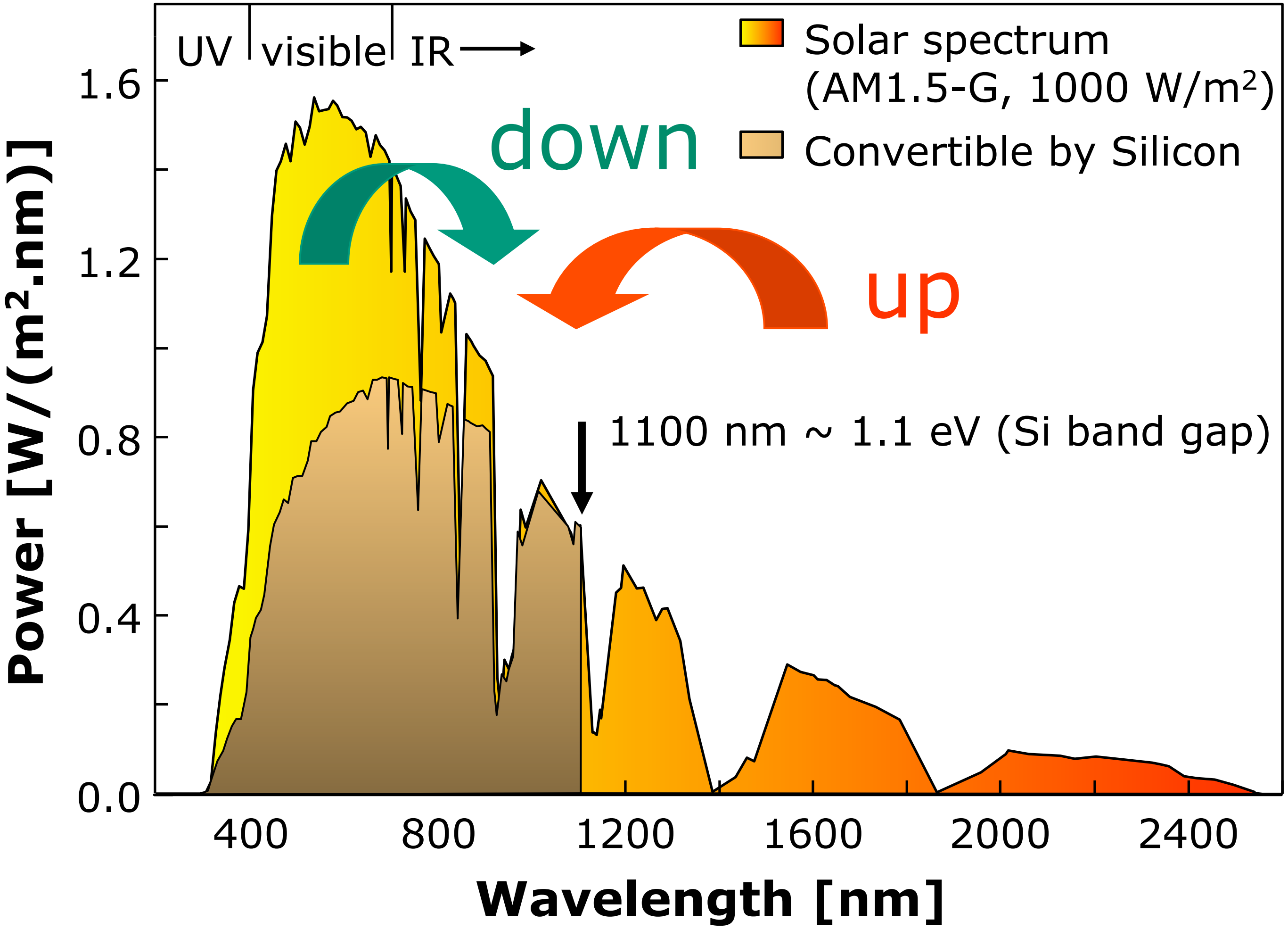
Spectral down/up conversion



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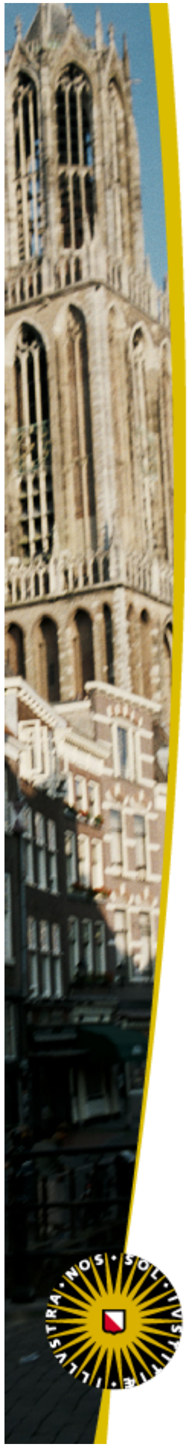
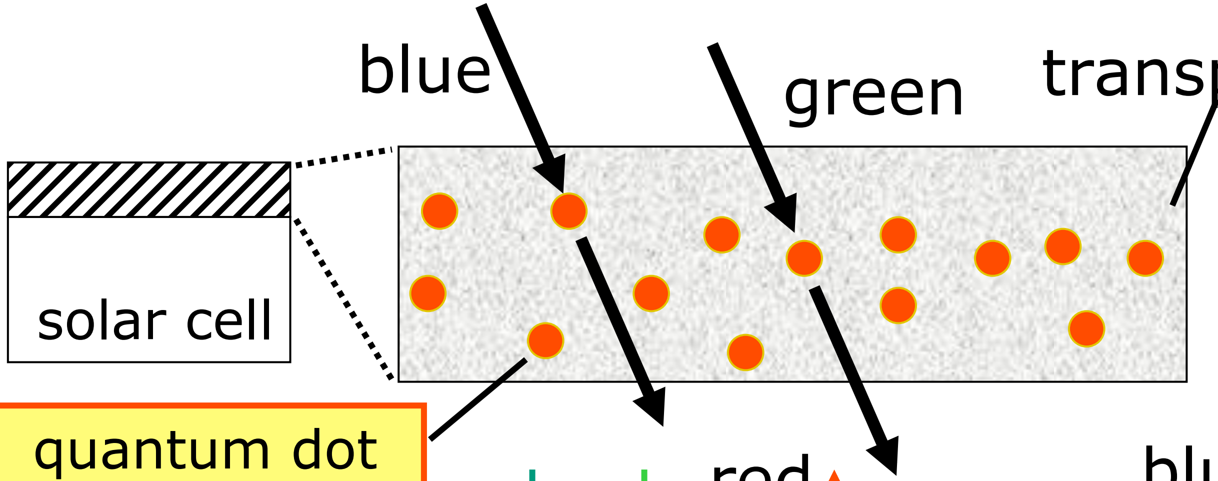
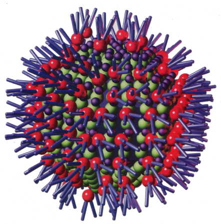
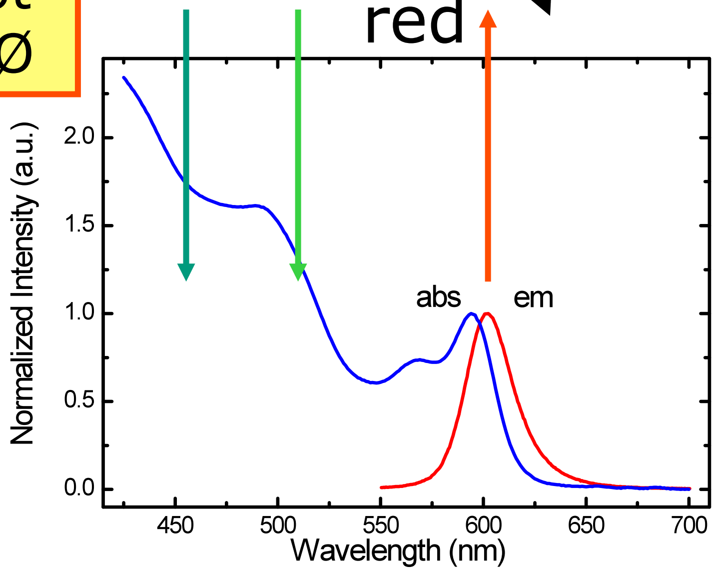


Example: spectral down shifter



quantum dot
CdSe, 4 nm Ø





blue and green absorption
→ red emission

AM1.5G: 10% increase in short circuit current
[Van Sark *et al*, Sol.Eng.Mat.Sol.Cells 2005]

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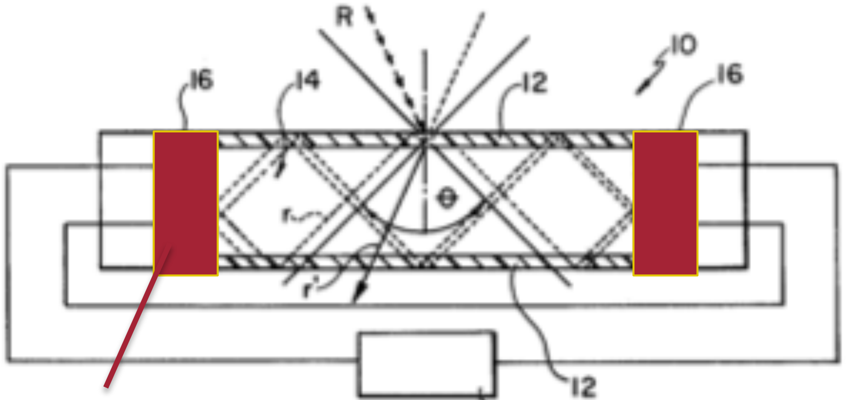
Introduction

- Luminescent solar concentrator (LSC) proposed as possible low-cost alternative for high-cost photovoltaic cells (Goetzberger, 1970s)
- LSC employs spectral down shifters/ converters
- US patent (1979)
  - 4,149,902



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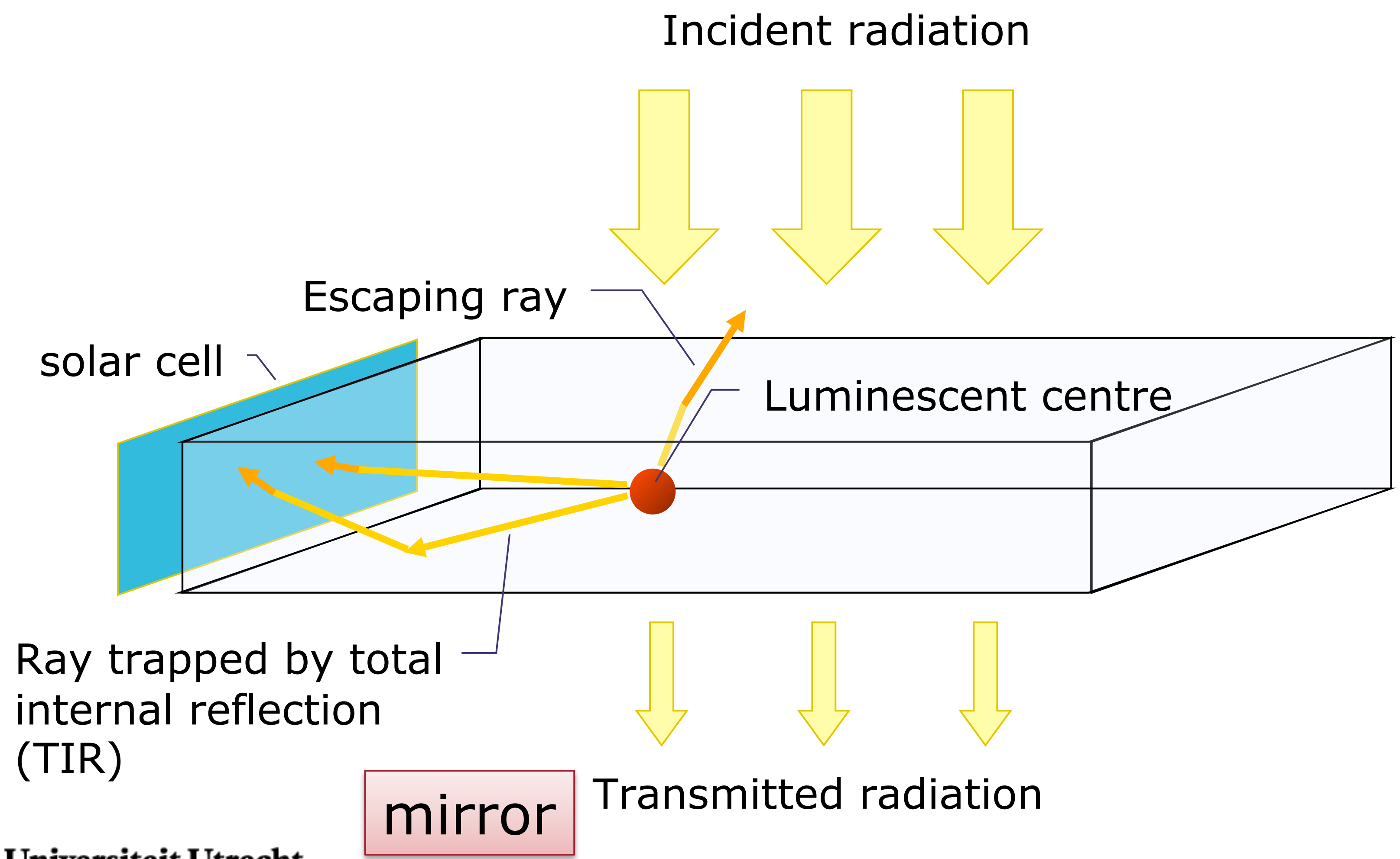
Luminescent Solar Concentrator



[Bose, 2007]

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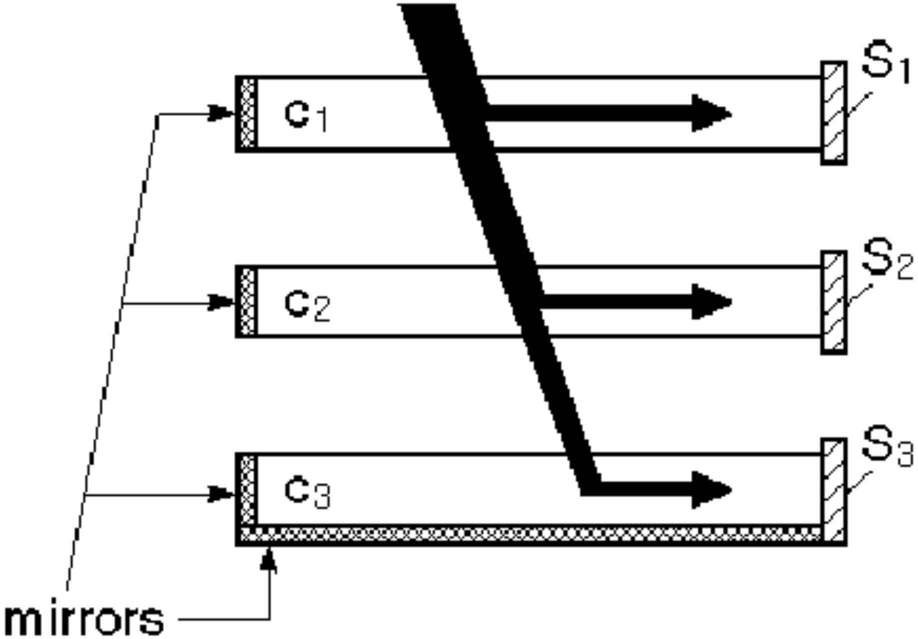
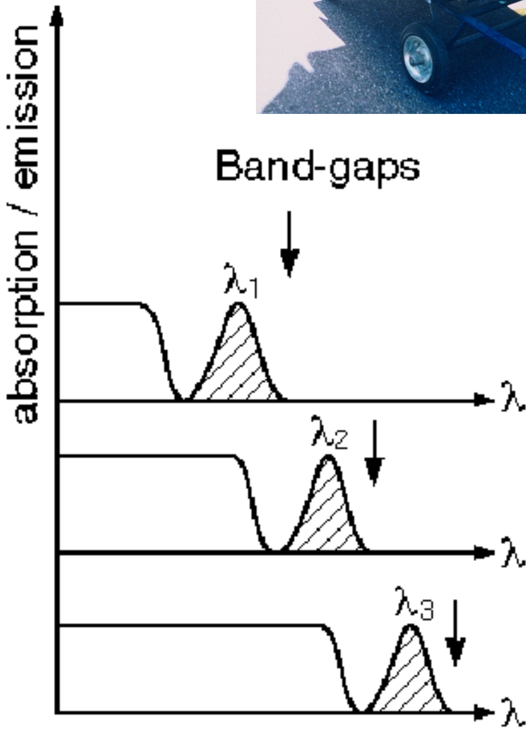
Stacks

- Similar to triple-junction solar cells





[Goetzberger, 1970s]

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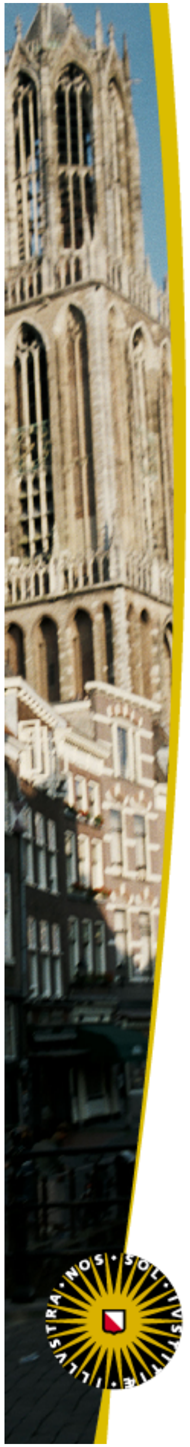

Introduction

- Diffuse solar irradiation constitutes half of irradiation at higher latitude → no conventional optical concentrators
- Polymer based materials "capture" diffuse irradiation due to low index of refraction, trapping efficiency ~75%
- Collects direct and diffuse light
  - In the UK over 7× as much solar energy falls on buildings as is consumed inside and about half of this is diffuse [Chatten, 2008]

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LSC advantages

- Concentration ratio 5-10X
- Non-tracking concentrator!
- Present efficiency record: 7.1%
- Reduce the costs of PV electricity
  - Large area cheap plastic
  - Small area not-so-cheap solar cell
- Ideally suited to building integration

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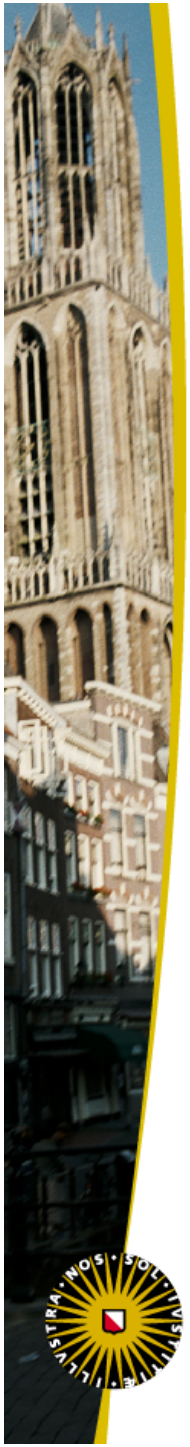

Basic principles

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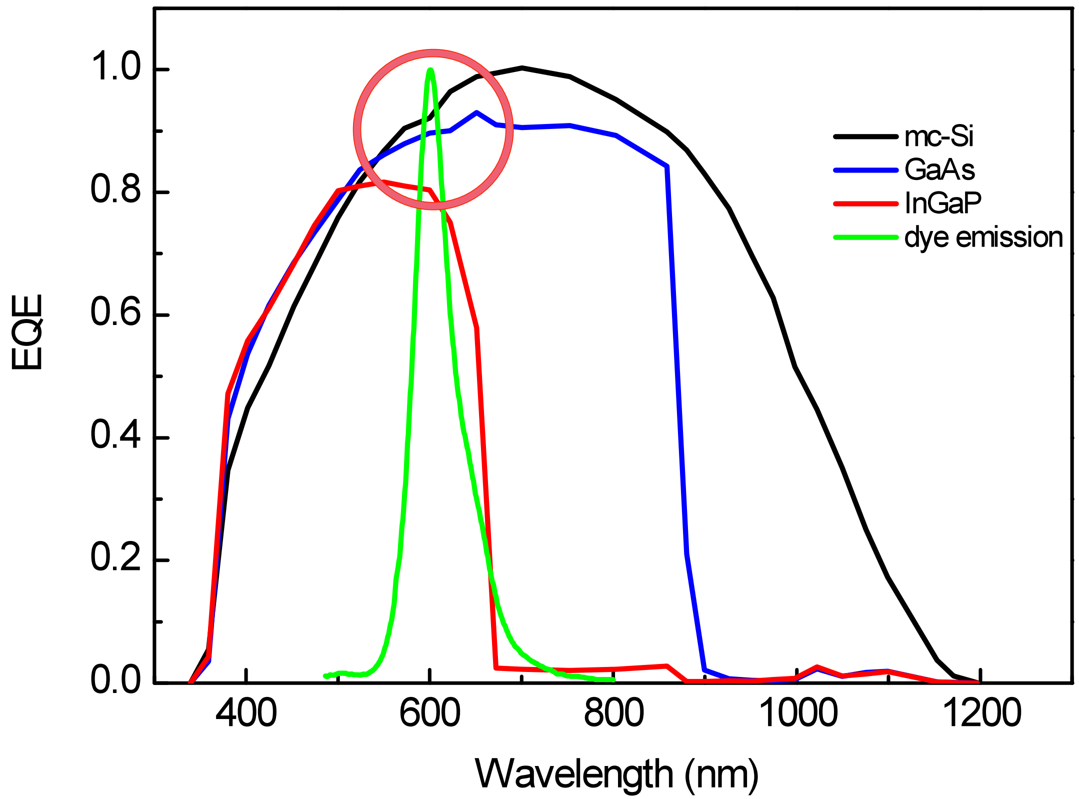
Basic principles

- Efficiency of LSC $\eta_{LSC} = \eta_{opt}\eta_{PV}$
- Optical efficiency η_{opt} ; PV efficiency η_{PV}
- Note: at emission wavelength, PV efficiency is high



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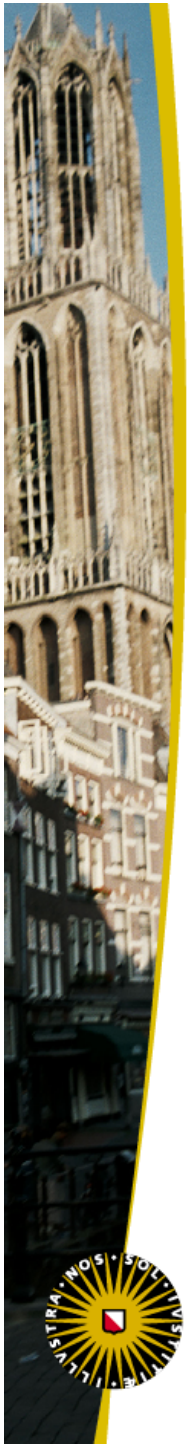

Optical efficiency

$$\eta_{opt} = (1-R)\,\eta_{abs}\eta_{LQE}\eta_{S}\eta_{trap}\eta_{mat}\,(1-\eta_{self})\,\eta_{TIR}$$

R	reflection coefficient
η_{abs}	absorption efficiency
η_{LQE}	luminescent quantum efficiency
η_{S}	Stokes' efficiency
η_{trap}	trapping efficiency
η_{mat}	transmission efficiency through matrix
η_{self}	efficiency of self absorption
η_{TIR}	total internal reflection efficiency

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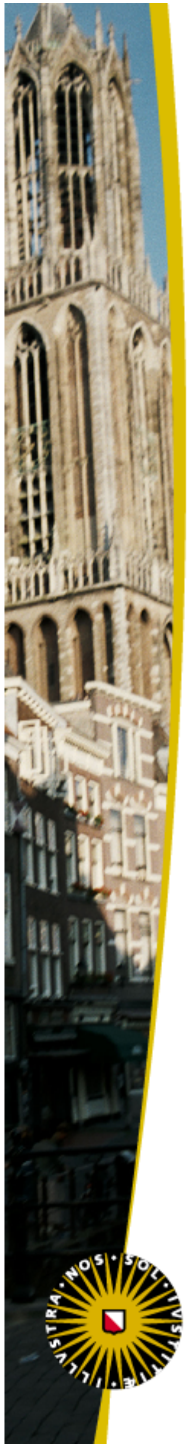


Optical efficiency

- Surface reflection loss (Fresnel)

$$1 - R = \left(\frac{n-1}{n+1} \right)^2$$

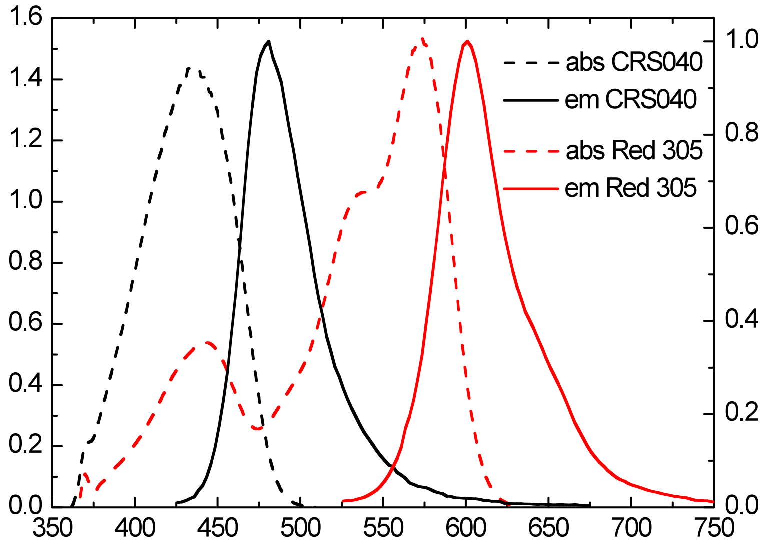
- Polymethylmethacrylate (PMMA):

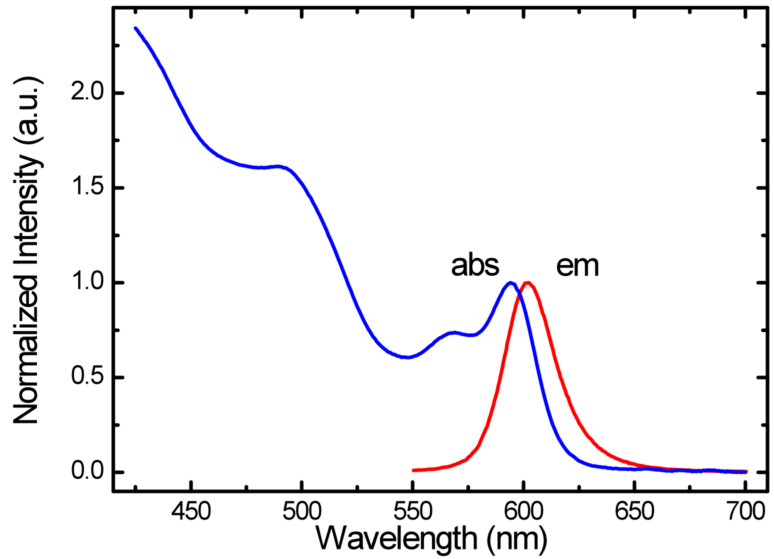
  $n = 1.49 \quad 1\text{-}R = 3.9\%$

- Can be lowered using anti-reflection coating

Optical efficiency

- Absorption efficiency η_{abs}
- Depends on luminescent species:
  - Organic dyes, narrow absorption bands
  - Nanocrystals, broad absorption bands





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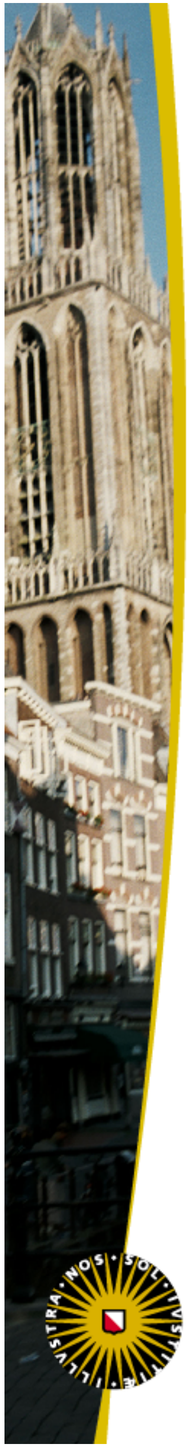
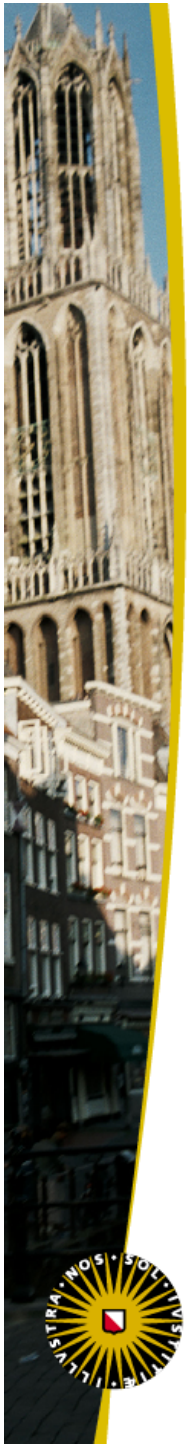


Optical efficiency

- Luminescent quantum efficiency η_{LQE}
- Depends on luminescent species:
  - Organic dyes: 90-95%
  - Nanocrystals: 20-80%

- Stokes' efficiency η_S
  - Must be small for low energy loss
  - Must be large for low self-absorption

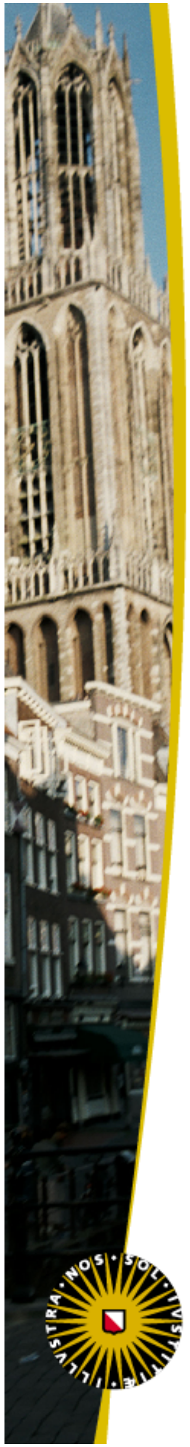


Optical efficiency

- Trapping efficiency

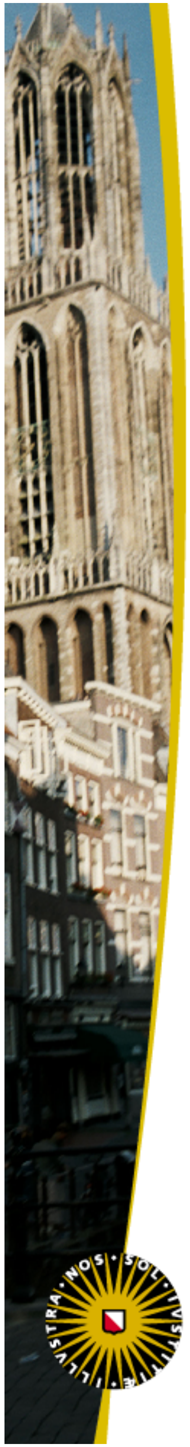
$$\eta_{trap} = \frac{\sqrt{n^2 - 1}}{n}$$

- For PMMA: $\eta_{trap} = 0.741$
- Can be enhanced by selective mirrors (dichroic/photonic)



Optical efficiency

- Transmission through material efficiency
  η_{mat}
- Depends on scattering in the matrix
  - Absorption coefficient ~1 m^{-1}
  - Lambert-Beer $I = I_o \exp(-\alpha x)$
- Self absorption depends on species, and leads to red shift of emission
- Total internal reflection depends on surface quality



Optical efficiency

$1-R$	reflection	96%
η_{abs}	absorption	15-20%
η_{LQE}	LQE	95%
η_{S}	Stokes'	85-95%
η_{trap}	trapping	74%
η_{mat}	transmission	85-95%
η_{self}	selfabsorption	50-80%
η_{TIR}	TIR	90%

$$\Rightarrow \eta_{opt} = 3.2 - 8.8\%$$

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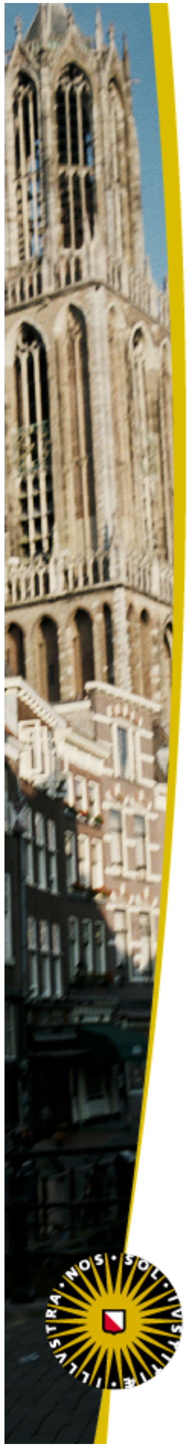
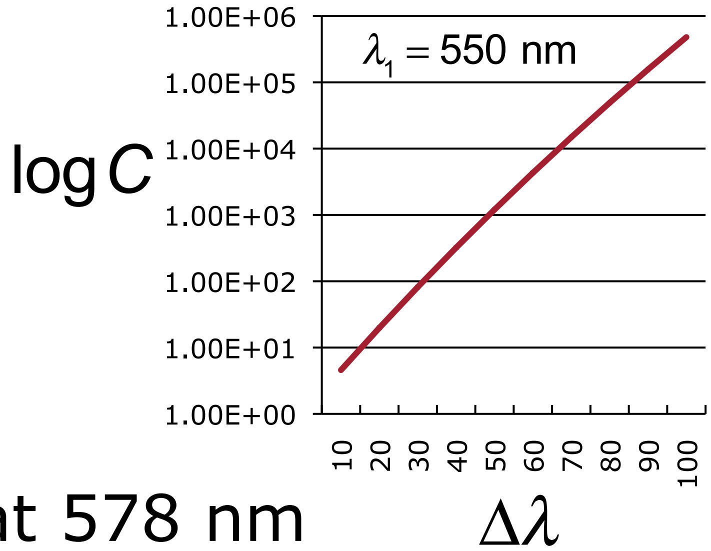


Concentration

- Maximum concentration depends strongly on Stokes' shift [Yablonovitch, 1980]

$$C \le \left(\frac{\nu_2}{\nu_1}\right)^2 \exp\left(-\frac{h\Delta\nu}{k_B T}\right)$$



- Lumogen F Red dye:
  - Absorption maximum at 578 nm
  - Emission maximum at 613 nm

→C=119

(order of magnitude larger than obtained in practice!)

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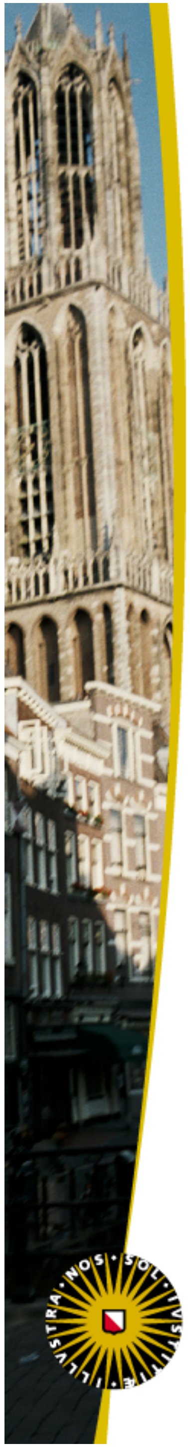
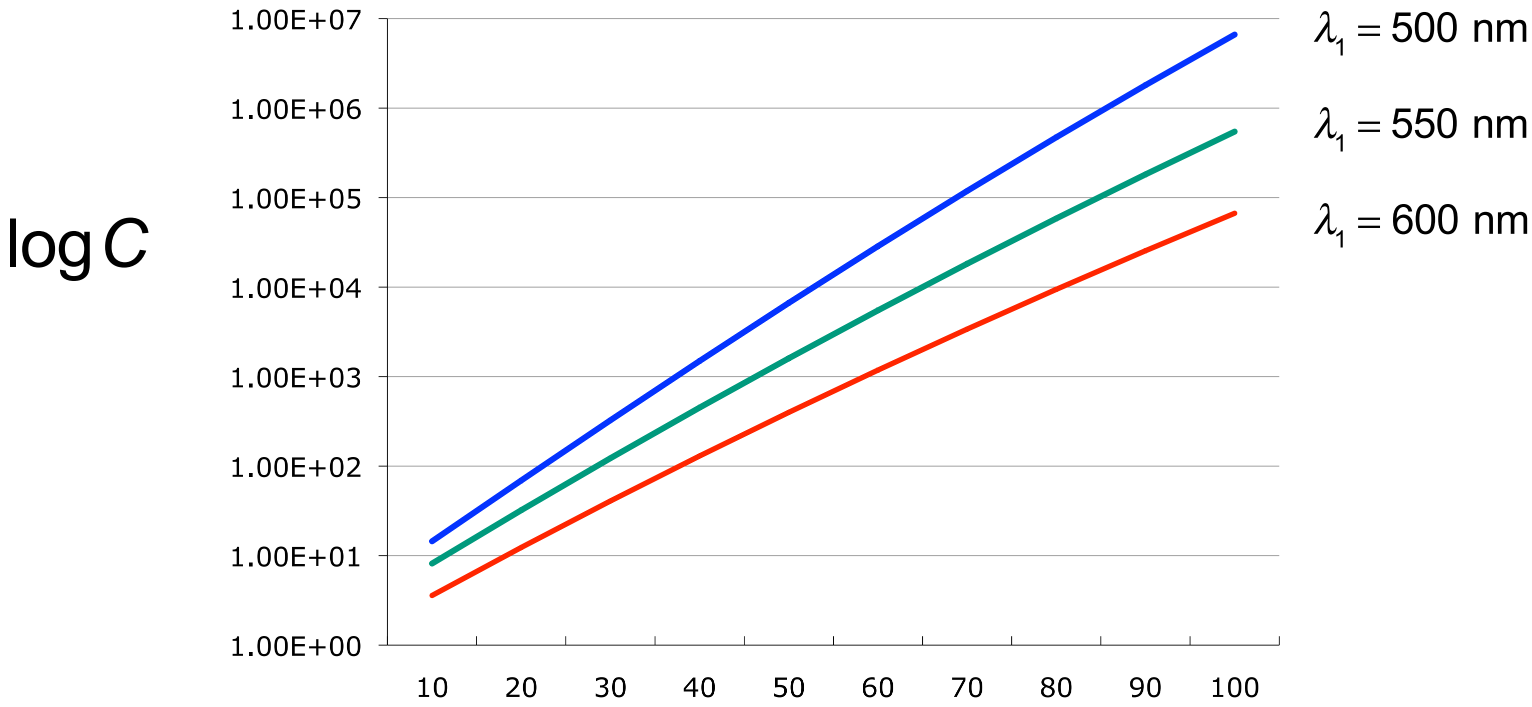


Concentration

- Dependence on absorption maximum wavelength

$$C \leq \left(\frac{\nu_2}{\nu_1} \right)^2 \exp\left(-\frac{h\Delta\nu}{k_B T} \right)$$



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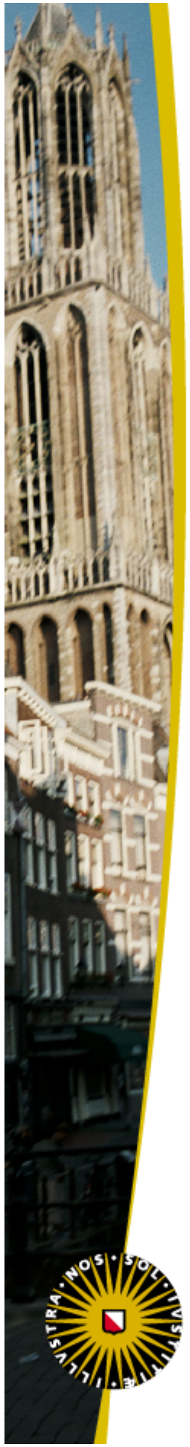

Modelling

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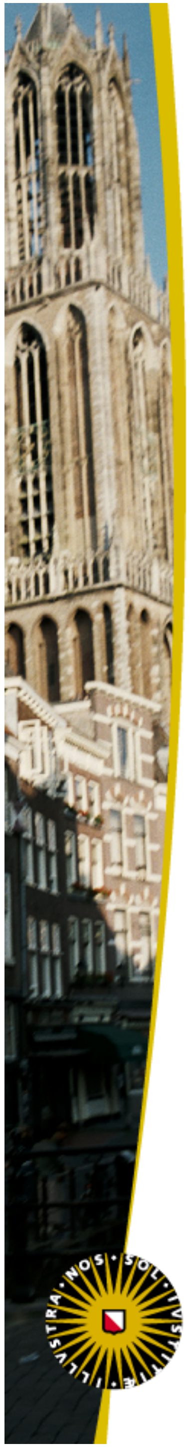
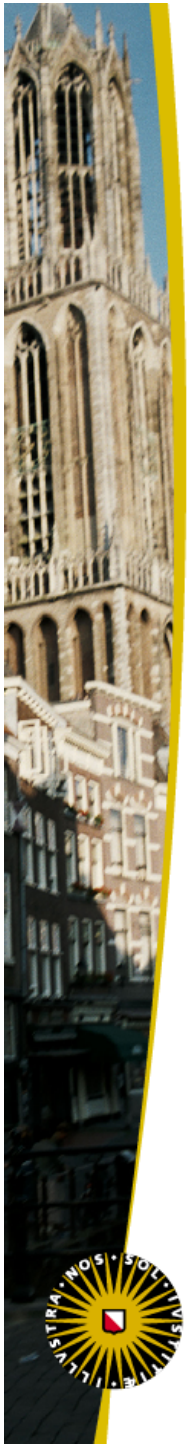


Modelling

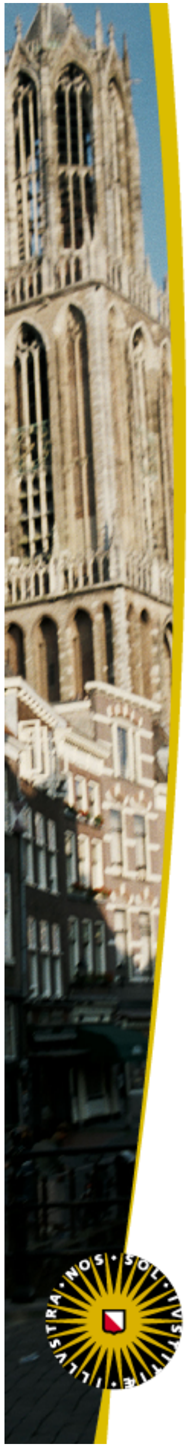
- Two models

- Thermodynamic model
  - Based on radiative energy transfer between points (of a mesh) in the concentrator
- Ray-trace model
  - Every incoming photon is tracked and its fate is determined using Monte Carlo principles



Thermodynamic model

- Yablonovitch [1980] was the first to develop a thermodynamic model
  - applying a detailed balance argument to relate the absorbed light to the spontaneous emission
  - 1D model: obtain the photon chemical potential as *f(x)* only
- Not accounted for
  - absorption of incident flux by matrix
  - spectral overlap of the incident radiation with the luminescence
  - re-absorption of radiation emitted into the escape cone
  - reflection at surfaces
  - losses owing to absorption in the host
- Chatten [2004] developed self-consistent 3D flux model, considering reflection and transmission at the surfaces



Thermodynamic model

- Brightness B of radiation field in equilibrium with electronic degrees of freedom of absorbing species

$$B(\nu) = \frac{8\pi n^2 \nu^2}{c^2} \frac{1}{e^{(h\nu - \mu)\beta} - 1}$$

n = refractive index
$\beta = 1/kT$
μ = chemical potential

[Yablonovitch, 1980]
[Chatten, 2004]

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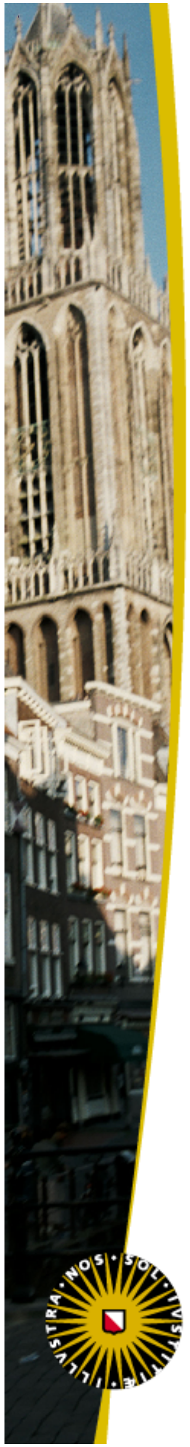

Thermodynamic model

- Applying the principle of detailed balance within the absorber leads to:

$$F(\mu) = \int d\nu N\sigma_e(\nu) I_C(\nu) - \int d\nu \frac{N\sigma_e(\nu)}{Q_e} B(\nu) = 0 = A - E_C$$

I_C = concentrated radiation field
Q_e = quantum efficiency
N = density of luminescent centres
σ_e = absorption cross section
W_c = escape cone
W_2 = 4π – 2
W_c totally internally reflected solid angle in 1D

$I_1(n)$
$z = 0$
W_c
W_2
W_c
$z = D$
x
y
z

[Chatten, 2004]

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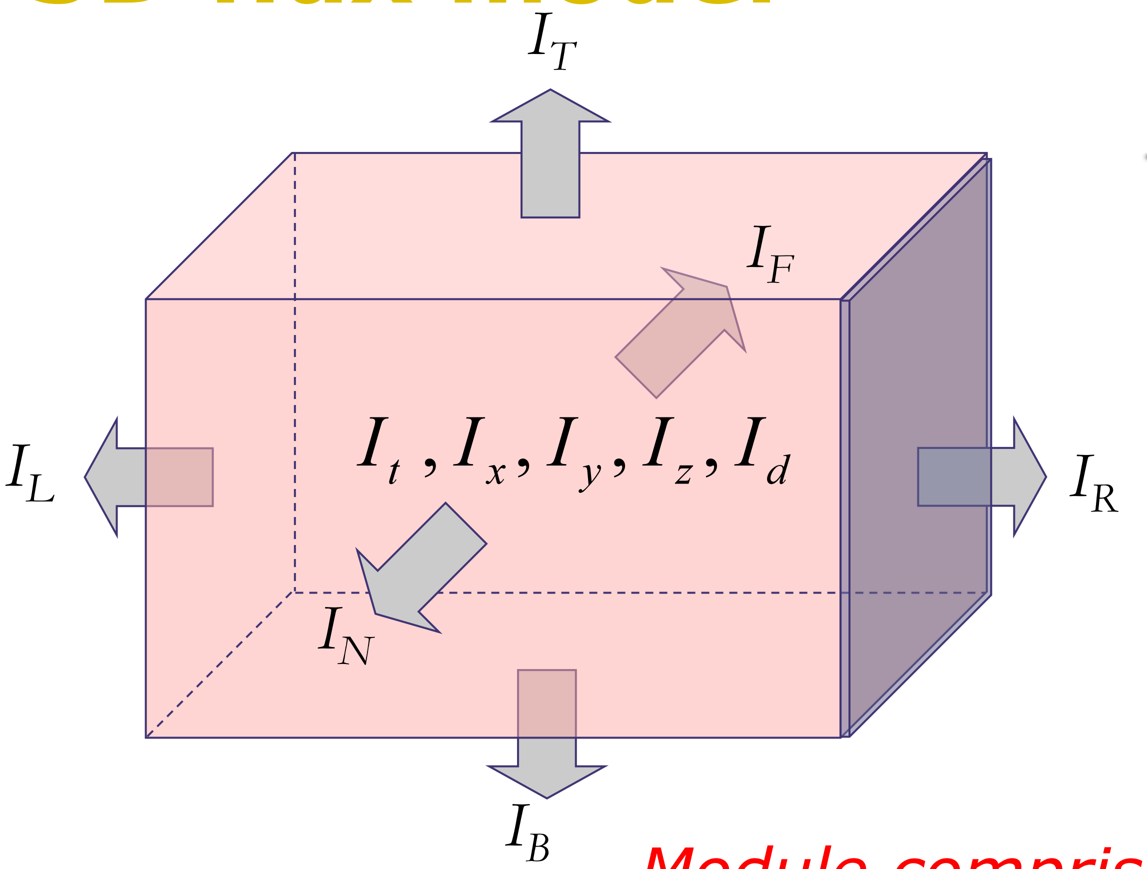
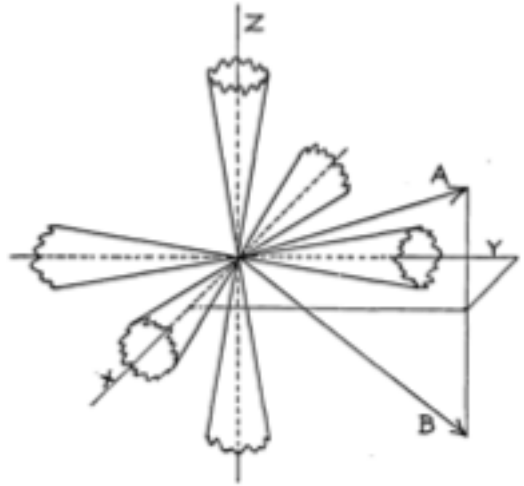
Yablonovitch, 1980

3D flux model





6 escape cones
[Shurcliff, 1949]

Module comprises a slab with a solar cell bonded to the right-hand surface

[Chatten, 2004]

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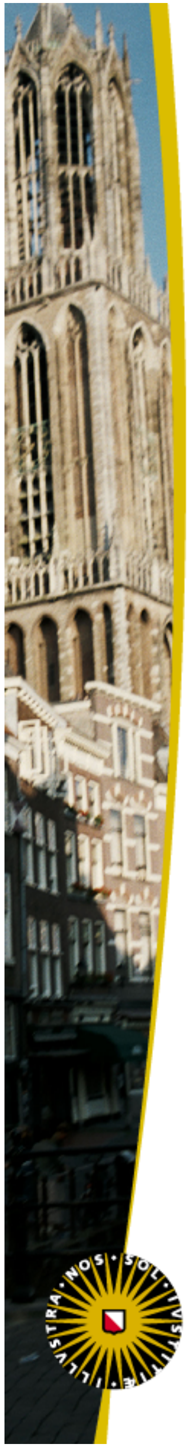

3D flux model

1. integrating the differential equations for the fluxes
2. evaluating the resulting expressions at the surfaces
3. applying appropriate boundary conditions considering reflection and transmission at the surfaces

→ derive the trapped and escaping intensities within the slab and fluxes exiting the surfaces

(thin plates: analytically) [Chatten, 2004]

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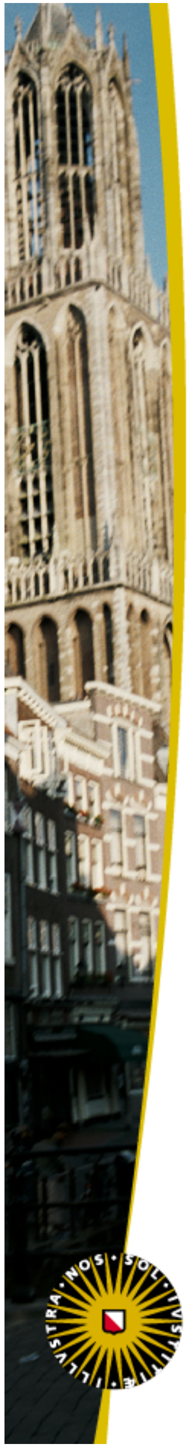
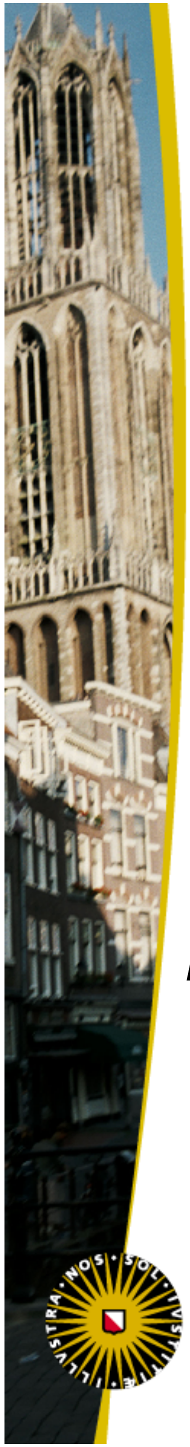


3D flux model

4. Chandrasekhar's general three-dimensional radiative transfer equation
5. Schwarzschild and Milne, detailed angular dependence of the radiative intensity is ignored; radiation is either forward (+) or backward (-) streams
6. Treat the escaping photons ($q < q_c$) and the trapped photons ($q > q_c$) as separate streams

[see for details: Chatten, 2004]



3D flux model

- Escaping intensity in x-direction:

$$I_x(x,y,z) = \frac{\Omega_c \lambda_e \cosh\left(\lambda_a x + \frac{\alpha_L}{2}\right)}{2\pi \sinh\left(\lambda_a L + \alpha_{LR}\right)} \int_0^L dx' \cosh\left[\lambda_a (L - x') + \frac{\alpha_R}{2}\right] B(x',y,z)$$

$$- \frac{\Omega_c \lambda_e}{2\pi} \int_0^x dx' \sinh\left[\lambda_a (x - x')\right] B(x',y,z)$$

- Trapped intensity

$$I_t(x,y,z) = \frac{\Omega_6 \lambda_{et} \cosh\left(\lambda_{at} x\right)}{4\pi \sinh\left(\lambda_{at} L + \frac{\alpha_t}{2}\right)} \int_0^L dx' \cosh\left[\lambda_{at} (L - x') + \frac{\alpha_t}{2}\right] B(x',y,z)$$

$$- \frac{\Omega_6 \lambda_{et}}{4\pi} \int_0^x dx' \sinh\left[\lambda_{at} (x - x')\right] B(x',y,z)$$

[Chatten, 2004]

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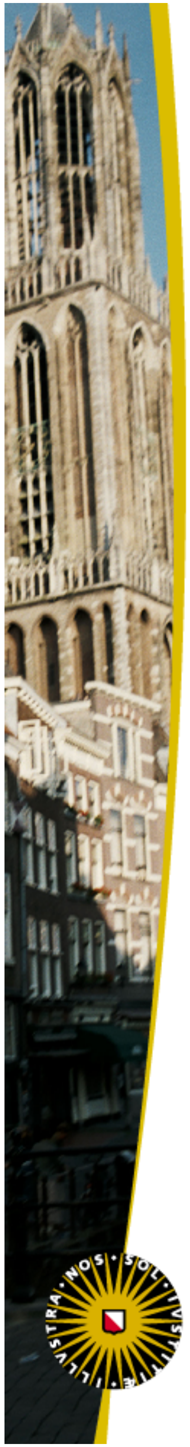

3D flux model

- Flux exiting on to the solar cell:

$$I_R(y,z)=\frac{\Omega_c\lambda_e}{2\pi}\frac{e^{-\alpha_{LR}}e^{-\lambda_a L}\sinh\left(\frac{\alpha_R}{2}\right)}{\sinh\left(\lambda_a L+\alpha_{LR}\right)}\int_0^L dx'\cosh\left[\lambda_a\left(L-x'\right)+\frac{\alpha_B}{2}\right]B\left(x',y,z\right)$$

$$+\frac{\Omega_c\lambda_e e^{-\frac{\alpha_R}{2}}\sinh\left(\frac{\alpha_R}{2}\right)}{2\pi}\int_0^L dx' e^{-\lambda_a\left(L-x'\right)}B\left(x',y,z\right)$$

$$+\frac{\Omega_6\lambda_{et}}{8\pi}\frac{e^{-\frac{\alpha_t}{2}}e^{-\lambda_{at}L}\sinh\left(\frac{\alpha_t}{2}\right)}{\sinh\left(\lambda_{at}L+\frac{\alpha_t}{2}\right)}\int_0^L dx'\cosh\left[\lambda_{at}\left(L-x'\right)+\frac{\alpha_t}{2}\right]B\left(x',y,z\right)$$

$$+\frac{\Omega_6\lambda_{et}e^{-\frac{\alpha_t}{2}}\sinh\left(\frac{\alpha_t}{2}\right)}{8\pi}\int_0^L dx' e^{-\lambda_{at}\left(L-x'\right)}B\left(x',y,z\right)$$

[Chatten, 2004]

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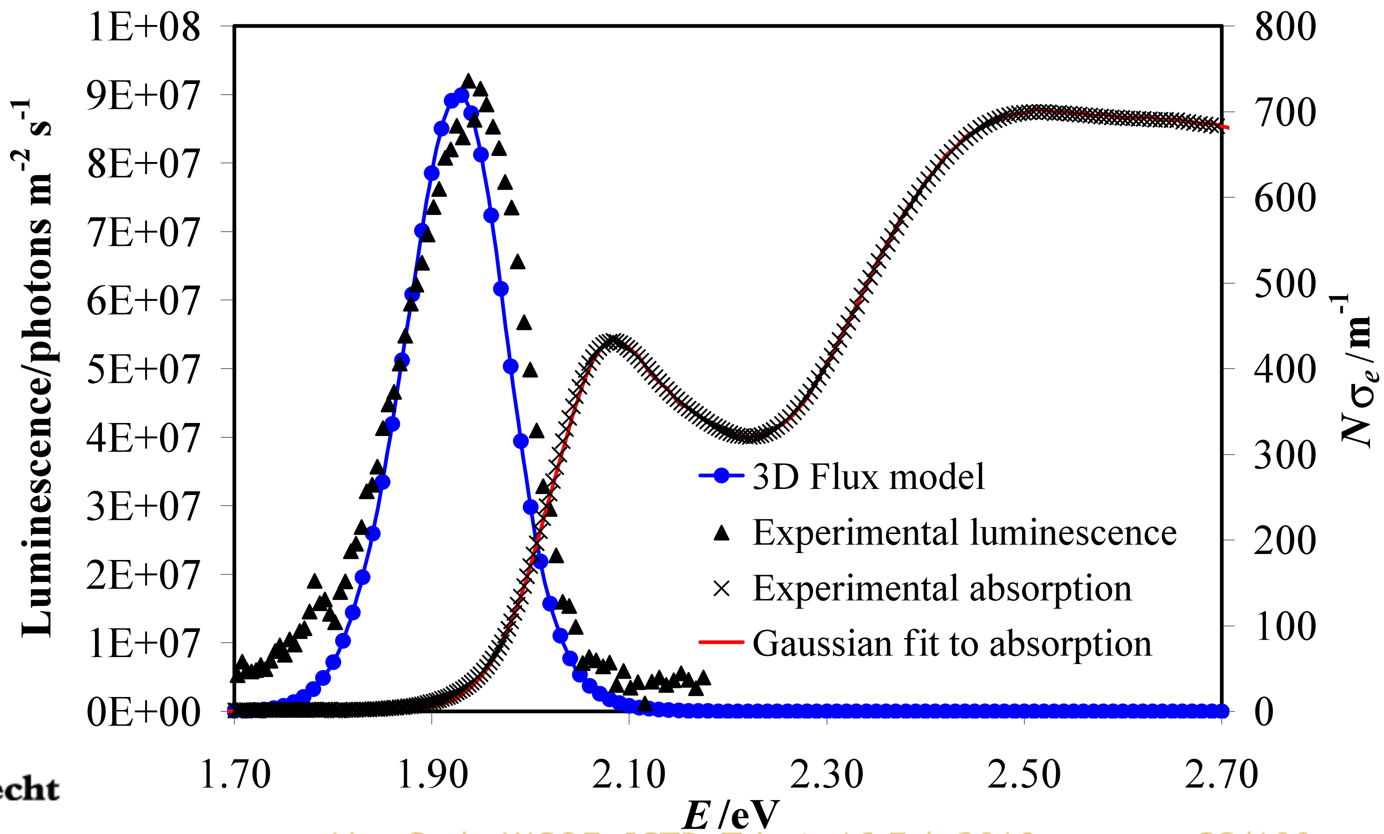
3D flux model - results

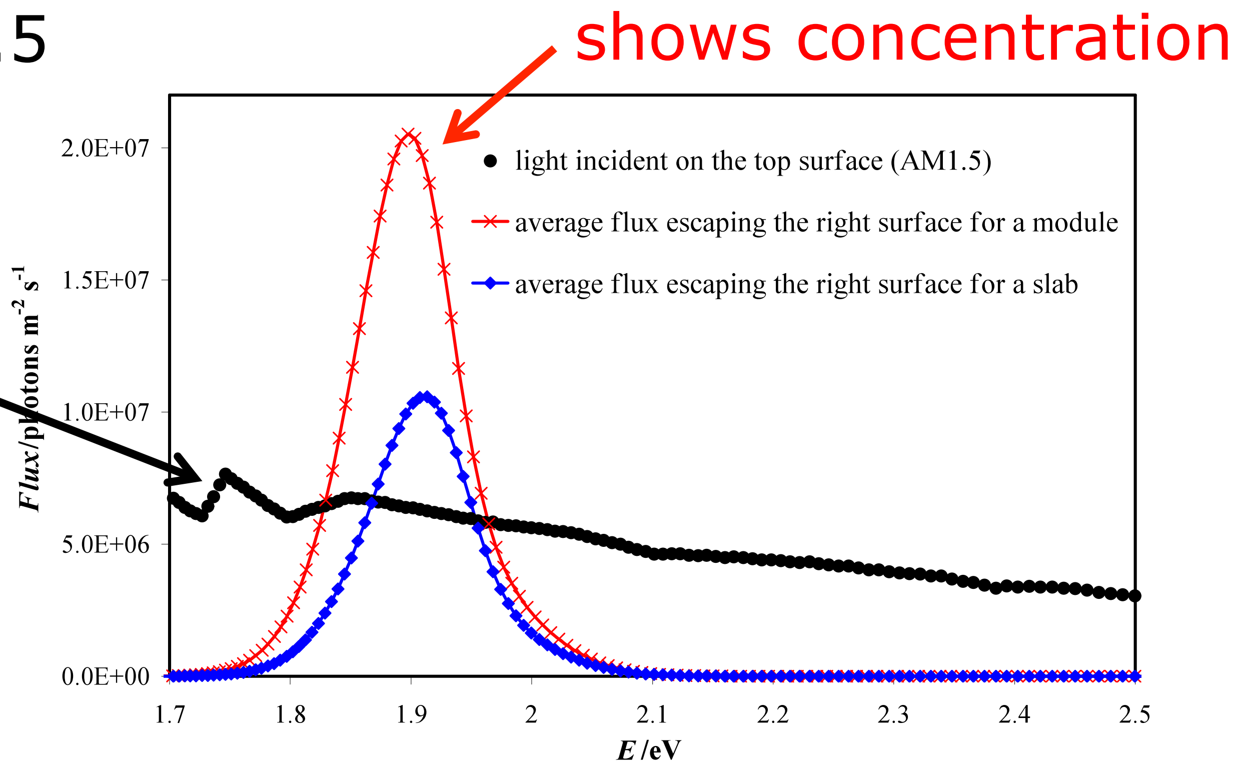
- Modelled and measured luminescence for a 1cm thick sample of CdSe/CdS core-shell dots in acrylic illuminated by a 530 nm laser

[Chatten, 2008]



3D flux model – predicted fluxes

- Predicted fluxes escaping right hand side
- $L \times W \times D = 42 \times 10 \times 5\ mm^3$ slab
- CdSe/CdS QDs in acrylic, connected to cell
- LQE of 0.5
- AM1.5



[Chatten, 2008]

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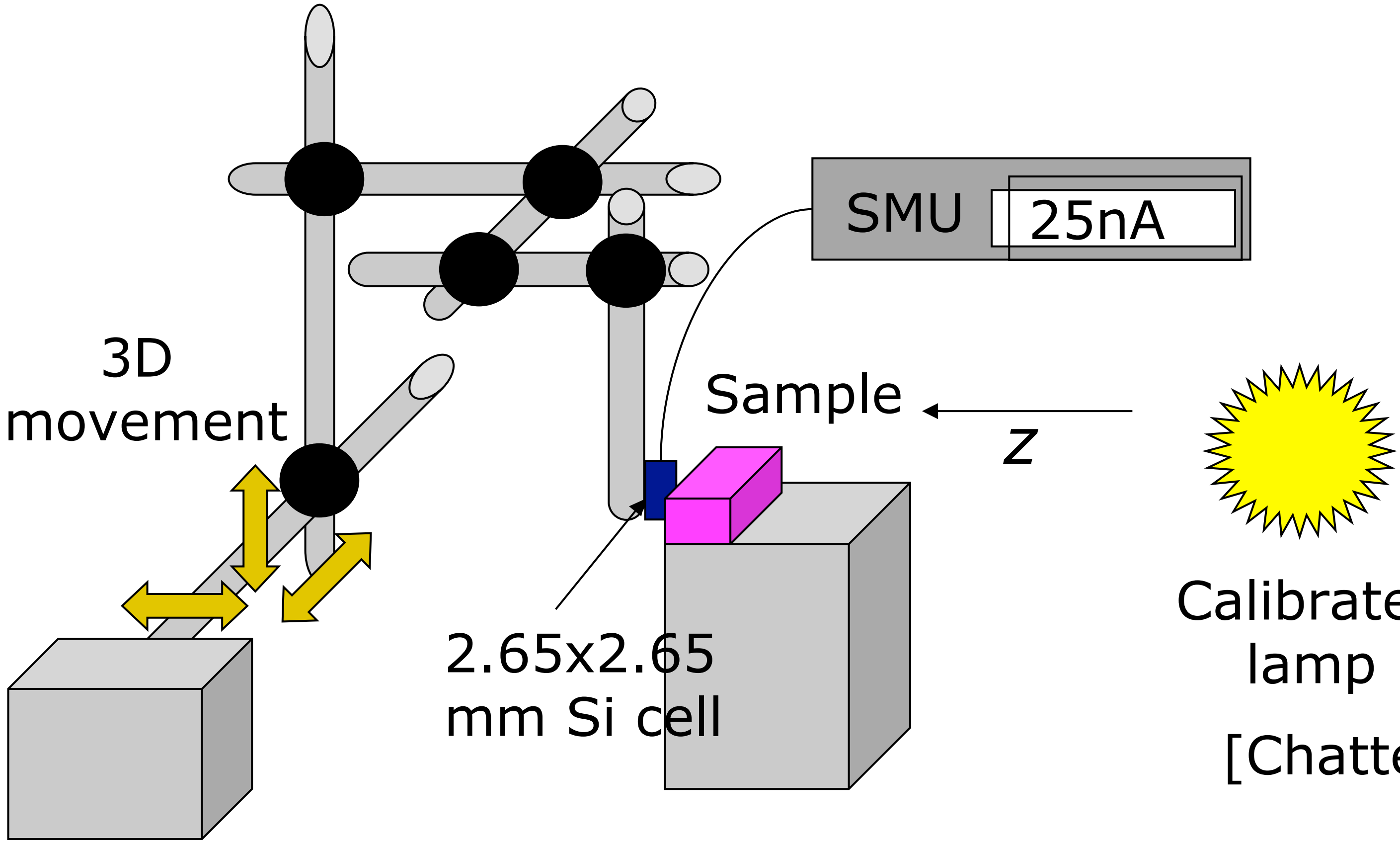
3D flux model - results

- Measure short circuit current I_{sc} of cell bonded to the right-hand surface for modules, or of 2.65mm cell flush to the right-hand surface for slabs



[Chatten, 2008]

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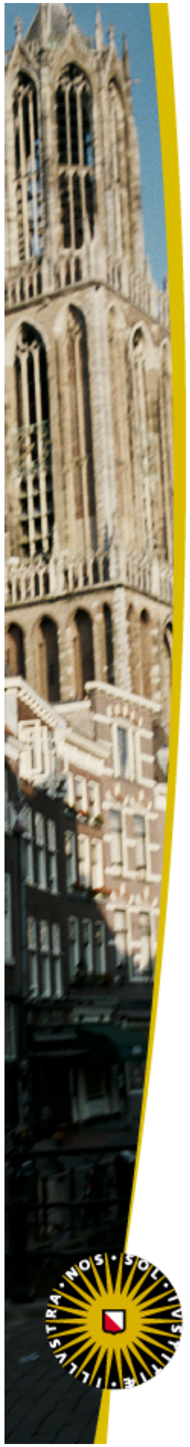

3D Flux model - results

- Measured and predicted short circuit currents, J_{sc}, for the slabs and module investigated → good agreement

Slab/Module	Slab Size (mm)	Q_e	J_{sc}/mA m^{-2} @ x =	
			Exp	Pred
CdSe/CdS QD slab	42×10×5	0.50	11.1±2.0	10.0±1.4
Red dye slab	40×15×3	0.95	20.1±2.0	22.1±1.7
Mirrored red dye slab	40×15×3	0.95	26.0±2.0	26.2±2.6
Red dye module	40×15×3	0.95	31.1±2.0	29.3±2.8

- Evaporated Al mirrors
- BP Si concentrator cell on RHS

[Chatten, 2008]

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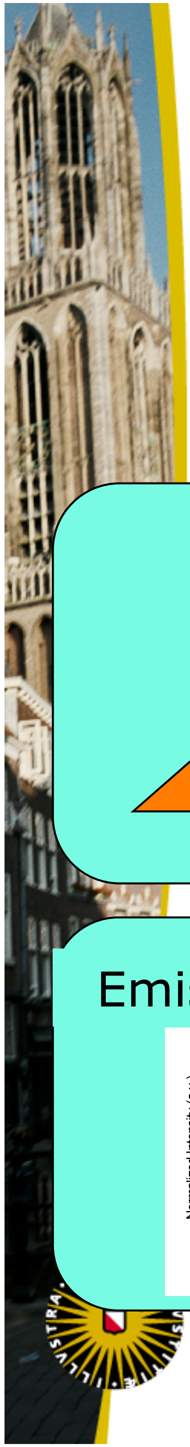
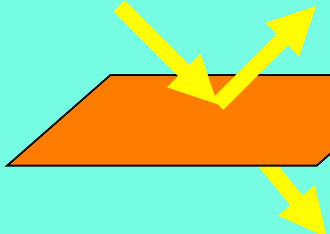


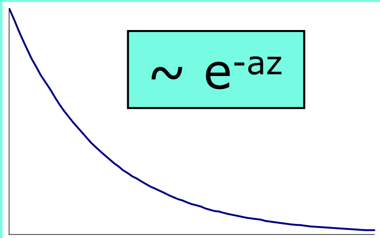
Ray trace model

- Tracing photons of specific wavelength using geometrical optics
- Random numbers determine outcome

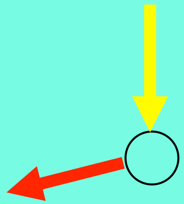
Reflection or transmission



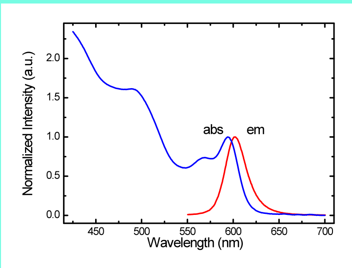
Absorption (path length)



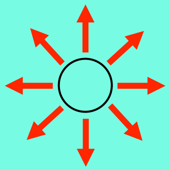
Re-emission



Emission wavelength



Direction of emission



+ versatile
- large number of rays required

Burgers, 2005
Bose, 2007

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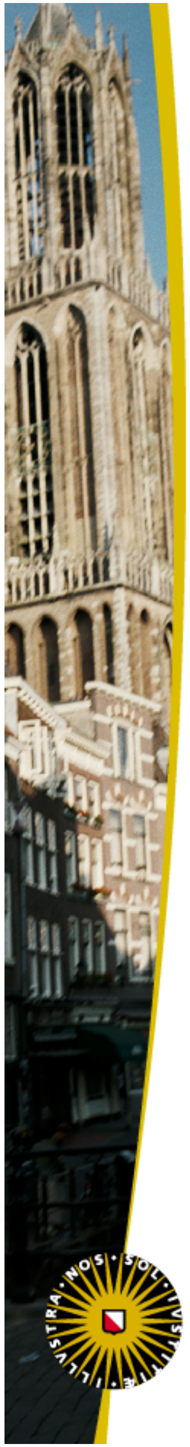
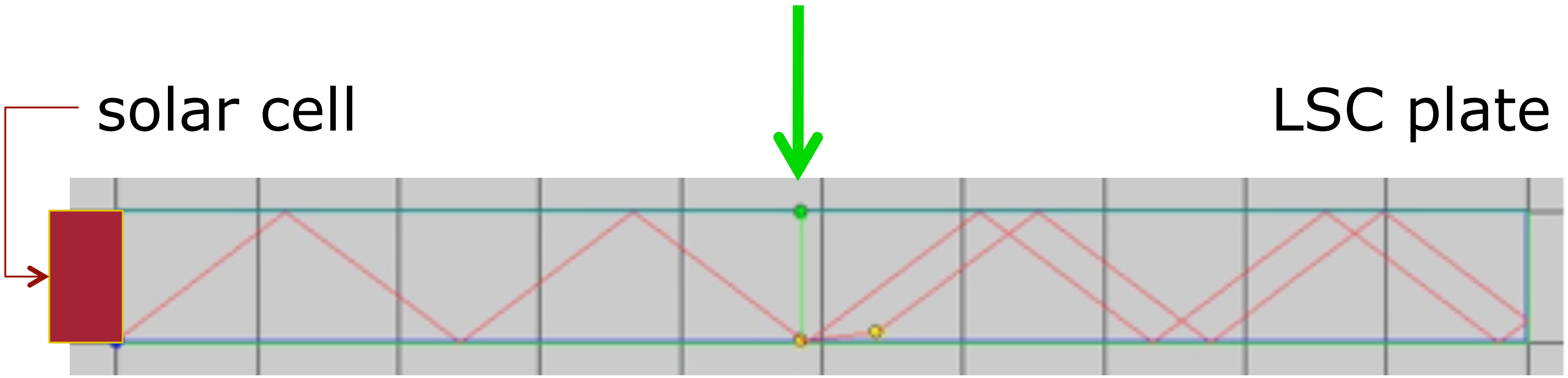


Ray trace model



Example path of the fate of an individual ray incident at the top of the LSC

- A green photon enters the LSC perpendicularly (centre)
- It is emitted as a red photon close to the bottom of the LSC
- It subsequently undergoes several internal reflections to finally arrive at the left side of the LSC where it is absorbed by the solar cell

[Gallagher, 2004; Burgers, 2005]

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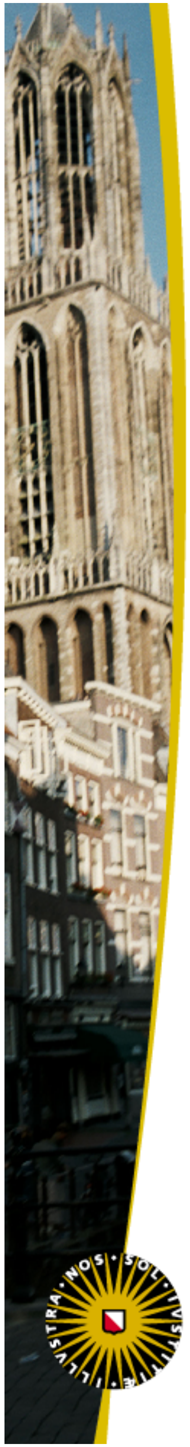

Models compared

- Thermodynamic model requires minimum of input data, and runs quickly, but limited to square geometries and single, homogenously doped with luminescent species
- Ray-trace approach is more flexible allowing multiple dopant dyes, thin-films and different geometries
- Do they yield similar results?

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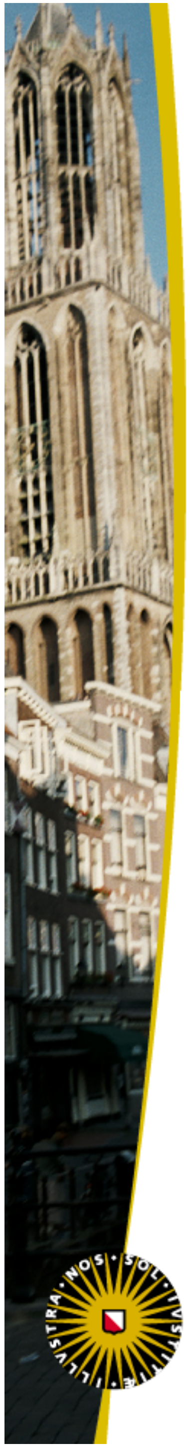
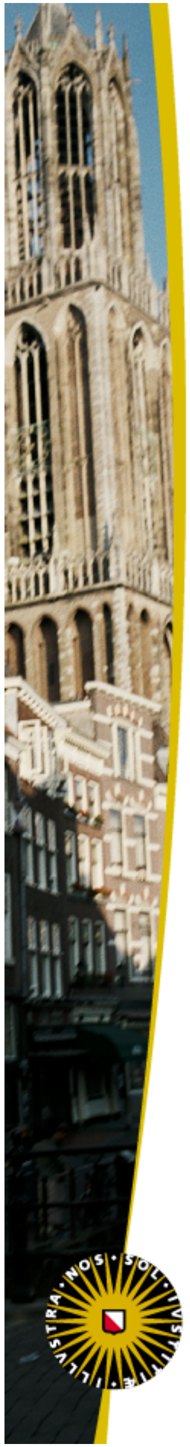


Models compared

- four Plexit slabs
- different sizes
- different dyes
    - Red and Yellow Coumarin

slab	dimensions (cm^3)	measured J_{sc} (mA/m^2)	predicted J_{sc} (mA/m^2) Thermodynamic	predicted J_{sc} (mA/m^2) Ray-trace
Red large	4.78×1.7×0.255	53.2 ± 2.0	51.6	51.9
Red small	1.93×0.994 ×0.25	22.5 ± 2.0	23.9	24.9
Yellow large	4.78×1.78×0.269	10.4 ± 2.0	10.2	9.3
Yellow small	2.26×1.0×0.27	5.2 ± 2.0	5.0	5.0

good agreement [Chatten, 2005]



Ray trace model

- Parametric study [Van Sark , 2008]
  - Mirror configuration
  - Polymer background absorption
  - Solar cell type
  - Infrared dyes
  - Wavelength selective mirrors
  - Geometry
  - Nanoparticles
- PMMA (n=1.49, abs 1.5 m^{-1})
- 5x5x0.5 cm^3, Si solar cell on one side
- CRS040 and Lumogen F Red dye (next slide)
- Modeled efficiency 2.45%

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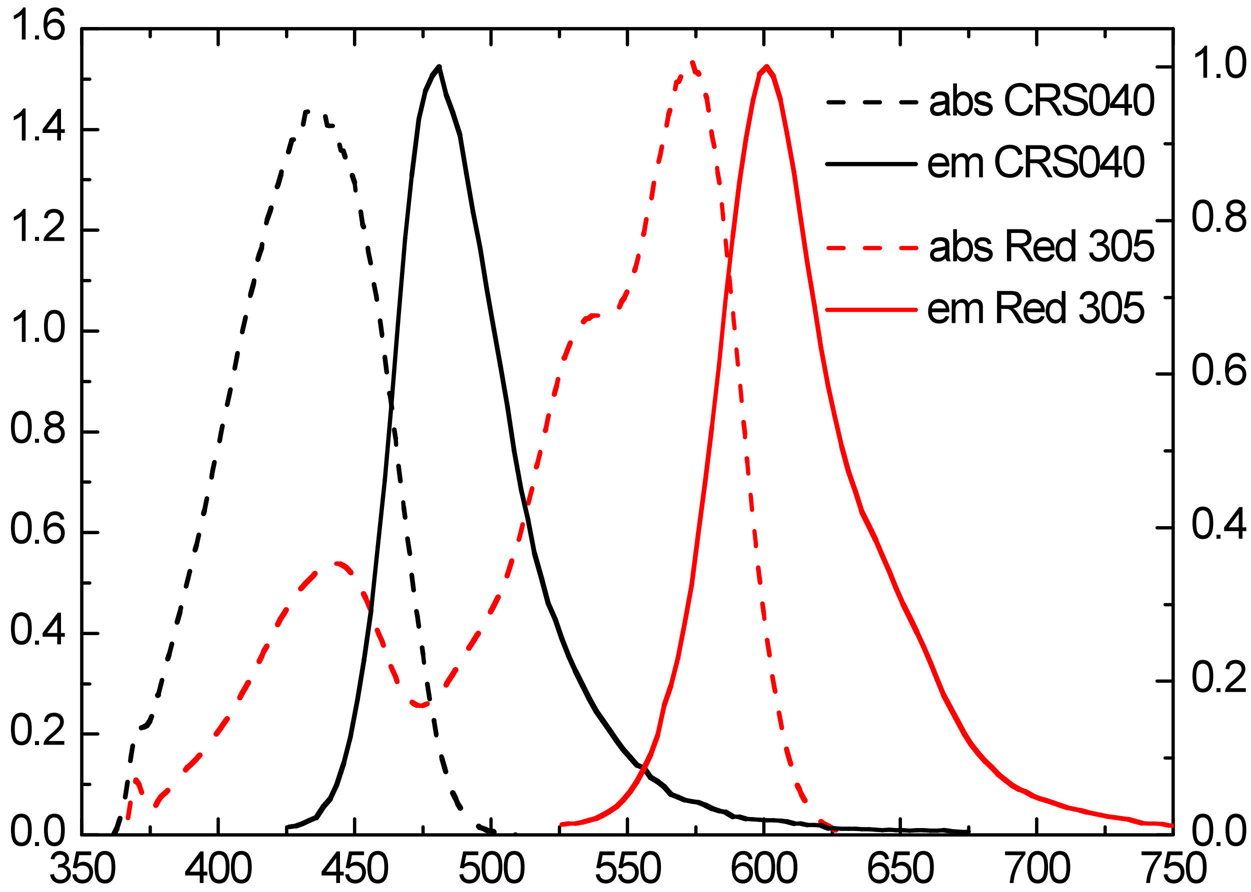
Ray trace model

- CRS040 and Lumogen F Red dye (LQE 95%)



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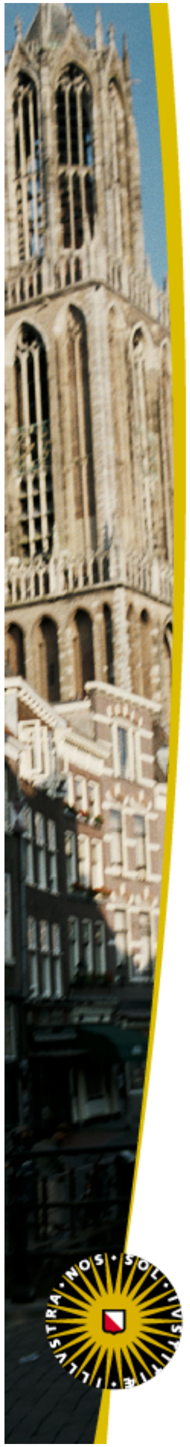
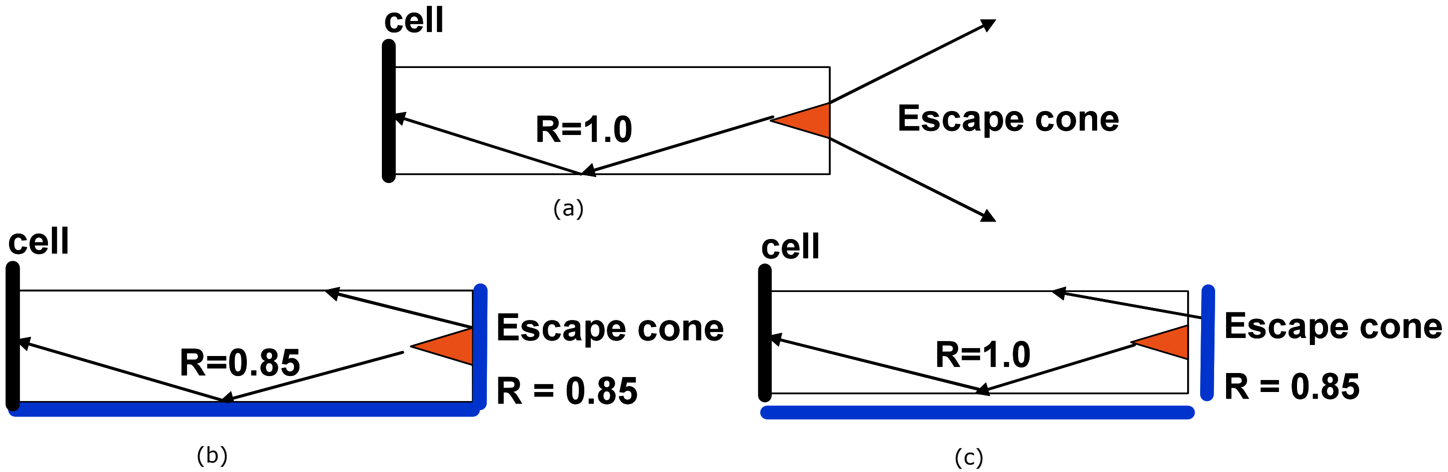


Ray trace model

- Parametric study: Mirror configuration
- Adding mirrors directly to sides removes TIR, reflection coefficient of mirror
- Air gap restores TIR
- Lambertian bottom Mirror (R=97%)
- 3M adhesive silver foil on sides (R=97%)
- Efficiency up from 2.45% to 2.97%



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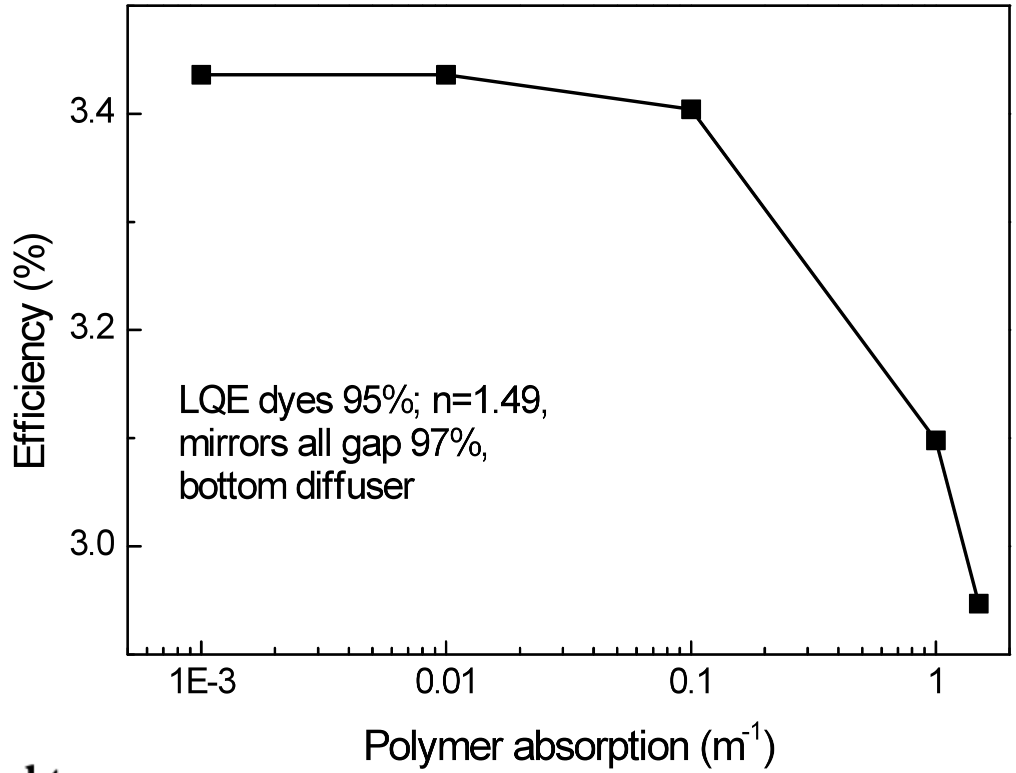
Ray trace model

- Parametric study: background absorption
- Efficiency further up from 2.97% to 3.42% (with n=1.7, efficiency would be 3.8%)



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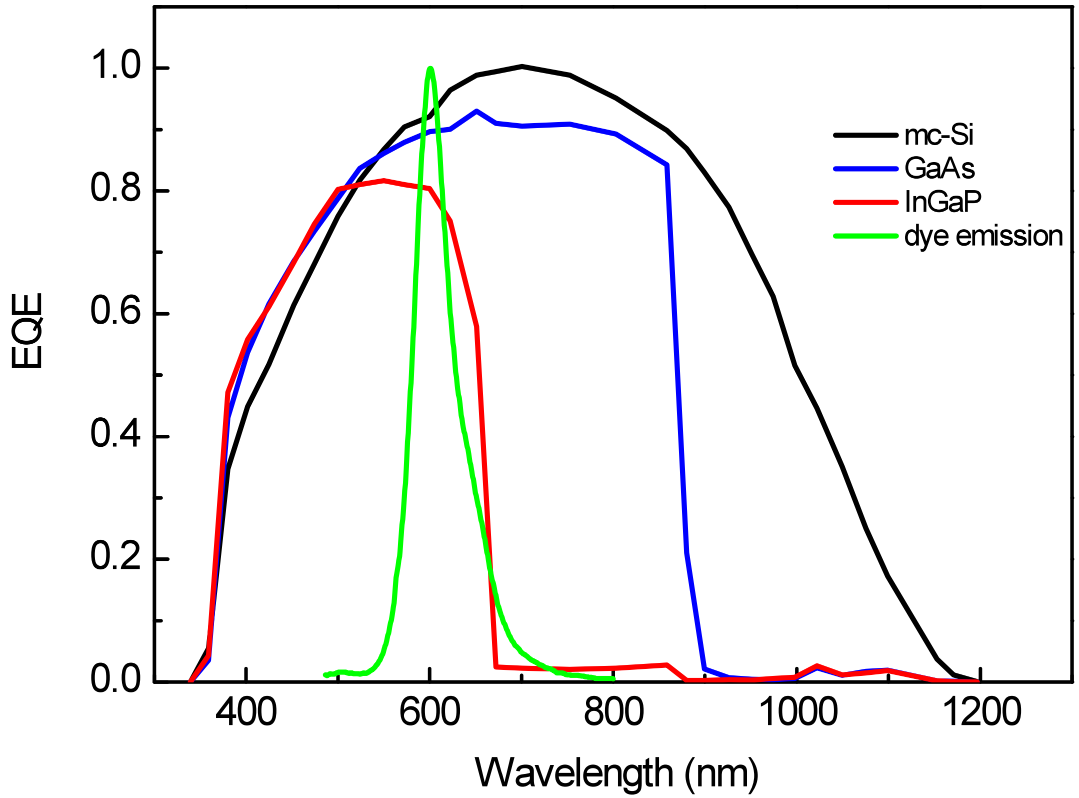
Ray trace model

- Parametric study: solar cell type
- Si cells not optimized for emission dyes
- 650-1050 nm spectral range not used



band gap	
Si	1.1 eV
GaAs	1.45 eV
InGaP	1.9 eV

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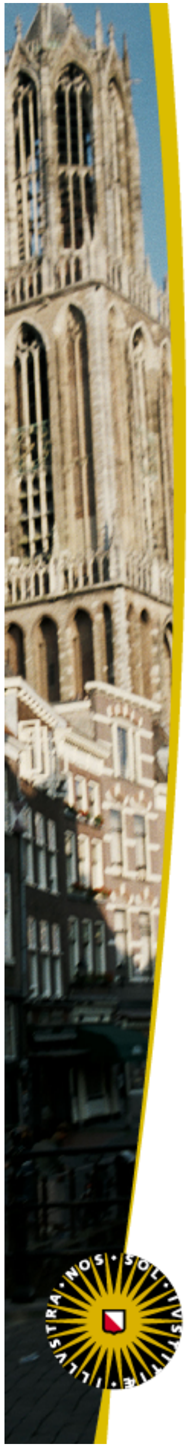
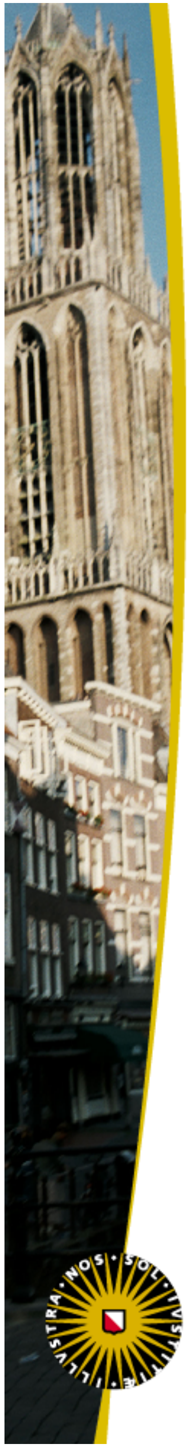


Ray trace model

- Parametric study: solar cell type
- The higher the band gap, the higher efficiency

mc-Si	GaAs	InGaP	Parameters
2.4	4.2	5.9	fixed mirrors, 85% reflectivity, dyes with 95% LQE
2.9	5.1	7.1	97% reflectivity “air-gap mirrors” on sides, and 97% reflectivity Lambertian mirror at bottom
3.4	5.9	8.3	reduce background absorption of polymer matrix from 1.5 m^{-1} to 10^{-3} m^{-1}
3.8	6.5	9.1	increase of refractive index from 1.49 to 1.7

1.1 eV 1.45 eV 1.9 eV band gap



Ray trace model

- Parametric study: IR dyes
- Not yet available at high LQE (model 50%)
- Stacks: similar to tandem solar cells

dye // cell combination	efficiency (%)
single plate Red305+CRS040 // 1 c-Si solar cell	3.8
single plate Red305+CRS040+IR dye // 1 c-Si solar cell	2.3
stack Red305+CRS040 top/IR dye bottom // 2 c-Si solar cells	4.5
stack IR dye top/Red305+CRS040 bottom // 2 c-Si solar cells	4.3

- If LQE would be 95% → efficiency 5.4% (in single plate)

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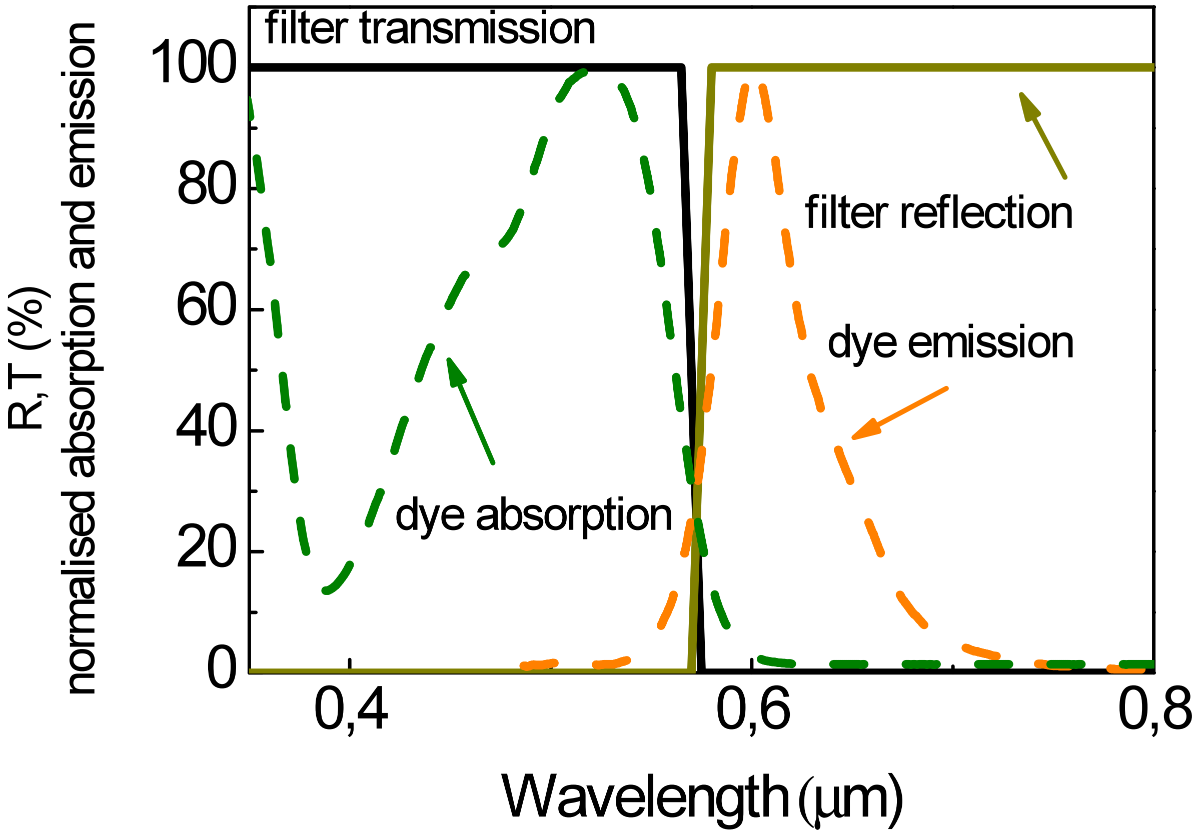
Ray trace model

- Parametric study: Wavelength selective mirrors to reduce top escape losses



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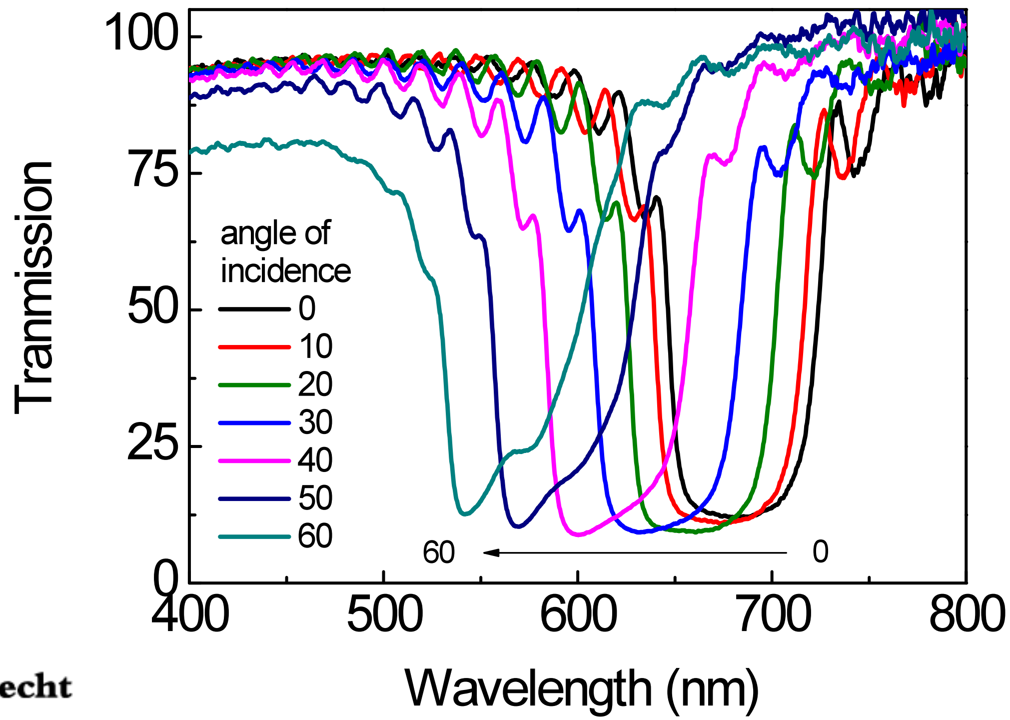
Ray trace model

- Parametric study: Wavelength selective mirrors: cholesteric mirrors [Debije, 2006]
- Low transmission in dye emission range
- However, depends on angle of incidence



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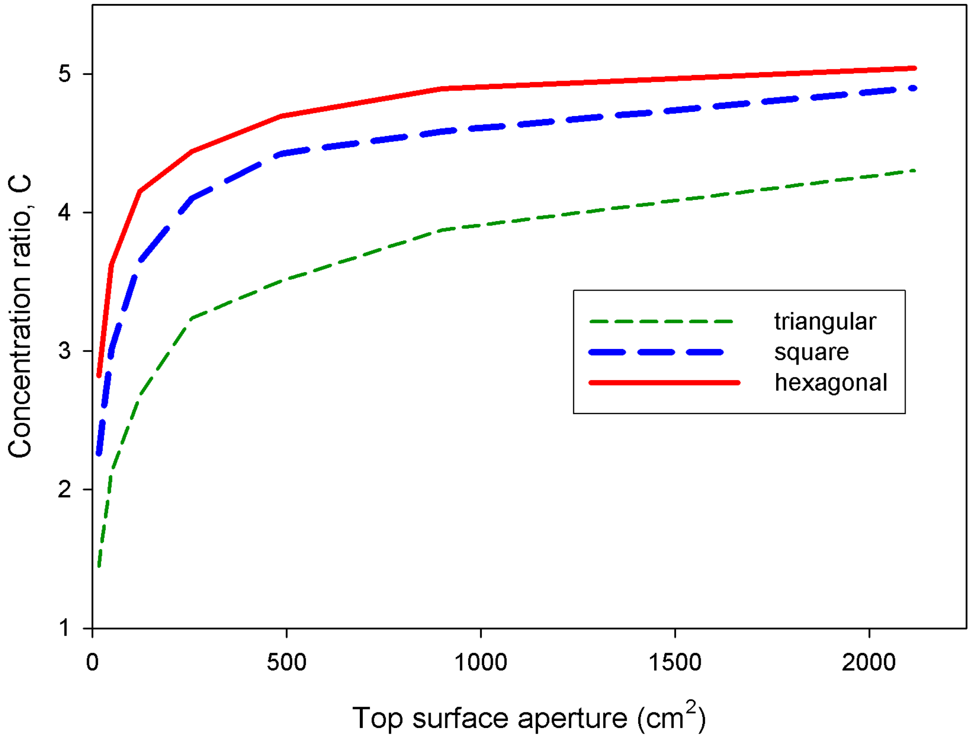
Ray trace model

- Parametric study: geometry
- Square, triangular, hexagonal shapes, but in terms of cost per unit of power no difference



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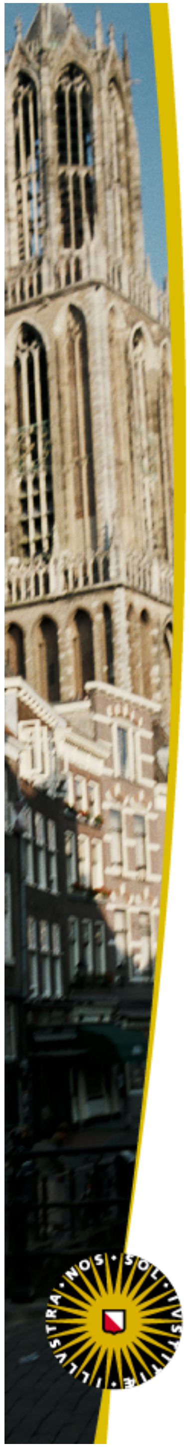
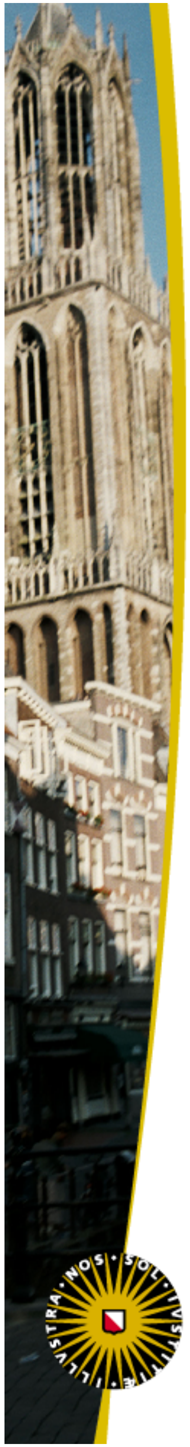


Ray trace model

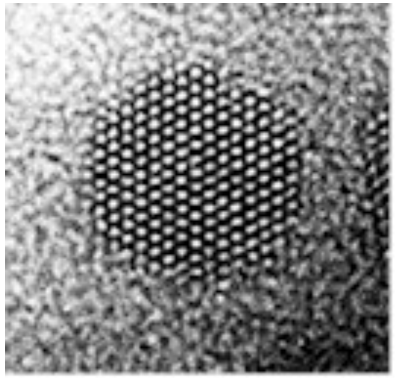
- Parametric study: nanoparticles
- Broad absorption
- Stable
- Tunable
- Example: [Kennedy, 2008]
- Three types of quantum dots
    - Green, 488 nm (commercial)
    - Orange, 605 nm (commercial)
    - Infrared, 690 nm (UU-research)

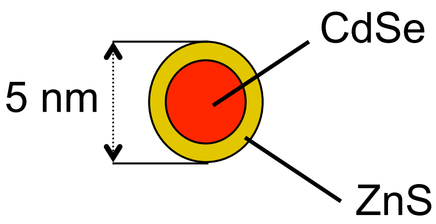
- QD Intermezzo

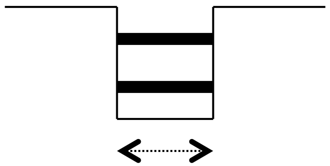
Intermezzo: quantum dots



- semiconductor nanocrystals
  - CdSe/ZnS
- quantum confinement
  - exciton is "particle-in-a-box"
  - radius smaller than exciton Bohr radius
- used as fluorescent probes
  - tunable emission as a function of size







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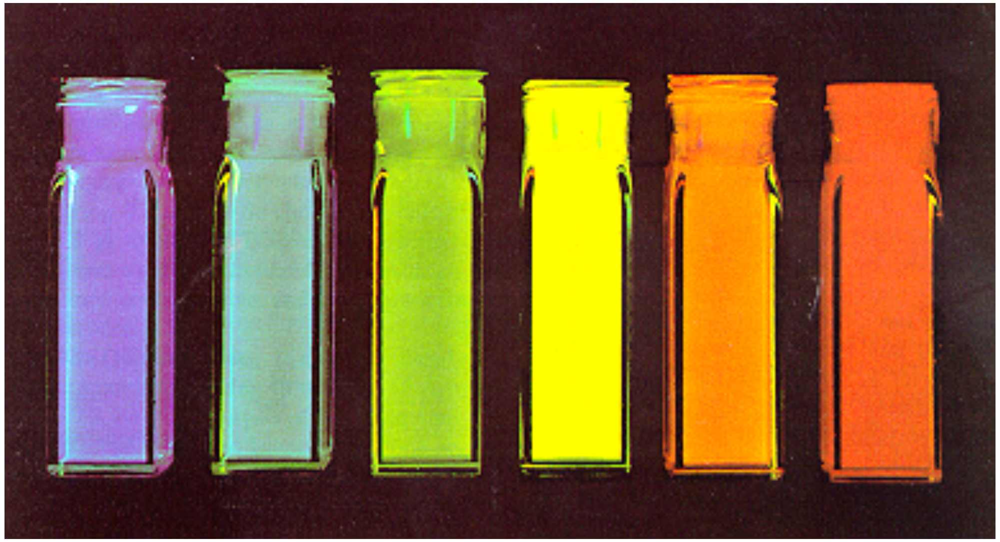
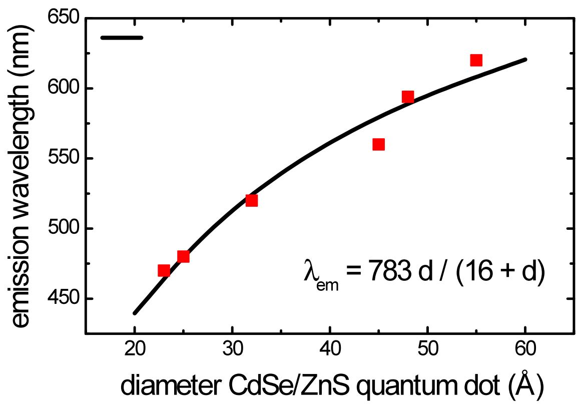
Tunable emission: QD size

CdSe/ZnS QDs





λ_{em}	470	480	520	560	594	620	nm
ø	23	25	32	45	48	55	Å

[Dabbousi, 1997]

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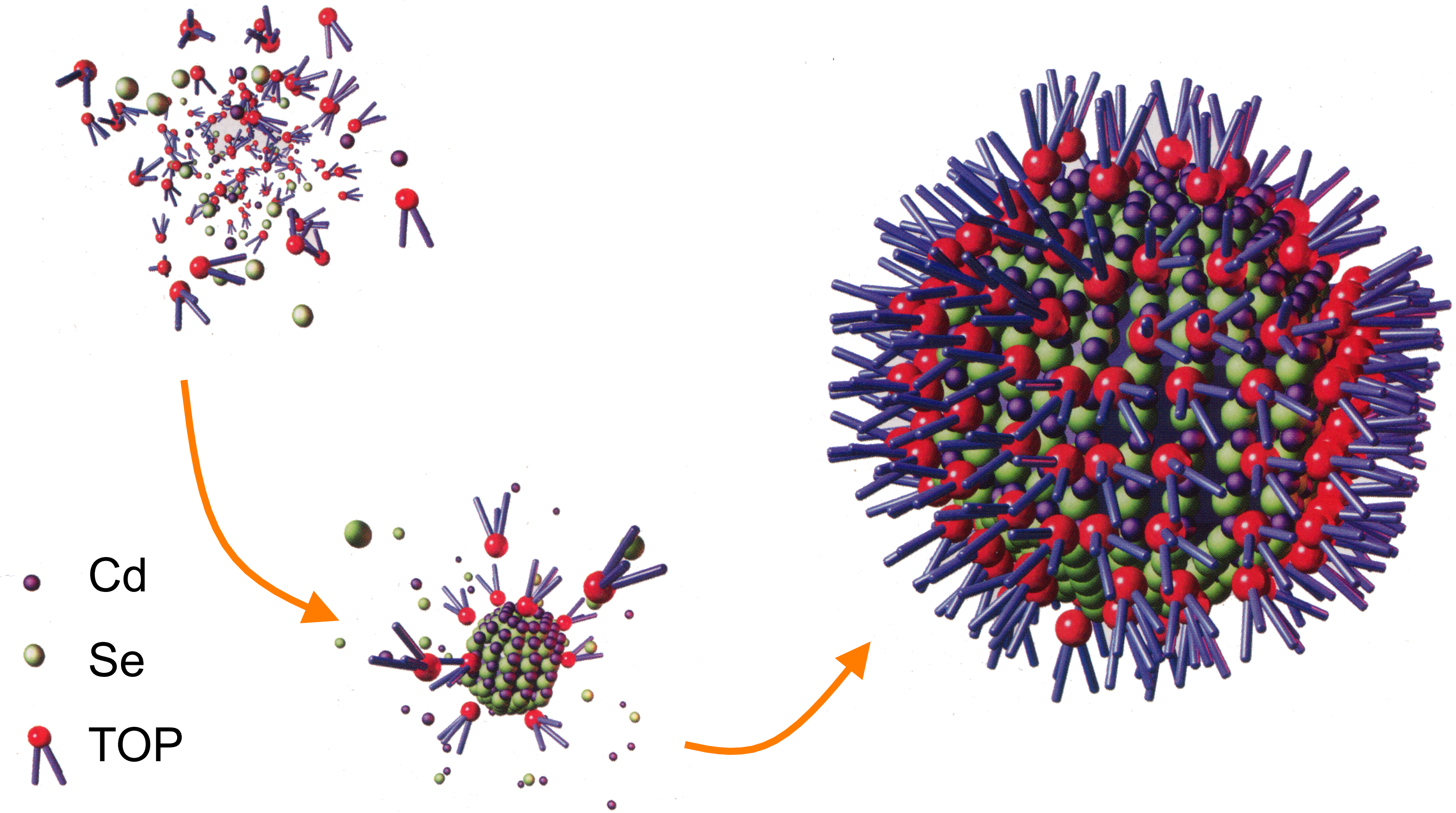
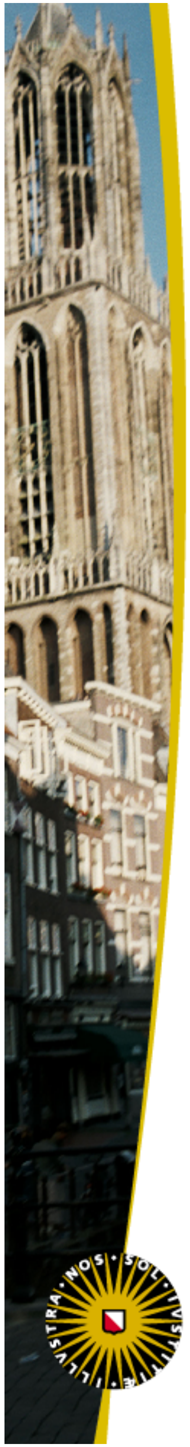
CdSe quantum dot assembly



Scientific American, sept 2001



CdSe synthesis at UU

Courtesy of Freek Suyver and Sander Wuister (Debye Institute, Condensed Matter and Interfaces, Utrecht University)

- in glovebox
- mix 100 ml heptane and 3 g surfactant (igepal)
- add 50 ml 1M $Cd(ClO_4)_2$ stir
- inject $(TMS)_2Se$ stir

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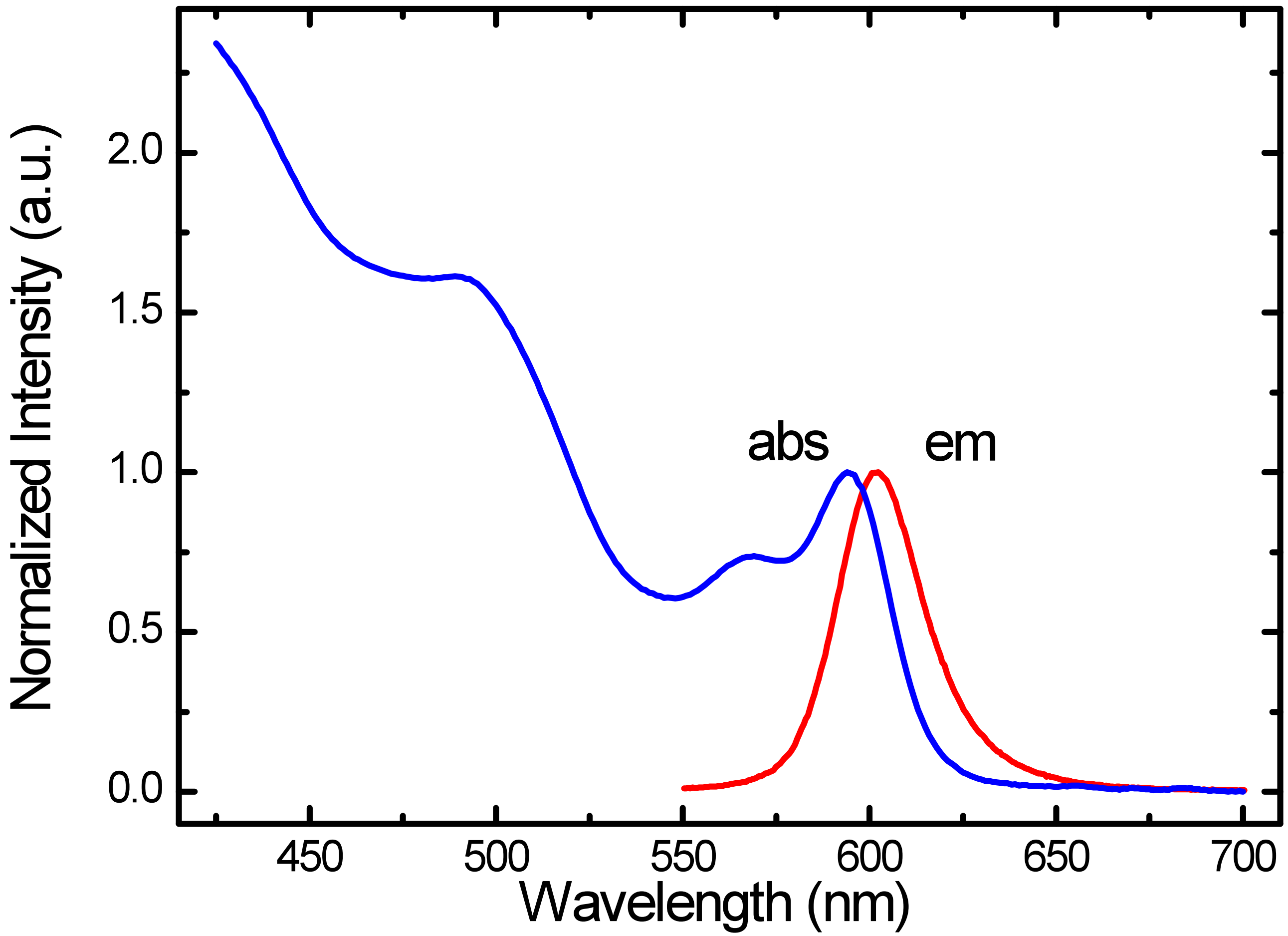
Absorption/emission spectra

CdSe/ZnS QDs, QE=80%



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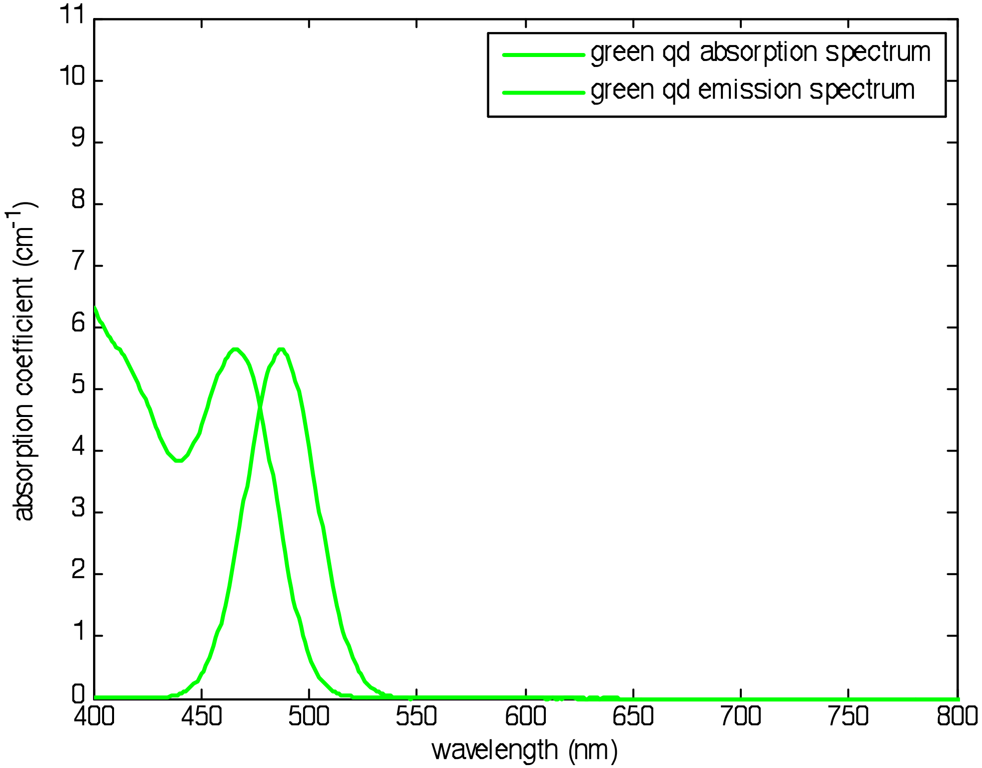
Back to: Ray trace model



Green emitting QDs

CdSe/ZnS. Emission peak 488 nm.
Nanoco Technologies

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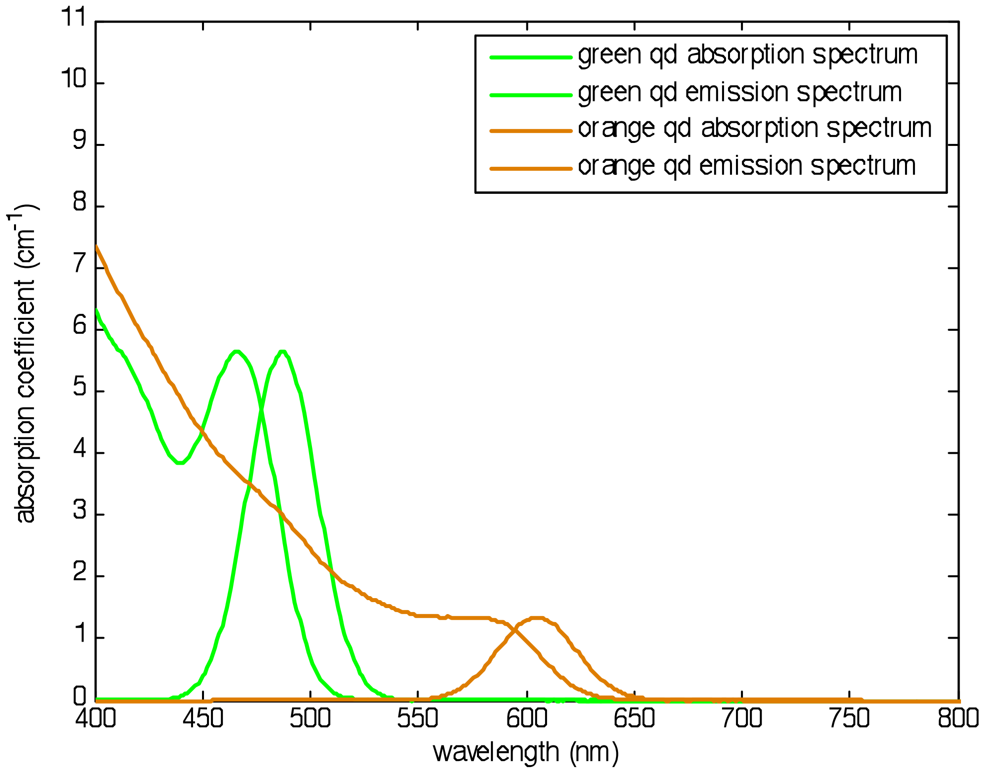
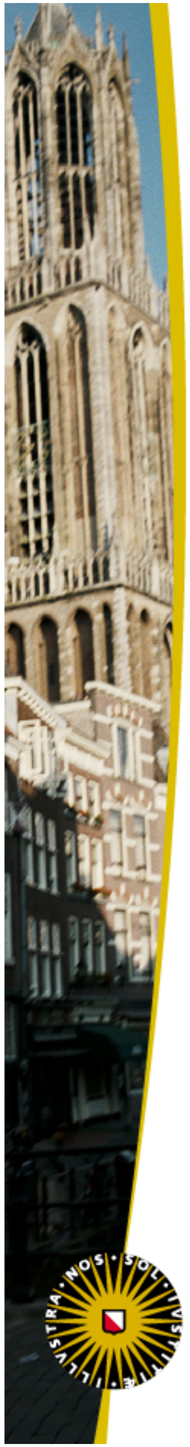
Ray trace model



Orange emitting QDs
CdSe/ZnS. Emission peak 605 nm
Evident



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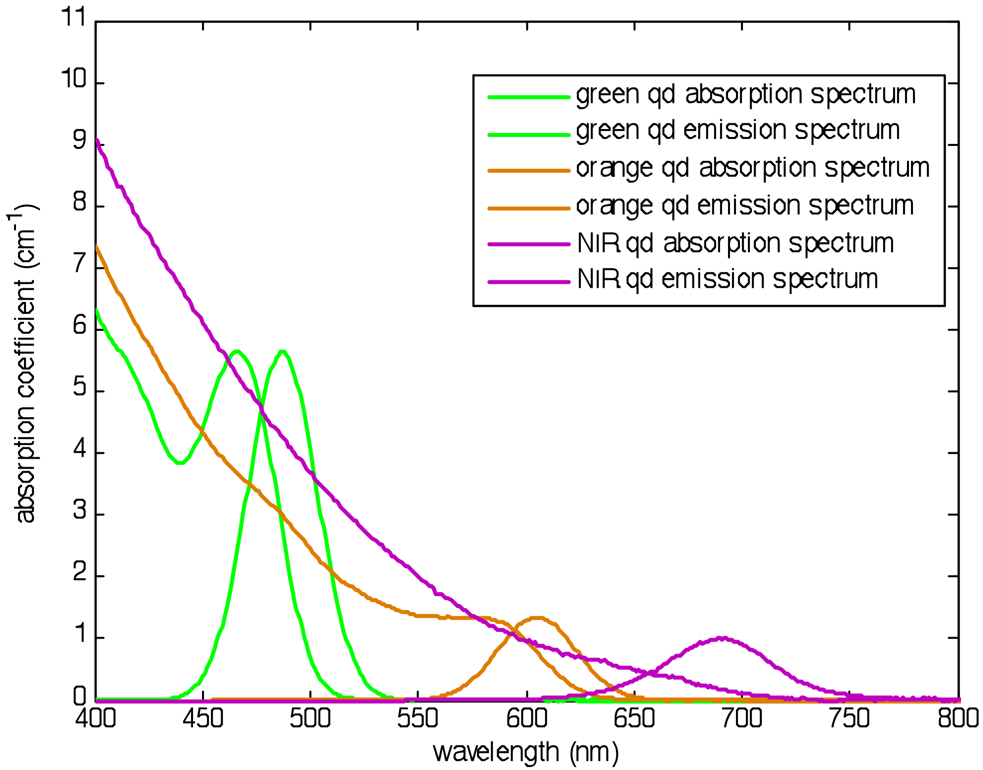
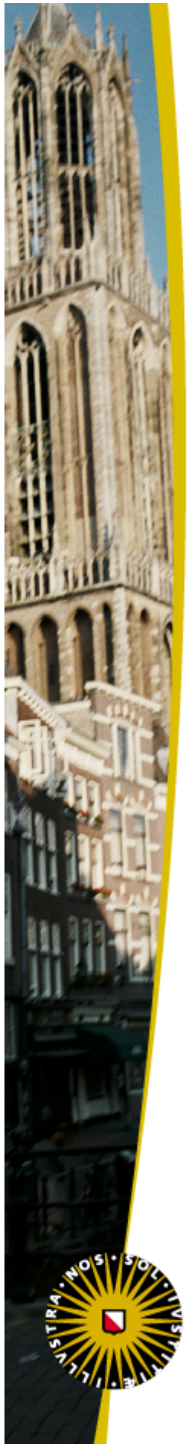
Ray trace model



'NIR emitting' QDs

CdSe/CdS/CdZnS/ZnS (SYN1CSS, UU)



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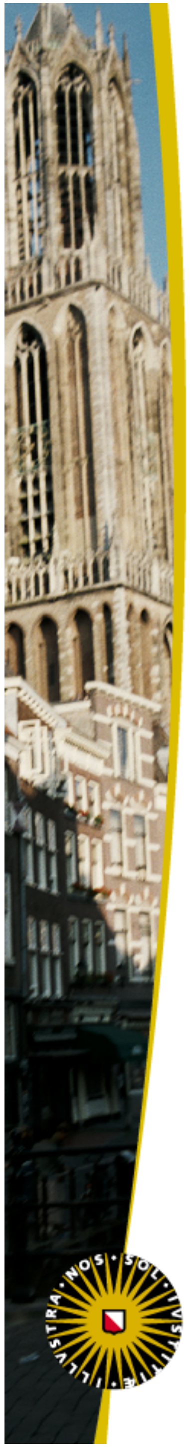


absorption efficiency (η_{abs}) fraction of incident photons absorbed by QDs

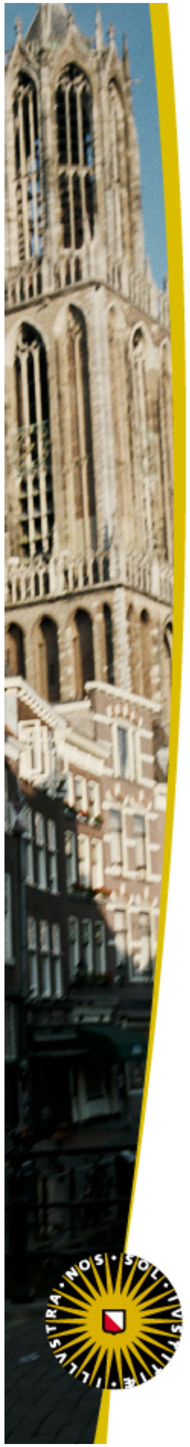
All absorbed photons are emitted (QD QY=100%)

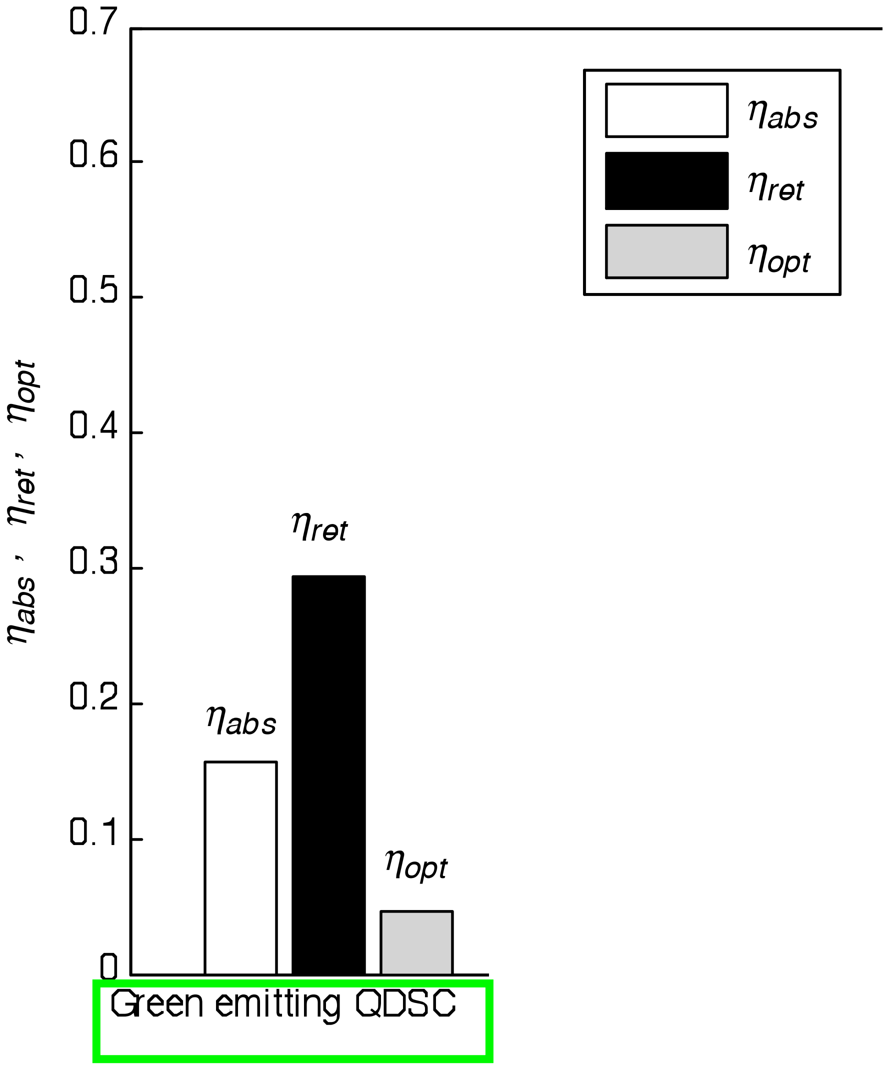
Only (internal) loss mechanism is escape cone loss

retention efficiency (η_{ret})= 1-total escape cone loss

optical efficiency (η_{opt}): fraction of incident photons transmitted to PV

$\eta_{opt} = \eta_{abs} \times \eta_{ret}$





	η_{abs}	Escape Cone (EC)	η_{ret} = 1 – EC	$\eta_{opt} = \eta_{abs} \times \eta_{ret}$
Green	0.16	0.71	0.29	0.046

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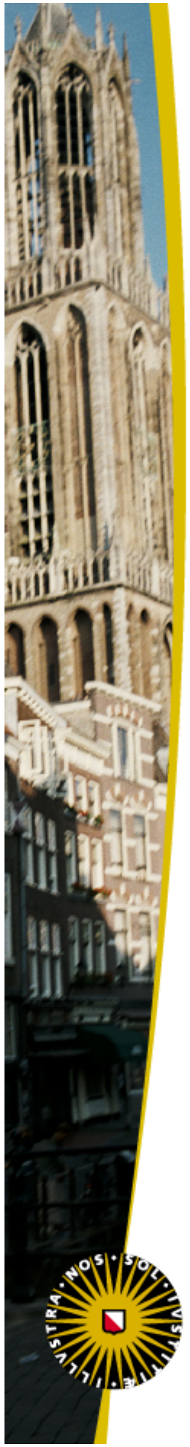

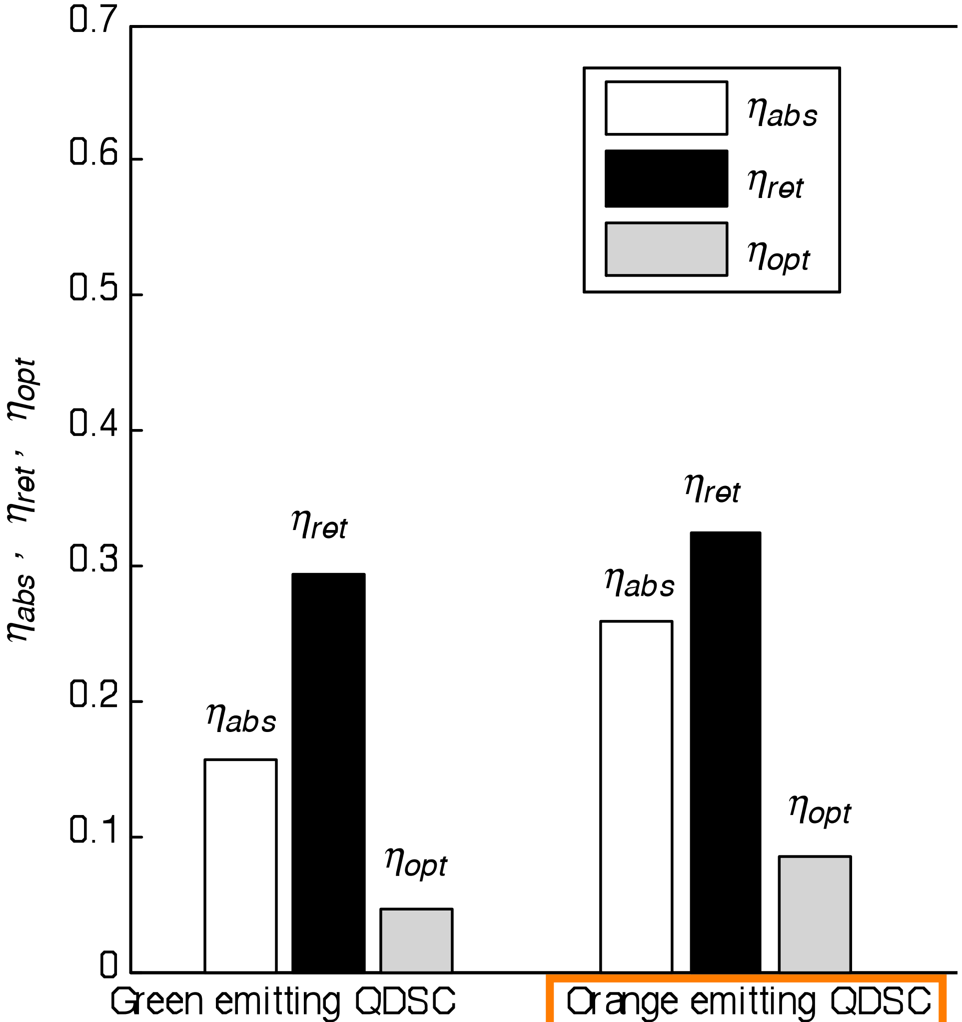

	η_{abs}	Escape Cone (EC)	η_{ret} = 1 – EC	$\eta_{opt} = \eta_{abs} \times \eta_{ret}$
Green	0.16	0.71	0.29	0.046
Orange	0.26	0.67	0.33	0.084

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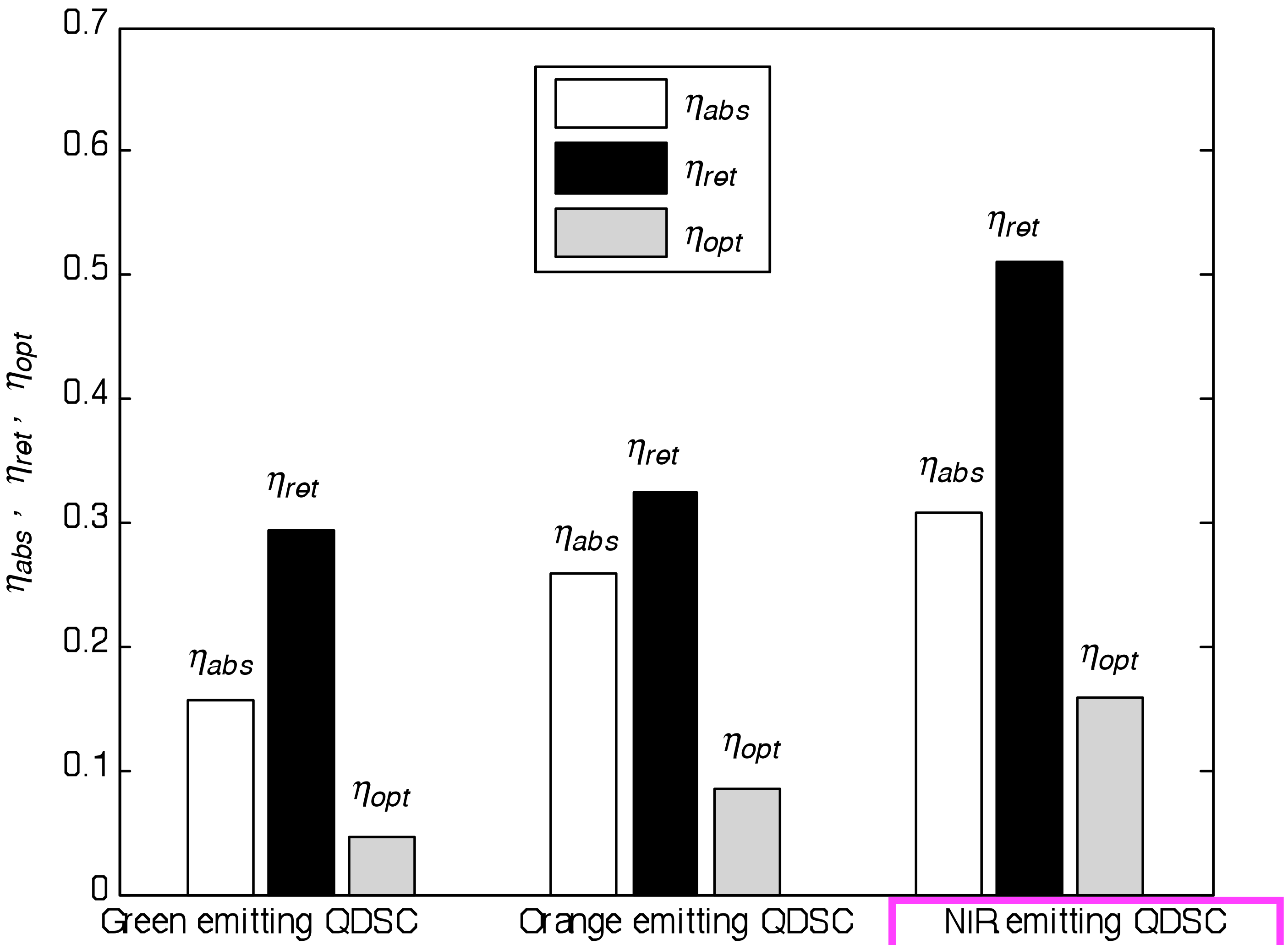
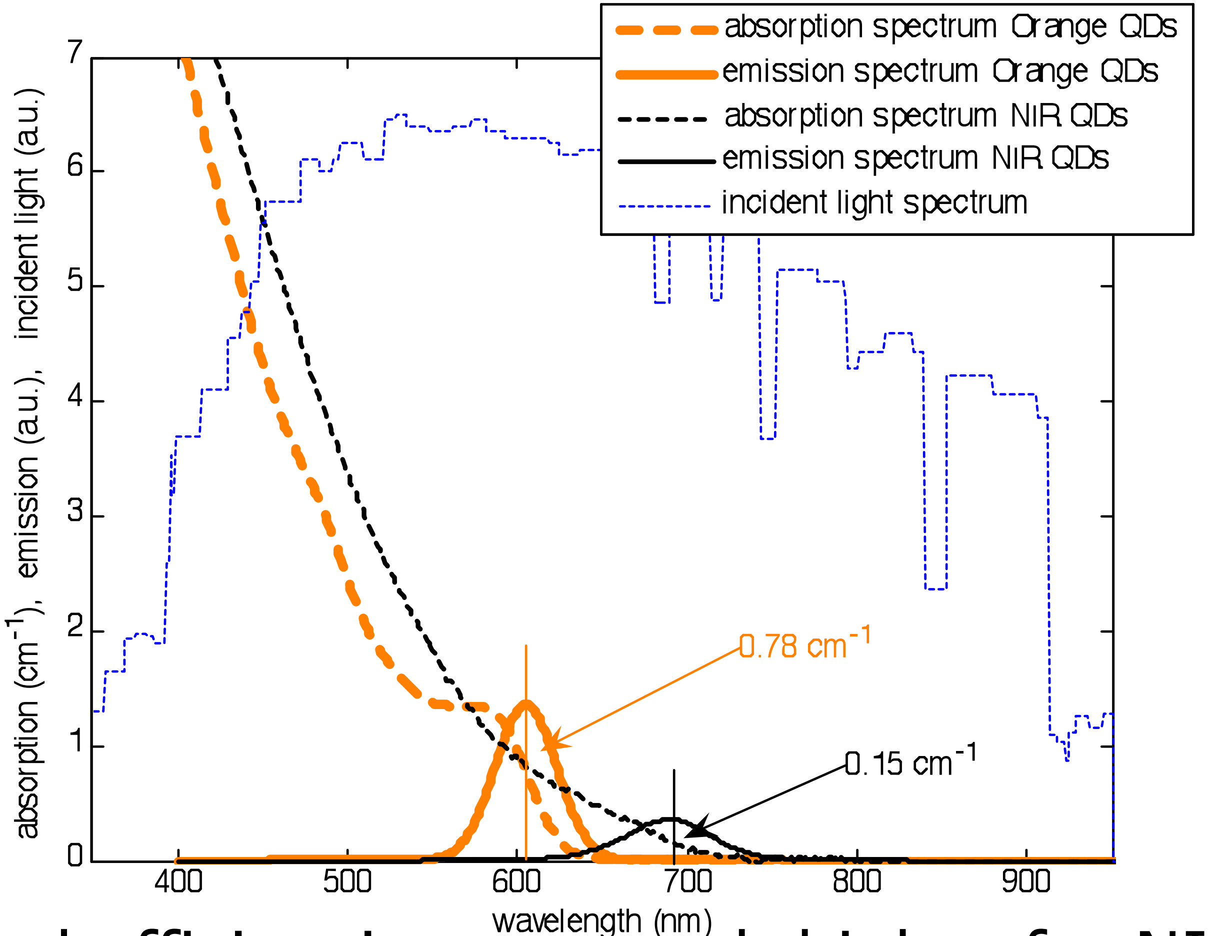


	η_{abs}	Escape Cone (EC)	η_{ret} = 1 – EC	$\eta_{opt} = \eta_{abs} \times \eta_{ret}$
Green	0.16	0.71	0.29	0.046
Orange	0.26	0.67	0.33	0.084
NIR	0.31	0.49	0.51	0.16



Optical efficiencies are much higher for NIR QDs than commercially-available visible emitting QDs
-partly due to broader absorption range
-*more significantly* due to lower re-absorption losses

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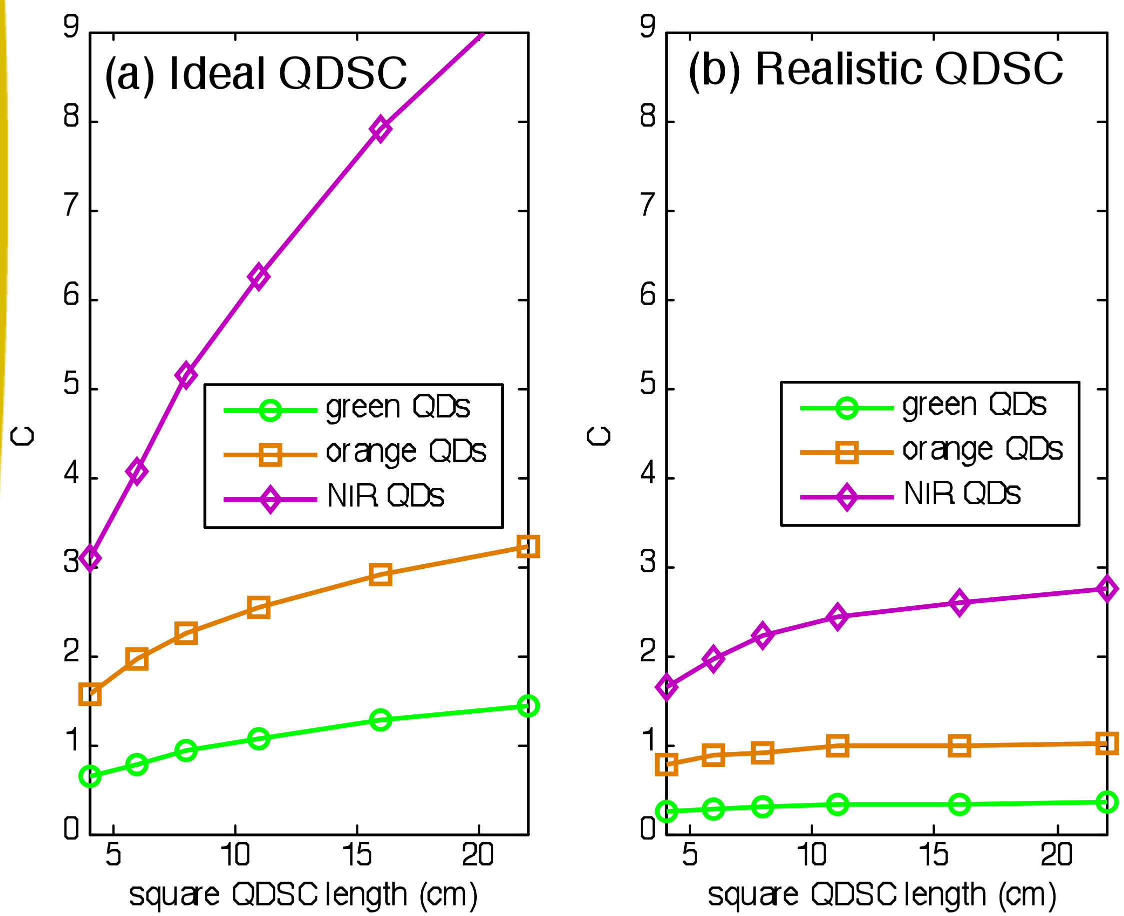
Ray trace model



Predicted Concentration Ratios using same QDs and more realistic parameters:

attenuation coefficient; 4 m^{-1}

Mirror reflectance: 0.94

QD QY: 85%

Re-absorption is less detrimental in NIR QDSC

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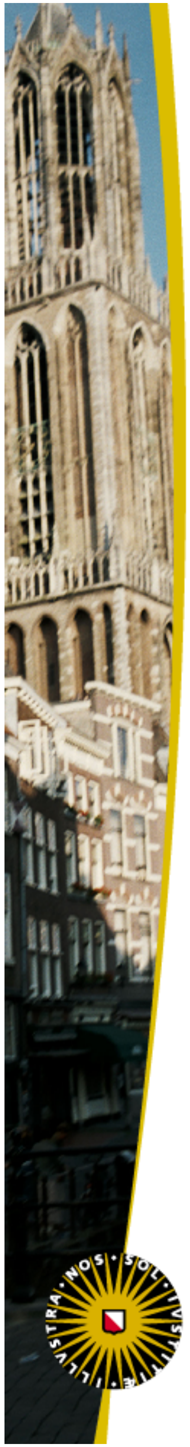

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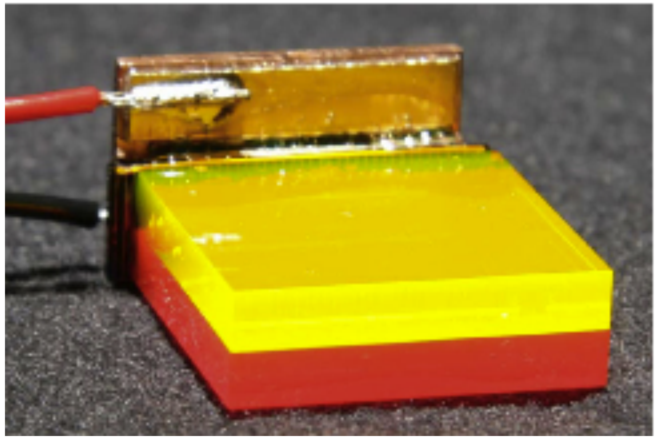
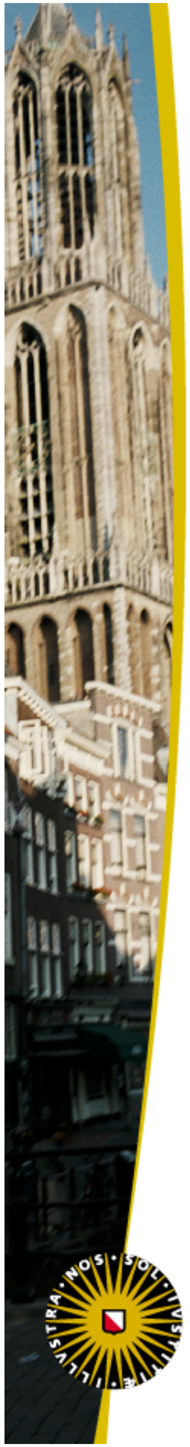
Experiments

Experimental LSCs

- Early work (Goetzberger's group): 4% for 40x40 cm^2
- Goldschmidt [2009]:
  stack of plates (2x2 cm^2)
  two different dyes
  InGaP solar cells
  → 6.7%

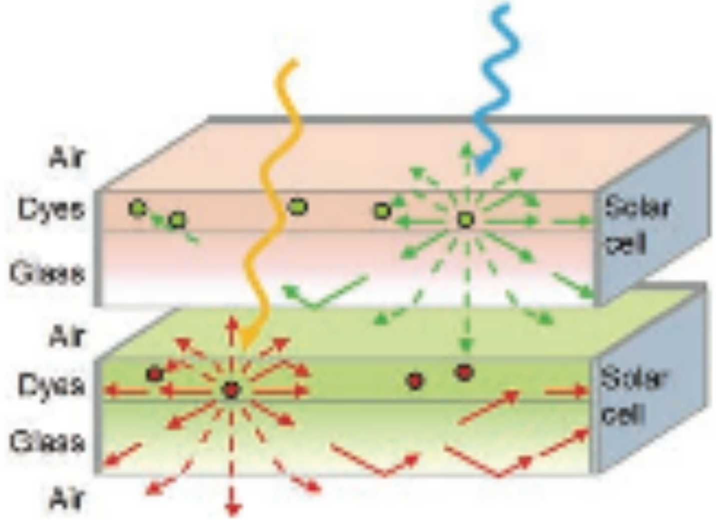


- When spectral range could be extended to infrared, 13.5% would be possible



Experimental LSCs

- Currie [2008]:
- stack of plates (2.5x2.5 cm^2)
- films of organic dyes on glass
- GaAs solar cell
- Efficiency 6.8%
- Projected 12-14.5% for CdTe or $Cu(In,Ga)Se_2$ solar cells



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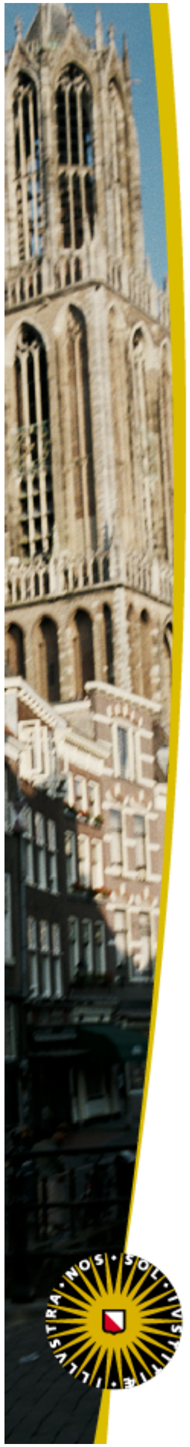
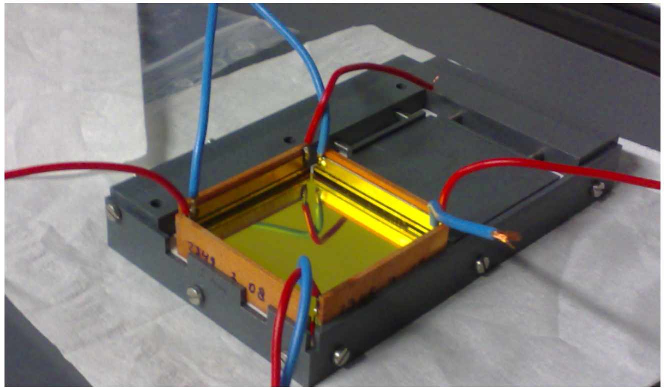
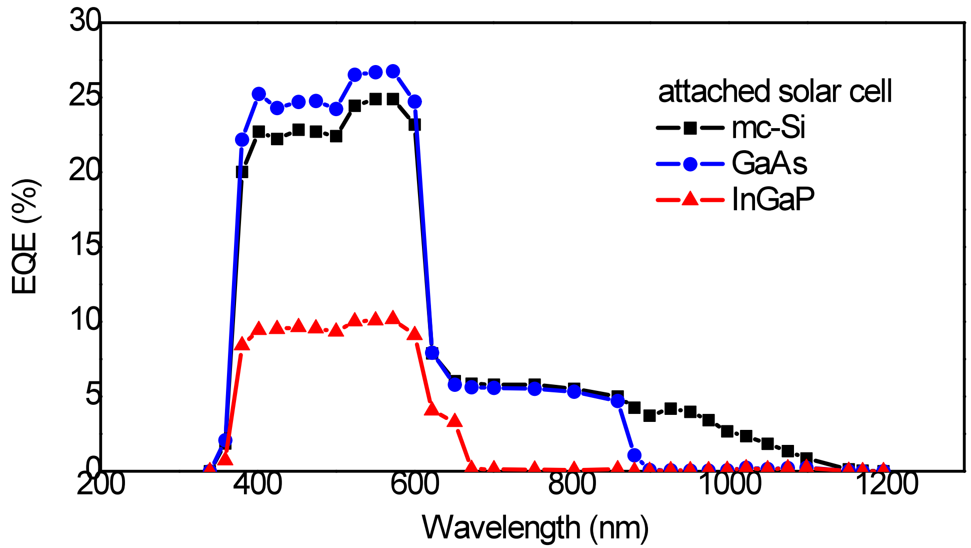


Experimental LSCs

- Slooff [2008]:
- Single plate (5x5 cm^2)
- Lumogen F Red 305
- Yellow CRS040
- PMMA (Plexit)
- 4 GaAs cells
- Efficiency 7.1%





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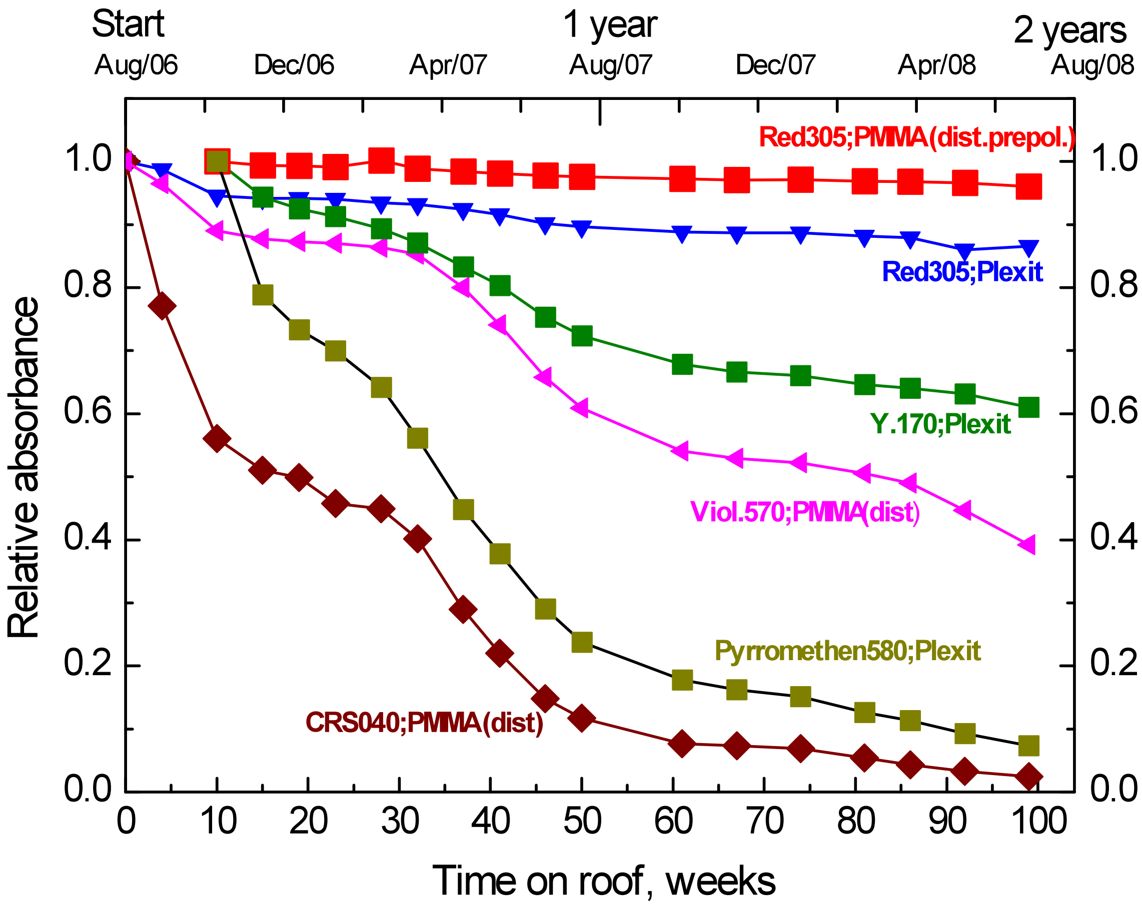
Stability

- Outdoor test, dye doped LSCs



"stable"

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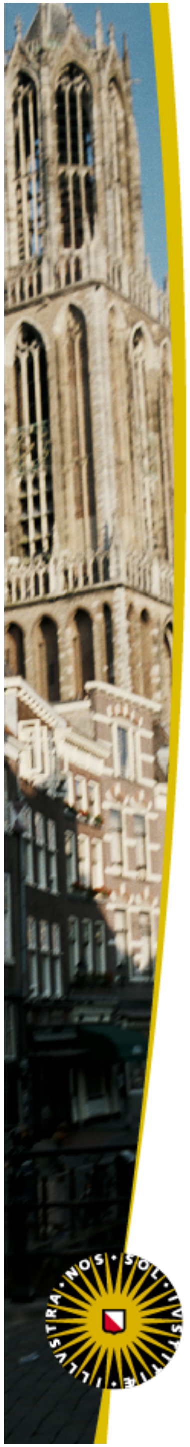
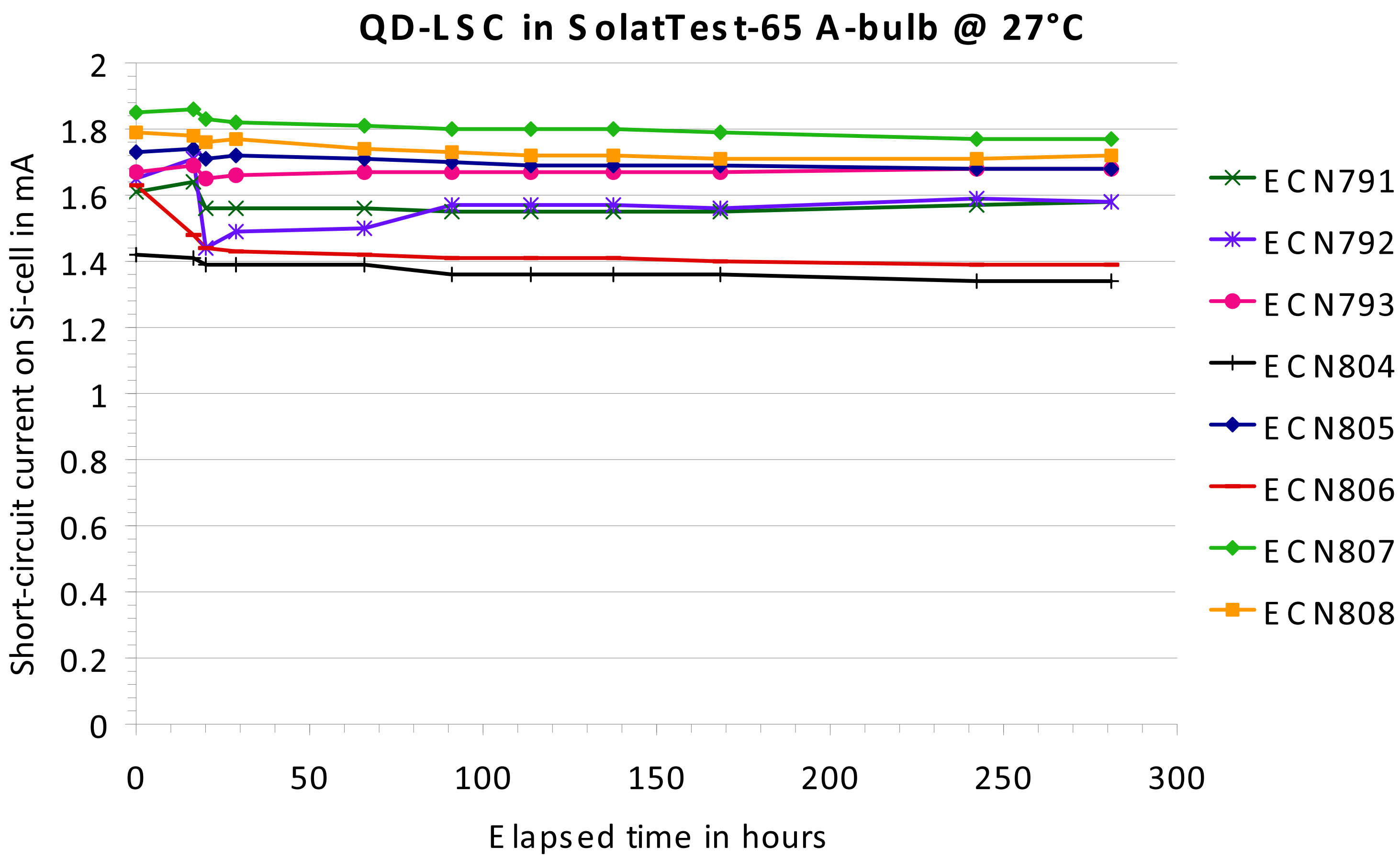


Stability

- Outdoor test, quantum dot concentrators



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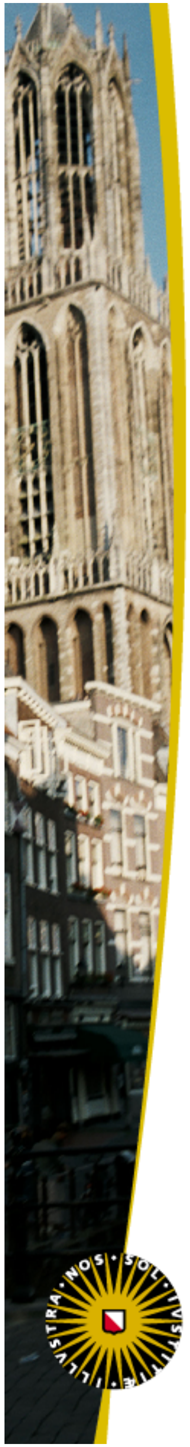

Outdoor performance

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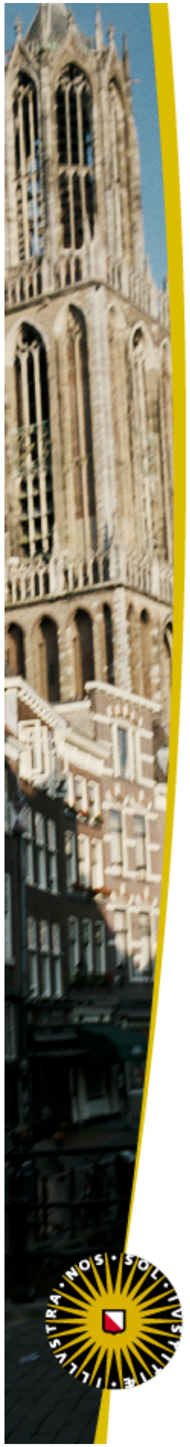
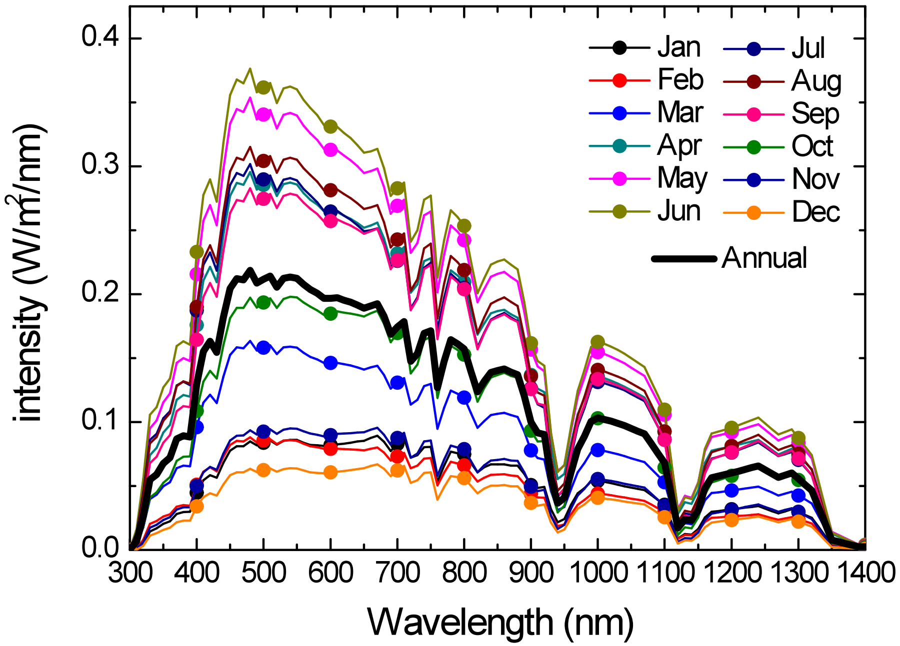


Outdoor performance

- Ray trace model
- 23x23 cm plate, 1 mm thickness
- Use actual spectra (modeled based on irradiation data, SEDES2), for the Netherlands



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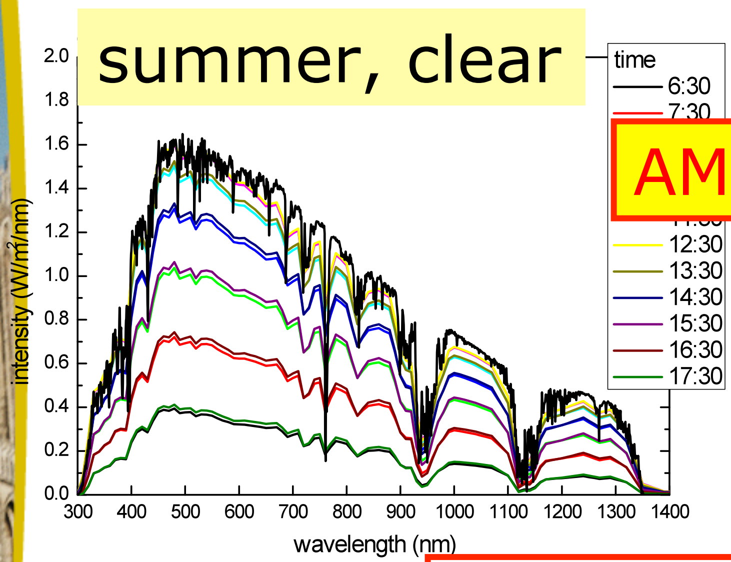
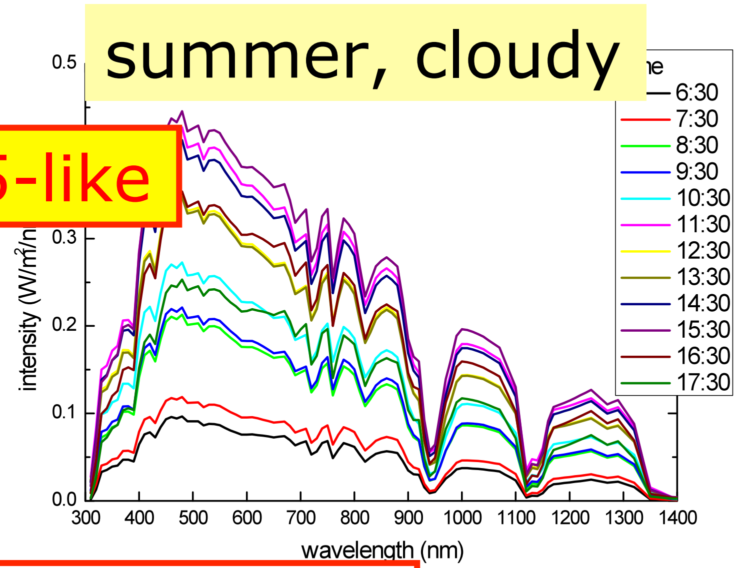
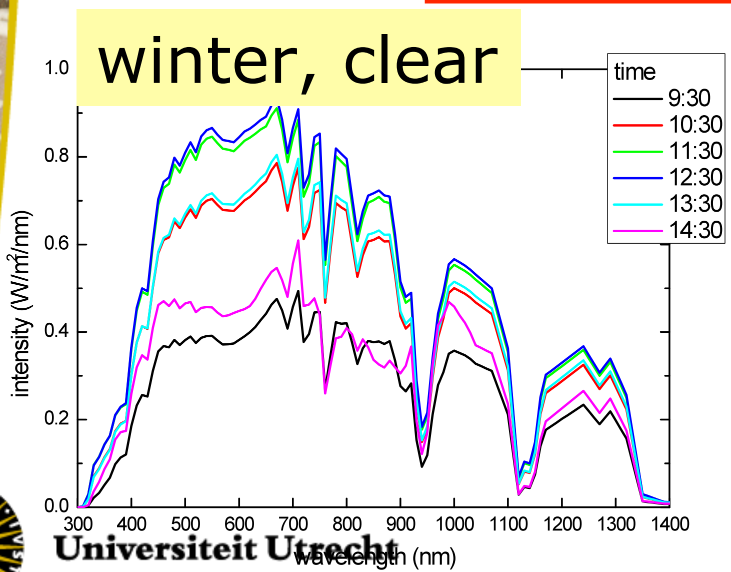
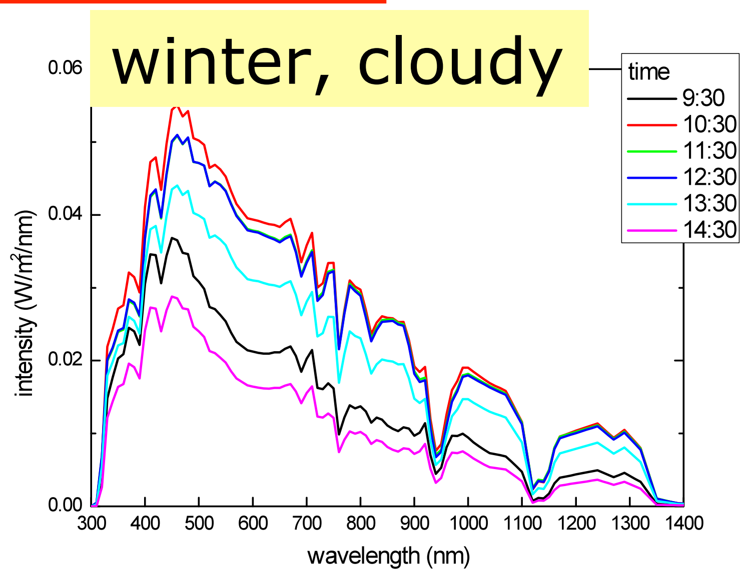
Four characteristic days

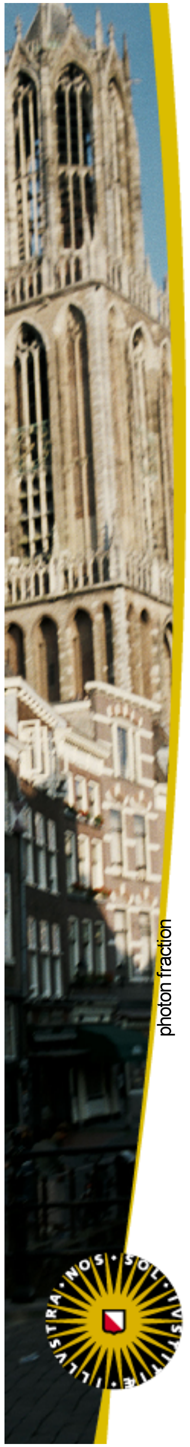








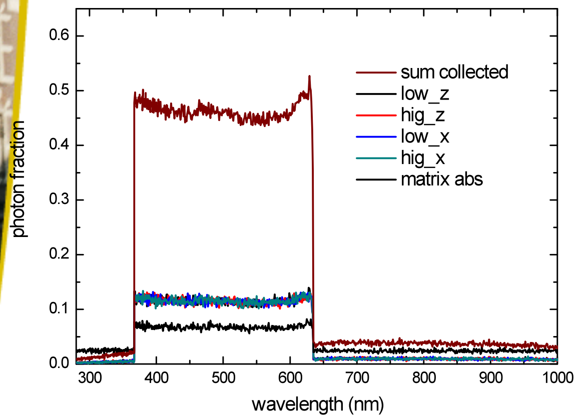
Note: different scales

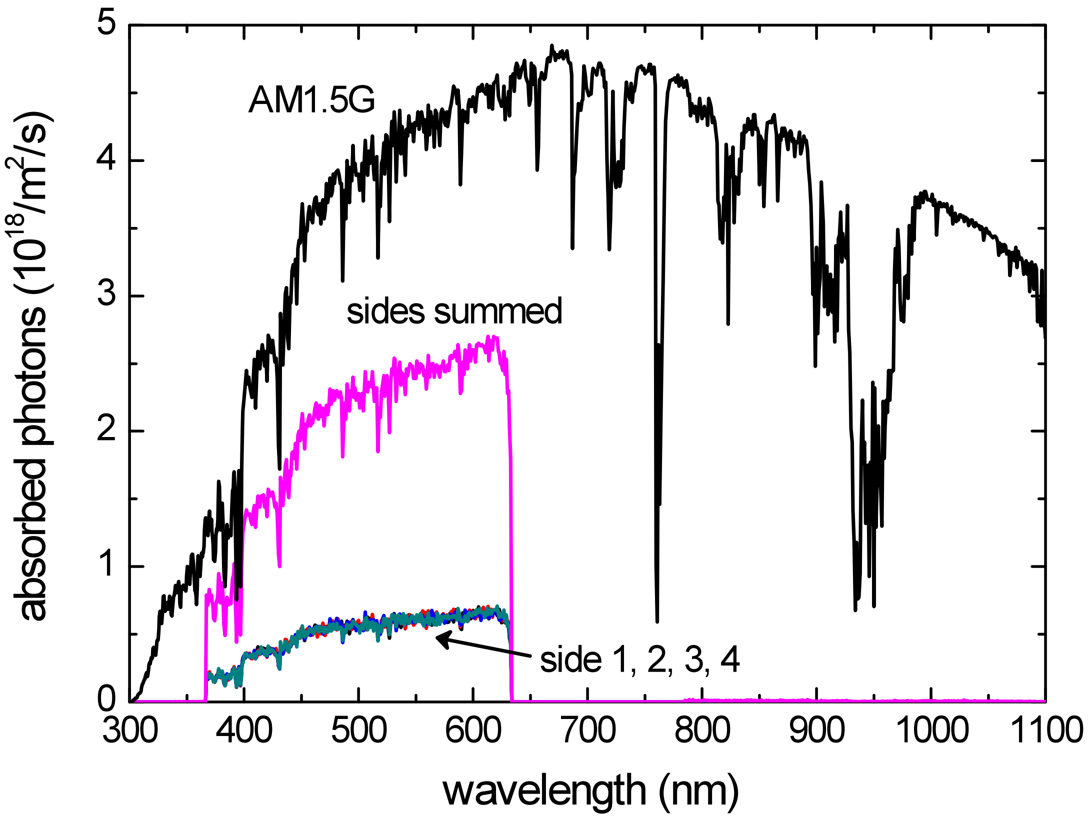


Outdoor performance

- Collected photons

fraction





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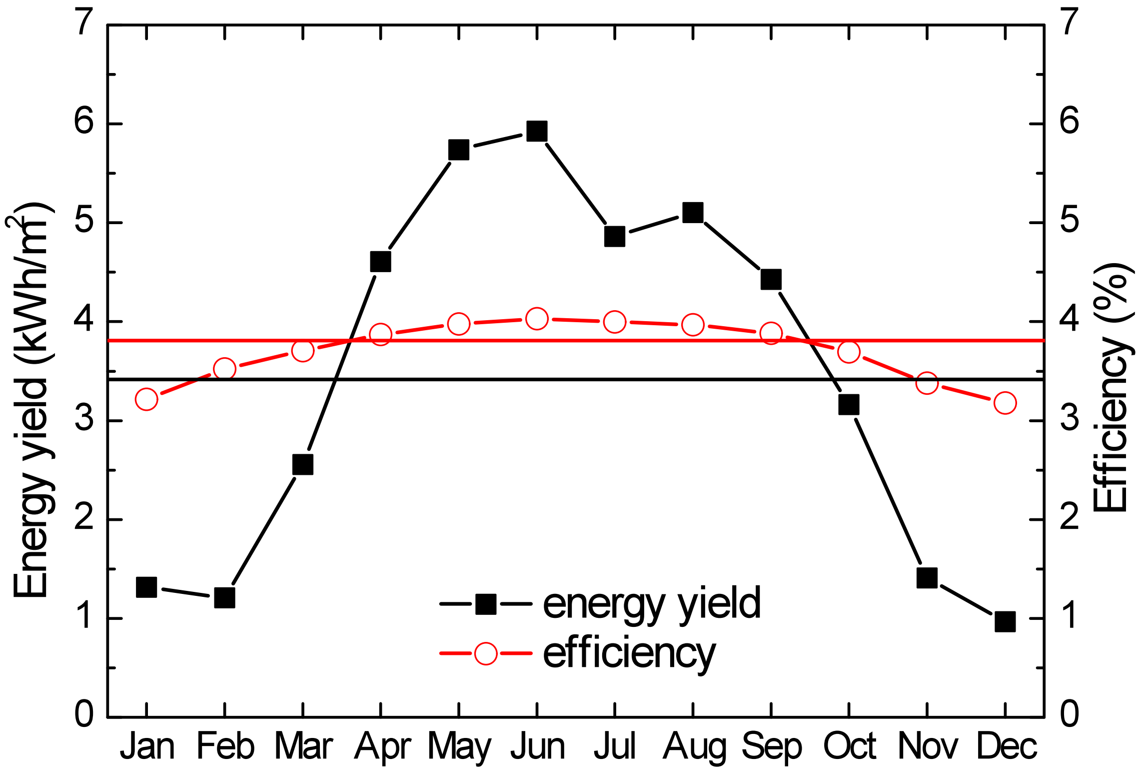
Outdoor performance

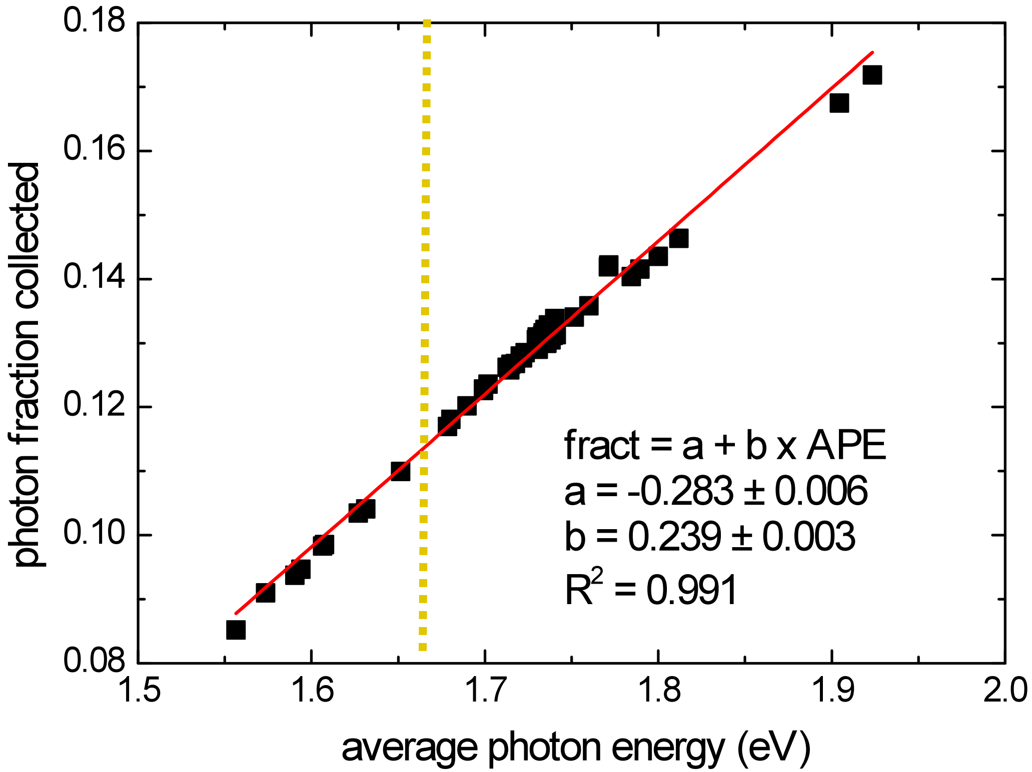
- efficiency
  - lower than AM1.5G efficiency (4.2%)
  - varies between 3% and 4 %
- energy yield follows spectral irradiance variation



Outdoor performance

- Collected photon fraction linearly dependent on average photon energy
- The bluer the spectrum (diffuse) the more photons are collected
- APE
  AM1.5G: 1.714 eV

- Annual energy yield: 41.3 kWh/m²
- Si: ~120 kWh/m²
- Cost?



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LSC cost

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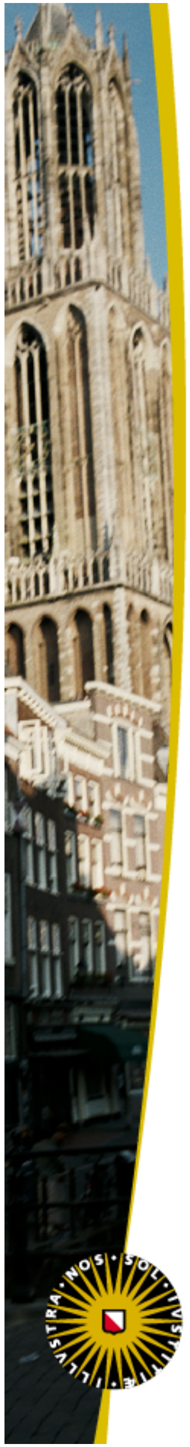

Cost calculations

- Relative cost

$$C_r = \frac{A_{top}[m^2]C_{PP}[€/m^2] + 2A_{side}[m^2]C_{PV}[€/m^2]}{A_{top}[m^2]C_{PV}[€/m^2]}$$

1/15 →

$$= \boxed{\frac{C_{PP}[€/m^2]}{C_{PV}[€/m^2]}} + \frac{2d}{l}$$

- Relative power

$$P_r = \frac{Ndl}{l^2} \cdot \frac{\phi_{FSC} EQE_{FSC}}{\phi_{AM1.5G} EQE_{AM1.5G}} \cdot \frac{V_{oc,FSC}}{V_{oc,PV}} \cdot \frac{FF(v_{oc,FSC})}{FF(v_{oc,PV})}$$

= 0.04 · 4.33 · 1.06 · 1.01 = 0.19

[Bende, 2008]

- Relative cost-per-unit-of-power: C_r/P_r

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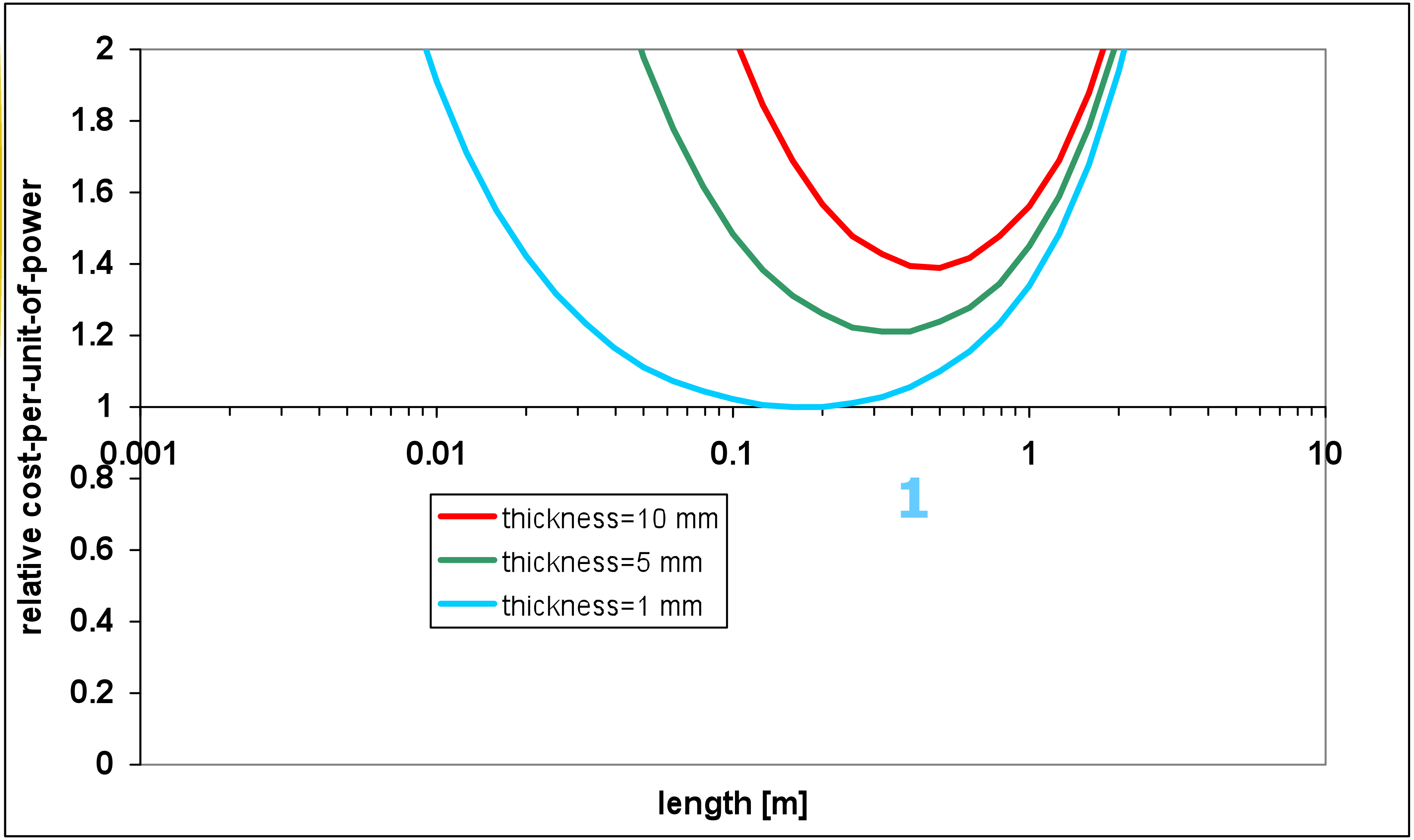
Cost-per-unit-of-power



C_{Red} =5.6·10^{24} m^{-3} , C_{Yel} =0 m^{-3}, cf =1/6 , Specular mirror

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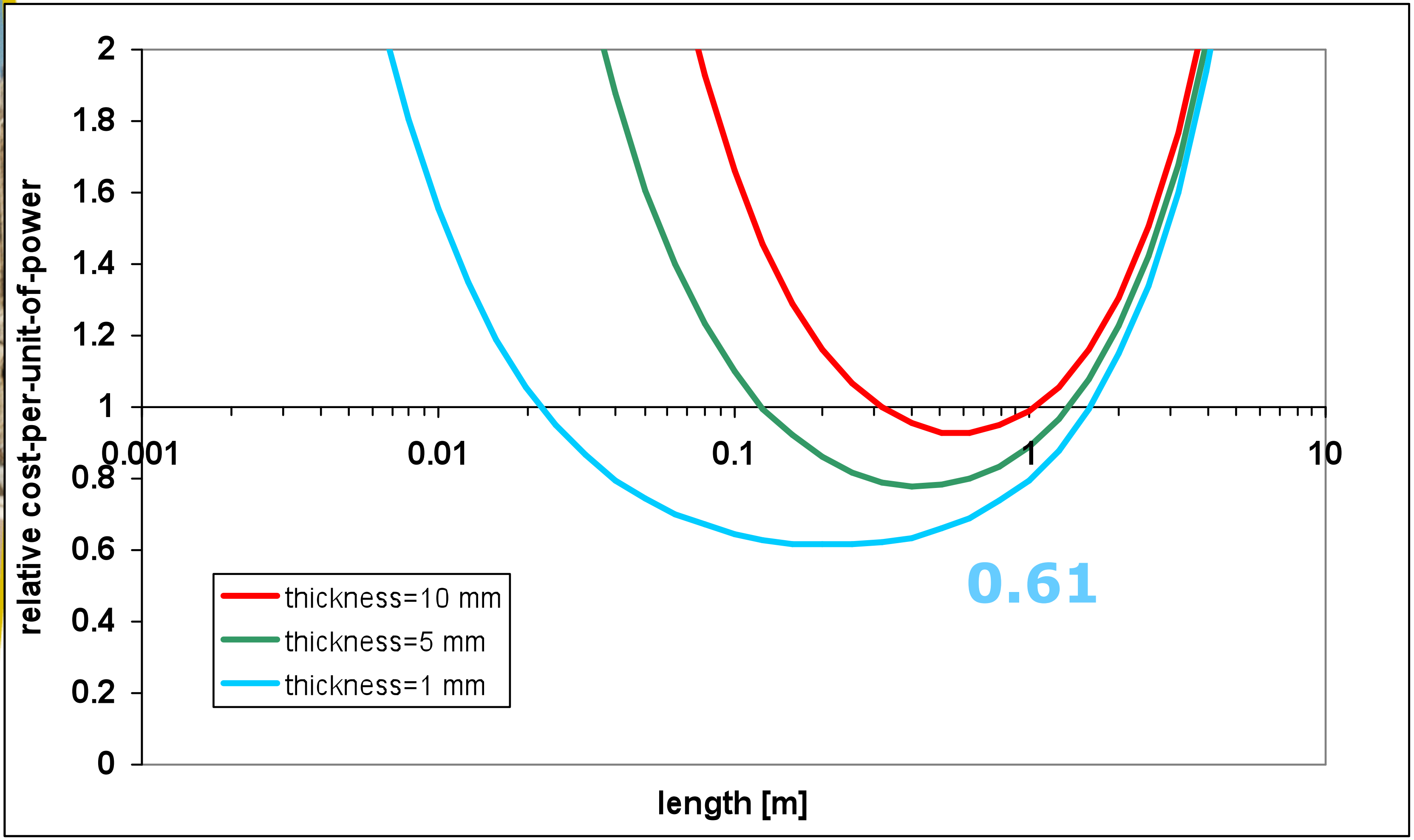
Cost-per-unit-of-power



C_{Red} =5.6·10^{24} m^{-3} , C_{Yel} =0 m^{-3}, cf=1/10 , Specular mirror

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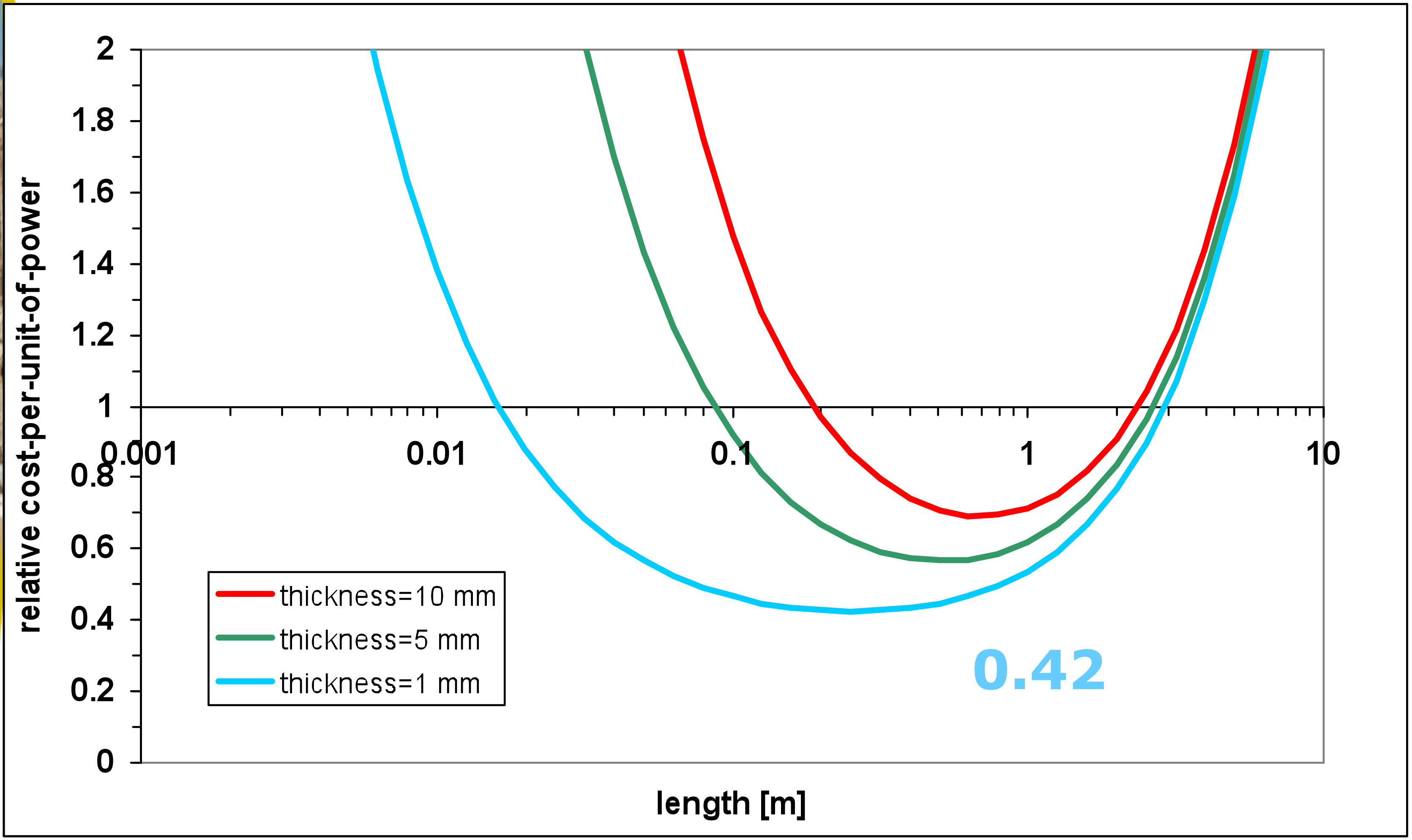
Cost-per-unit-of-power



C_{Red} =5.6·10^{24} m^{-3} , C_{Yel} =0 m^{-3}, cf =1/15, Specular mirror

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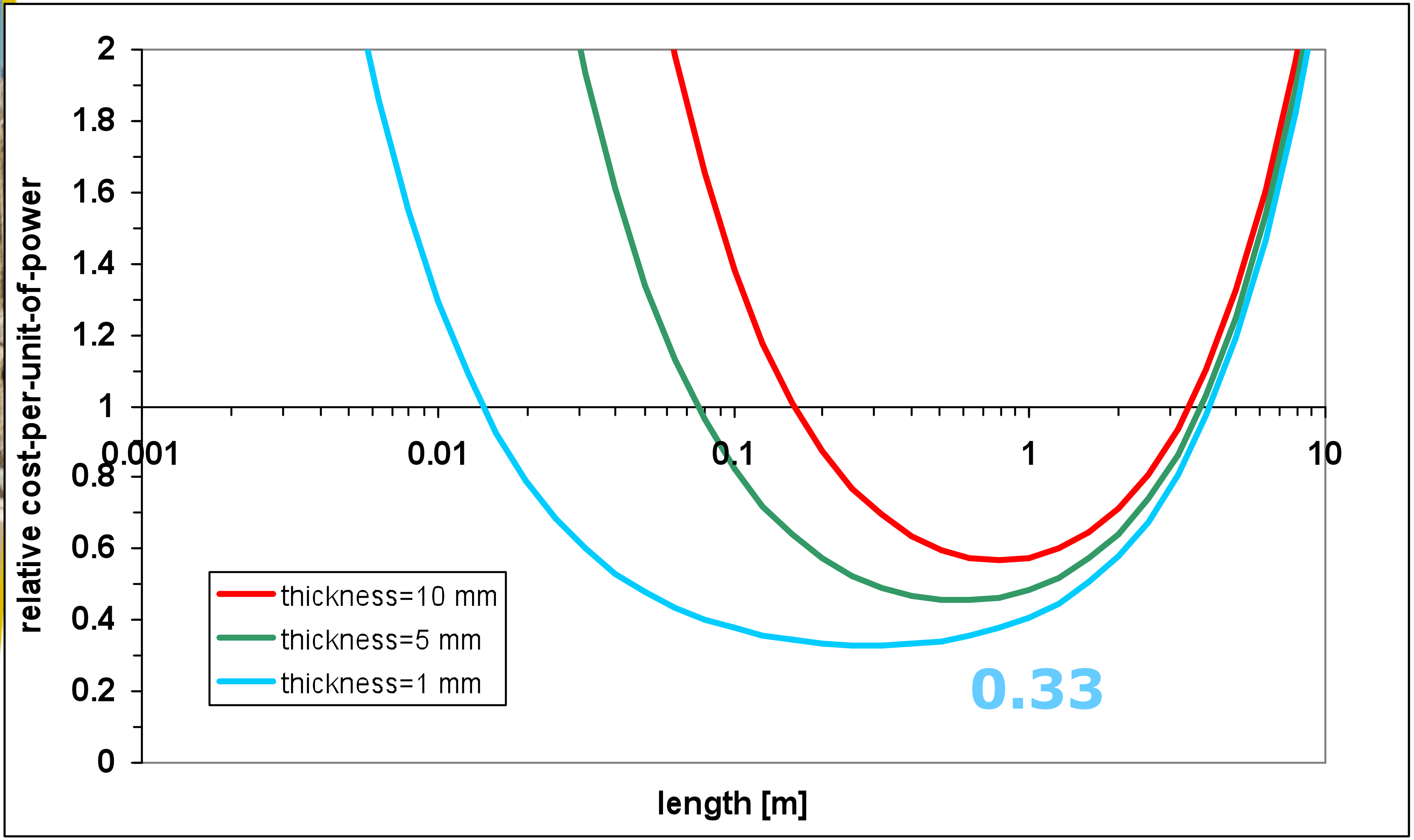
Cost-per-unit-of-power



C_{Red} =5.6·10^{24} m^{-3} C_{Yel} =0 m^{-3}, cf =1/20, Specular mirror

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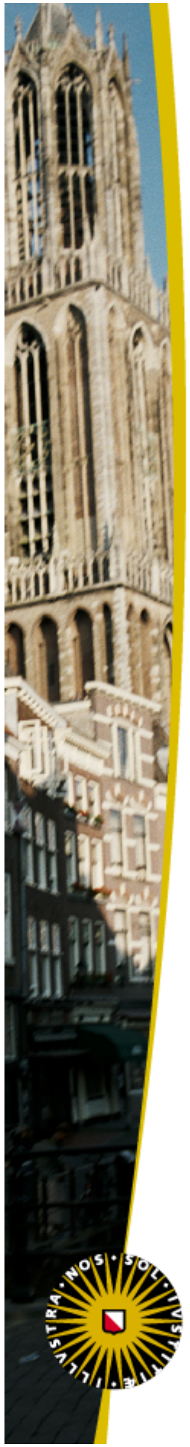

Outlook

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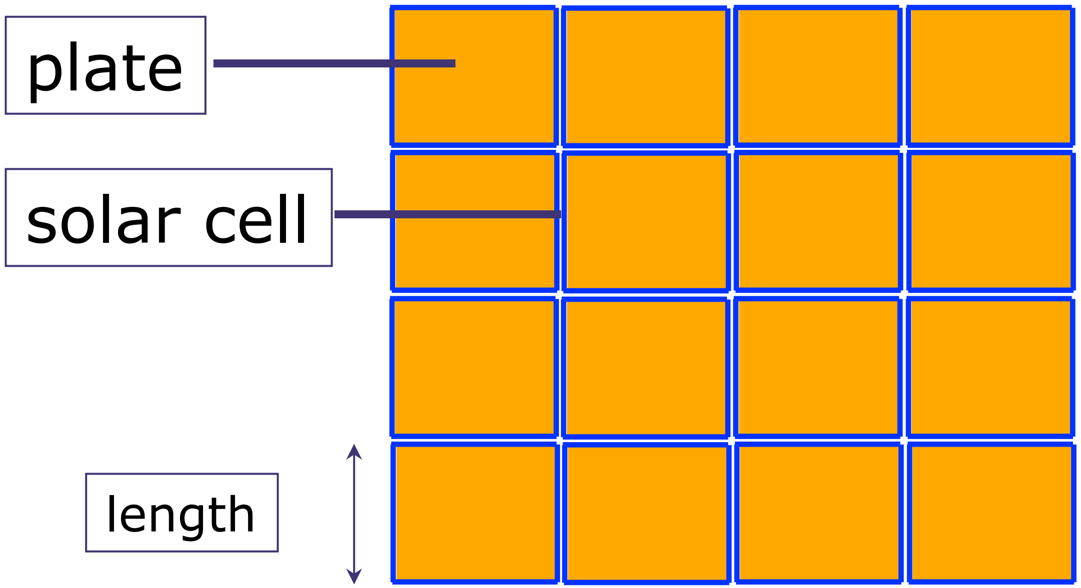
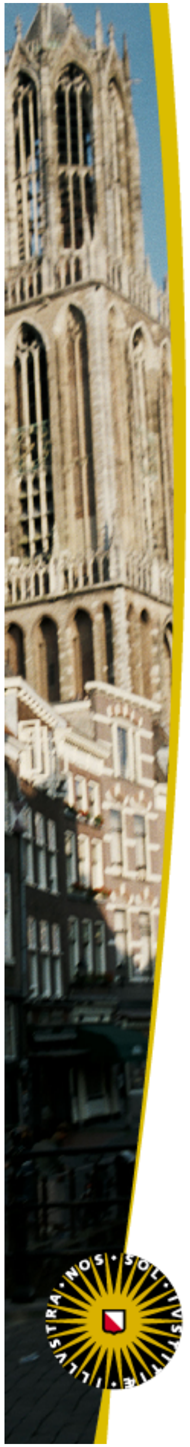
Possible LSC structure



- Length 10-100 cm
- Thickness 1-5 mm

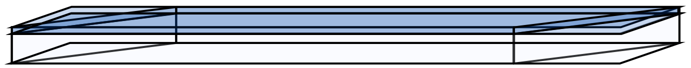


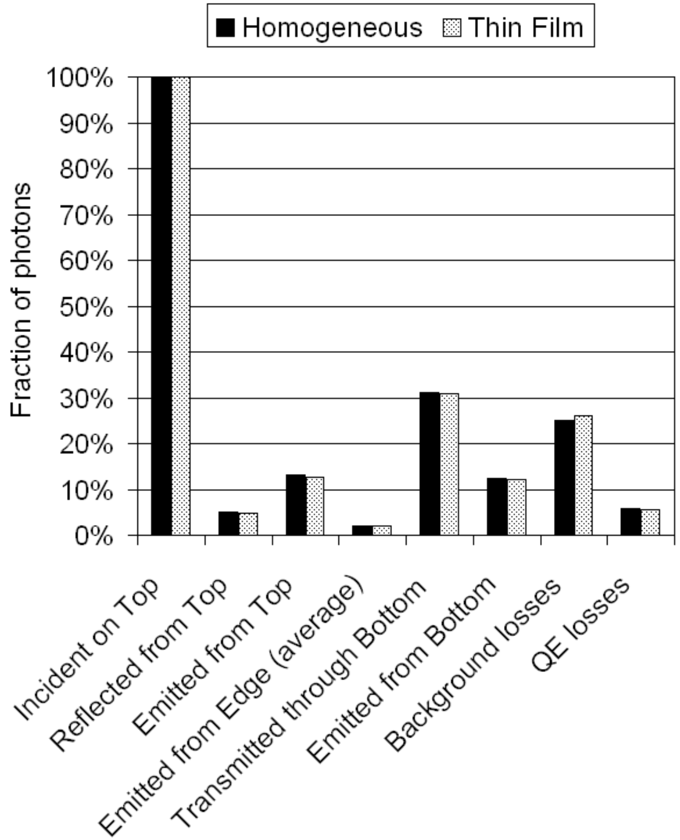
Thin film LSC

- Proposed to minimize re-absorption losses [Rapp, 1978]
- Thermodynamic modeling [Bose, 2007]

- Homogeneous

- Thin Film on glass substrate





SAME!

And probably cheaper!

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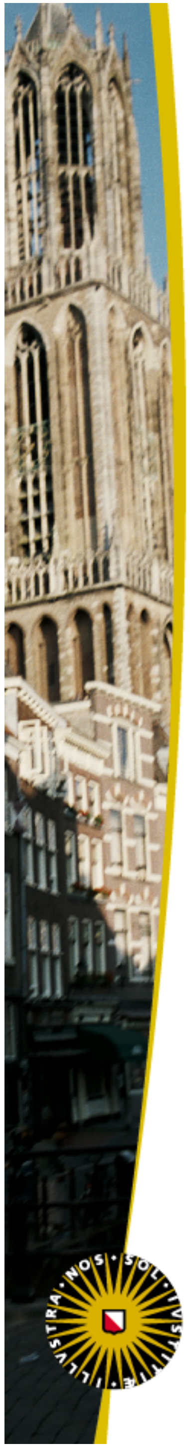
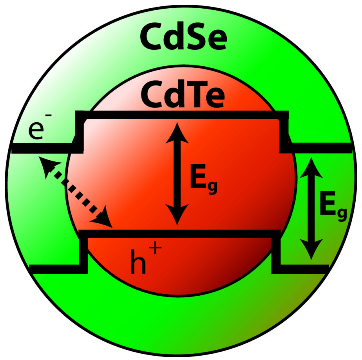
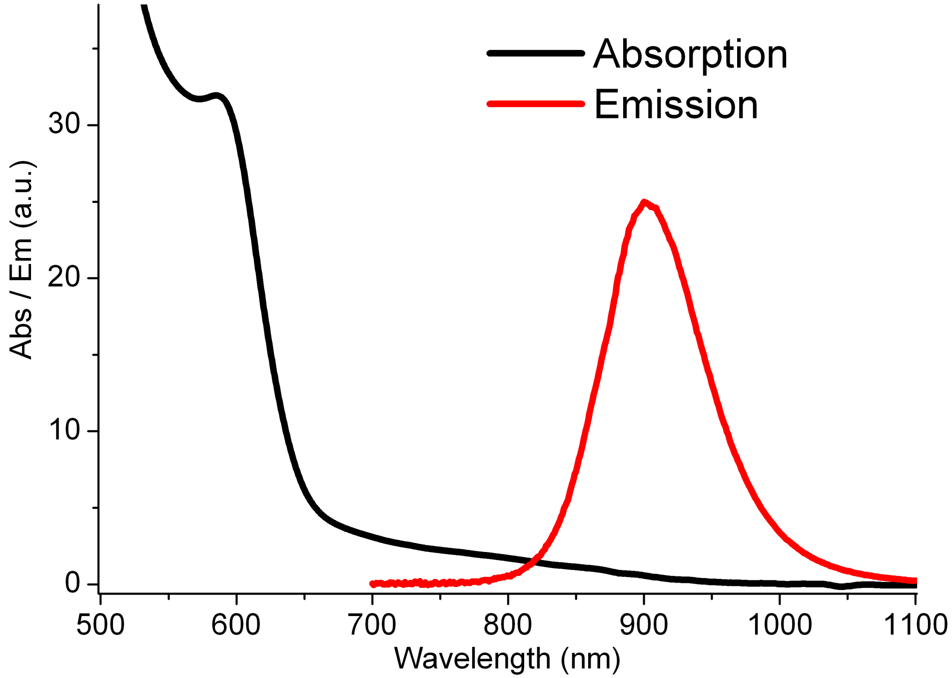


Large Stokes' shift QDs

- Synthesis of type II CdTe/CdSe core/shell QDs with a large Stokes'-shift, high QE, and NIR emission (>900nm)
- Large Stokes' shift prevents re-absorption
- Emission 900 nm perfect for Si cells attached to LSC sides
- Not air-stable yet





[Koole, 2008]

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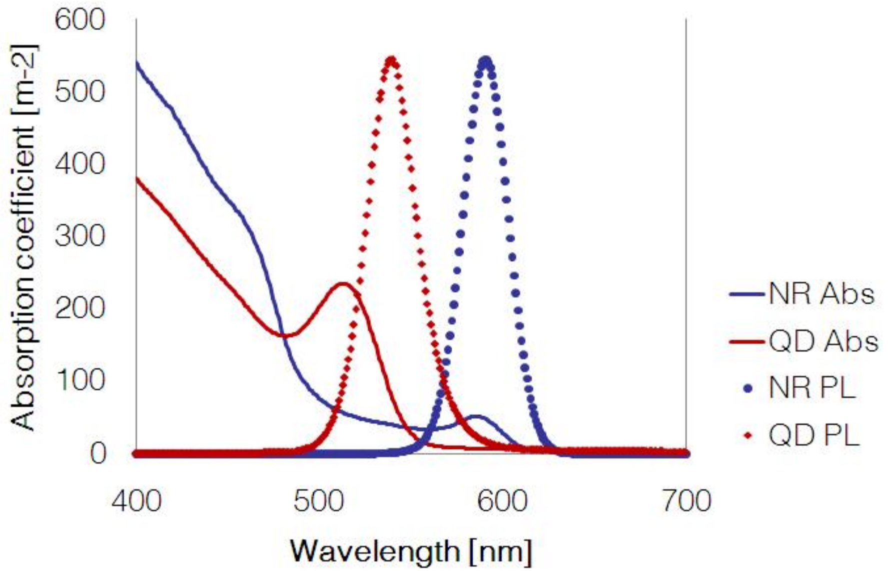
Nanorods

- CdSe/CdS nanorods provided by CNR-INFM and UCB
- Reduce reabsorption losses
- LQE of 70%



[Bose, 2008]

→ NRs double % of photons emitted from the LSC edges

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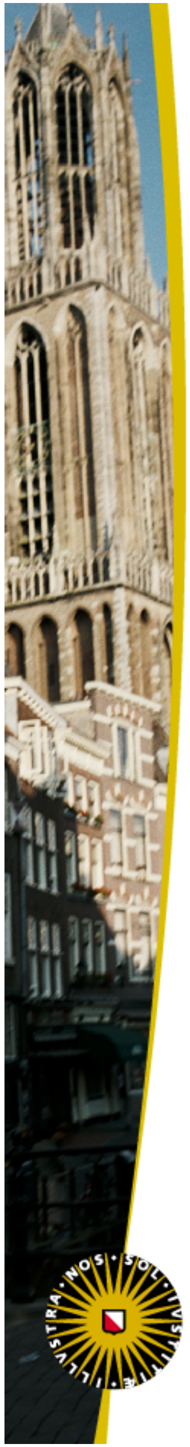
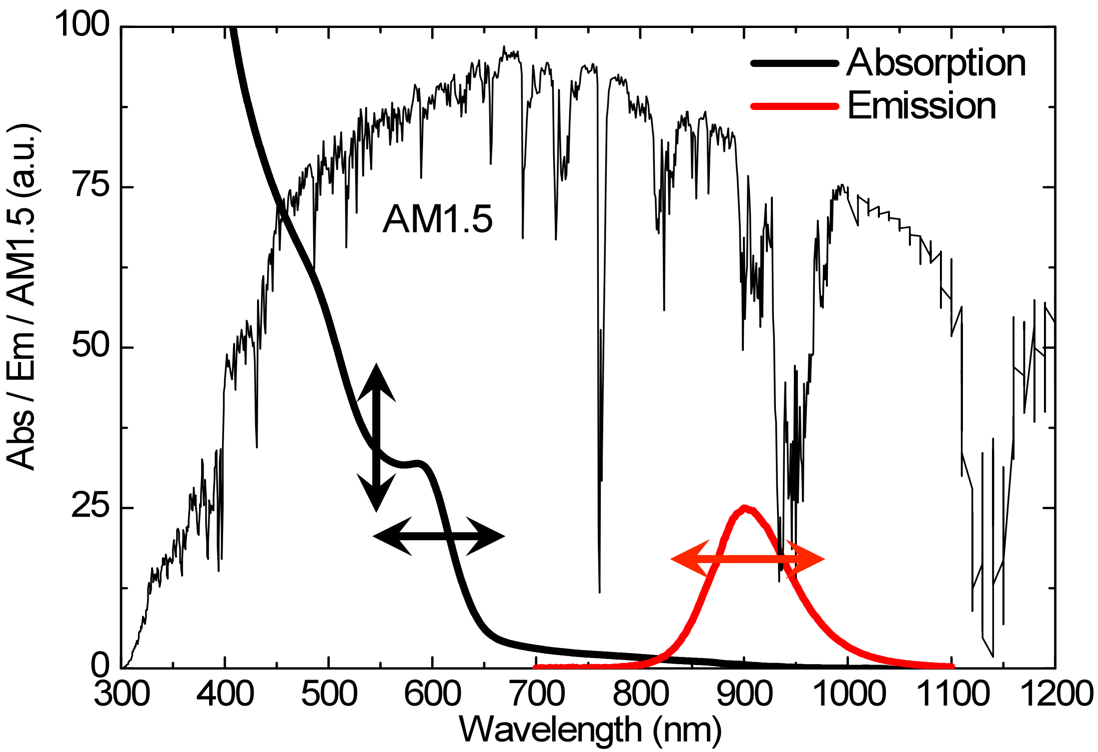


Matching emission with band gap

- Type II QDs with a-Si:H solar cells
- Tuning emission and tuning band gap
- Find optimum combination, project started at UU



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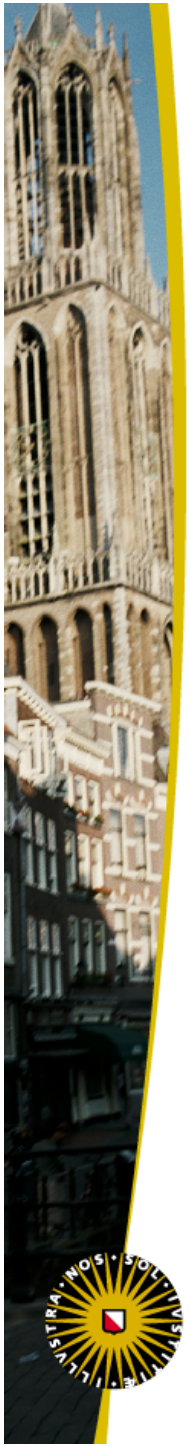
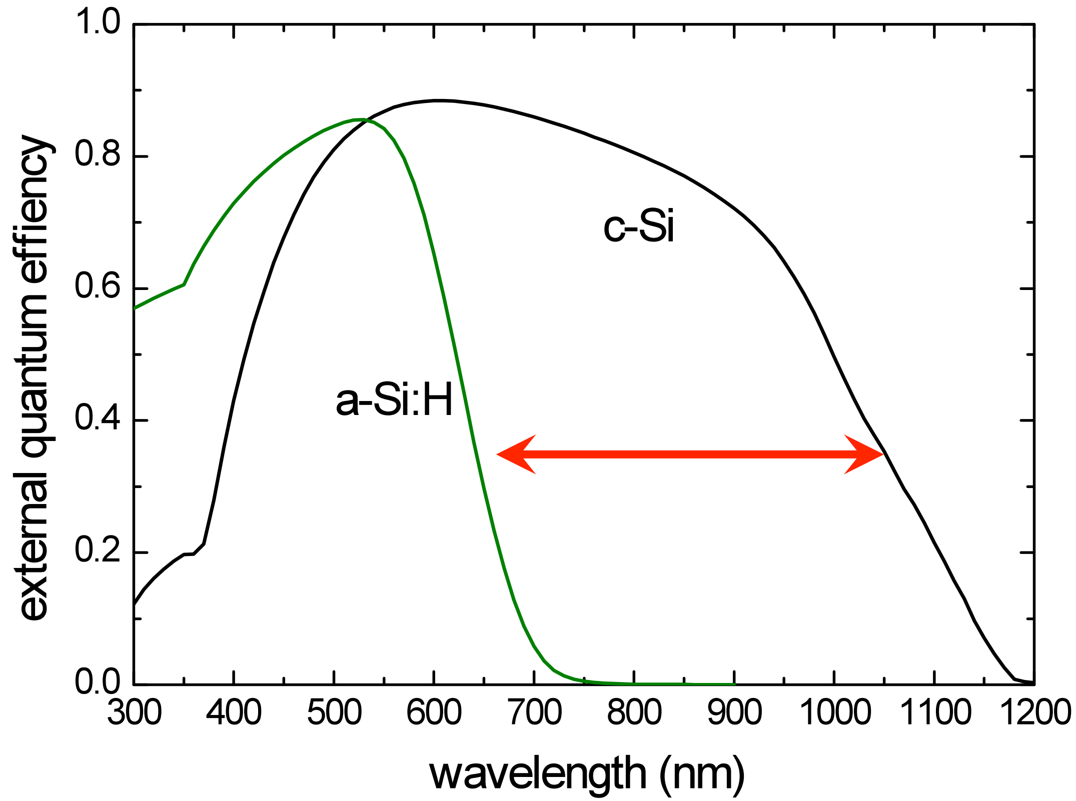


Matching emission with band gap

- Band gap variation 1.1 – 1.8 eV



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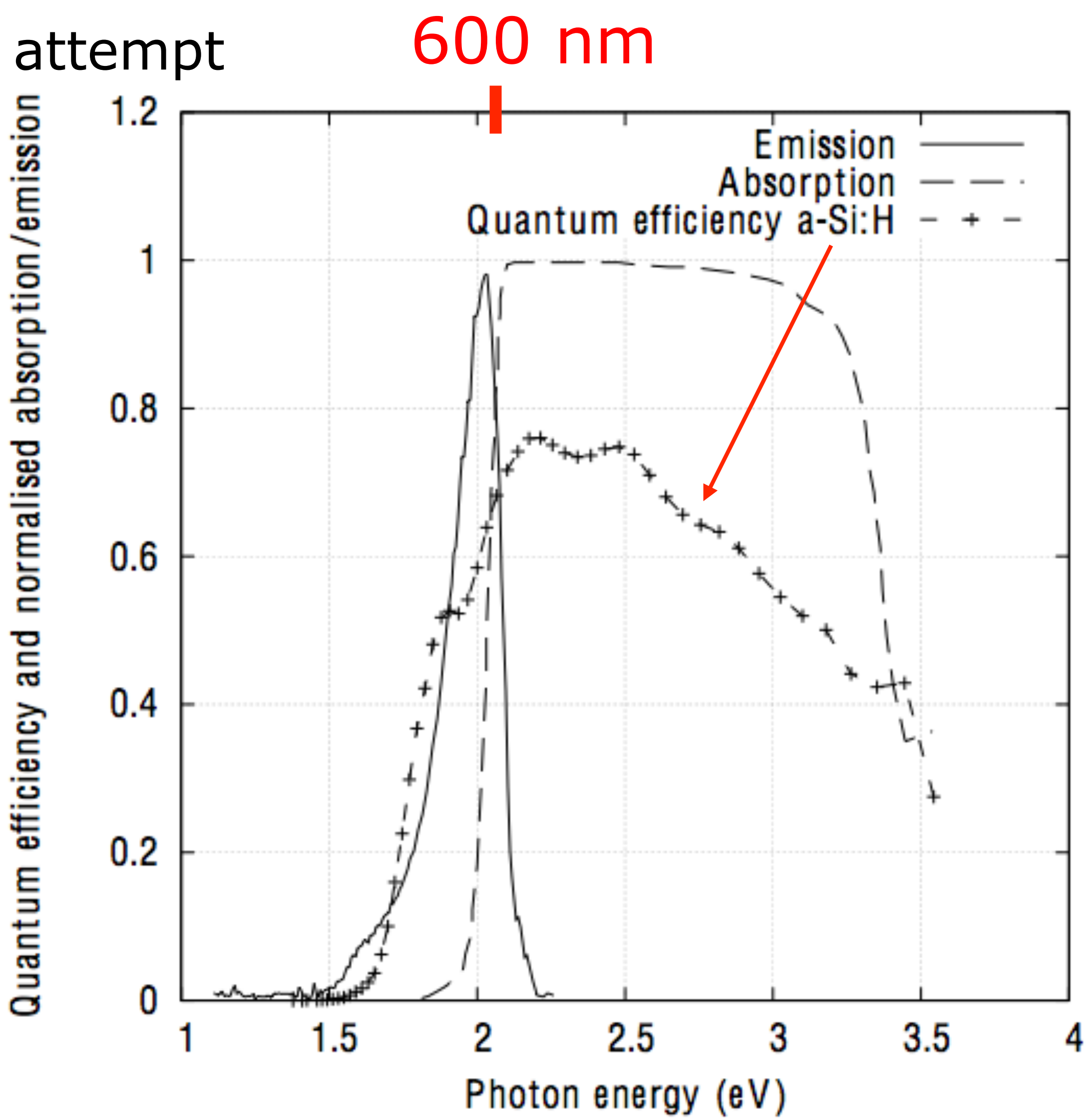
LSC/a-Si:H

- First attempt



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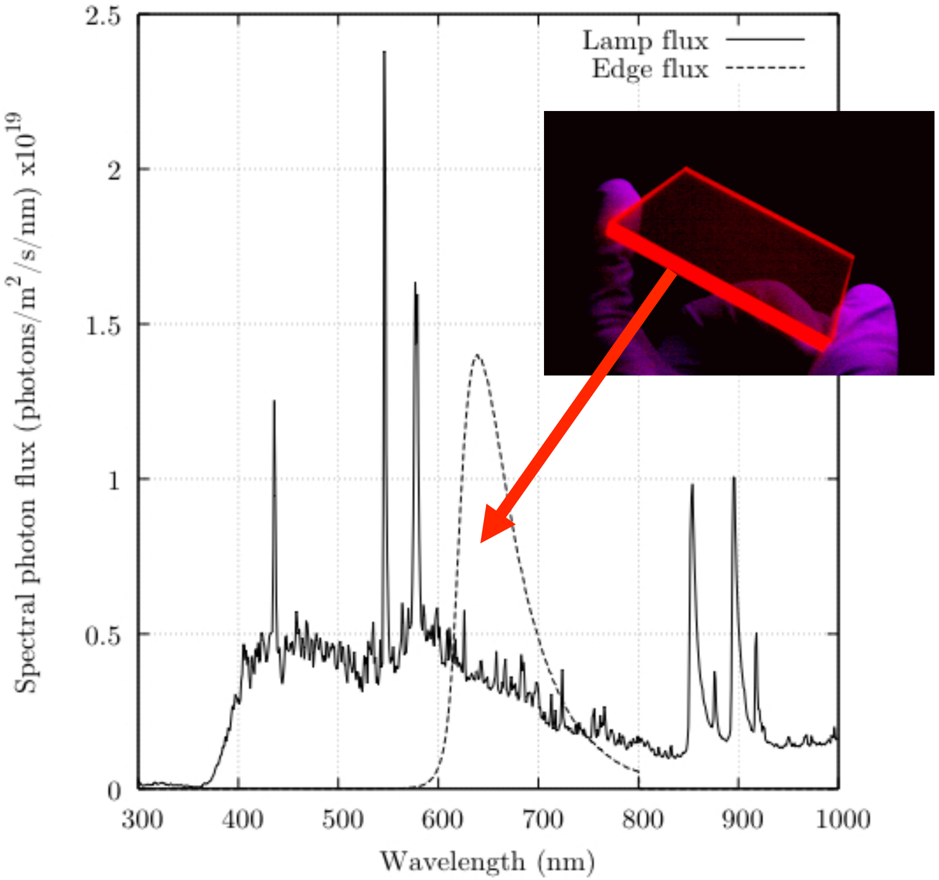
LSC/a-Si:H

Spectral photon flux (#/m^2/s/nm)

- Solar simulator
- Incident 693 W/m^2
- Edge 321 W/m^2
- Concentration effect: higher flux in same wavelength region



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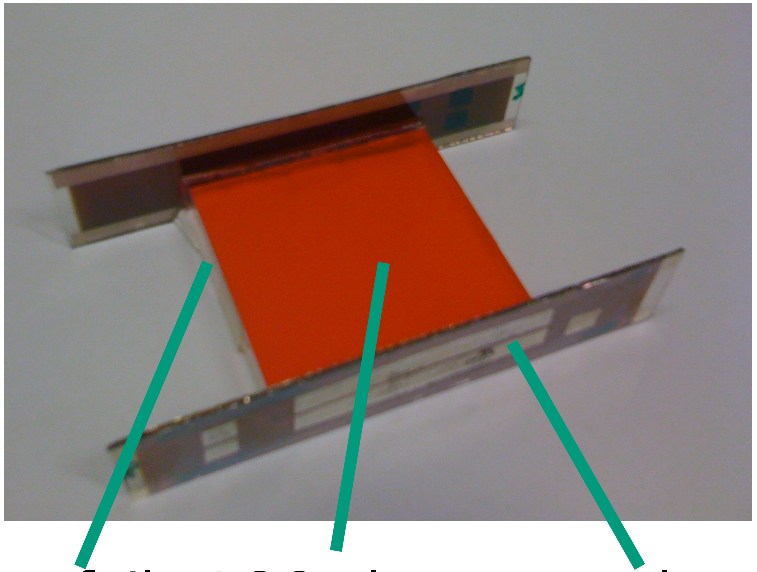
LSC/a-Si:H

- State-of-the-art a-Si:H cells (8%)
- 5x0.5 cm2, on 2 LSC edges
- 3M silver foil on other 2 edges
- Efficiency 1%   [Van Sark, 2010]



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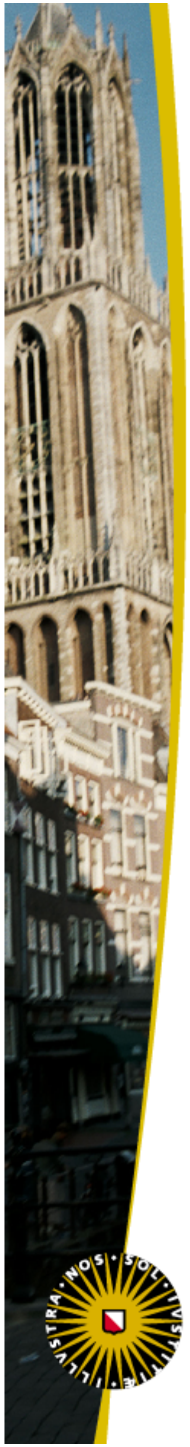
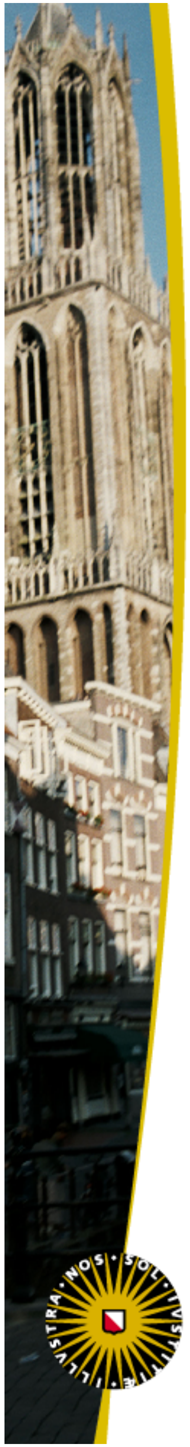


Conclusion



Conclusion

- Luminescent Solar Concentrator is a very good option to harvest cheap solar power, also at higher latitudes
- Modeling allows for parametric studies to find optimum design
- Many luminescent species available, nanoparticles are promising

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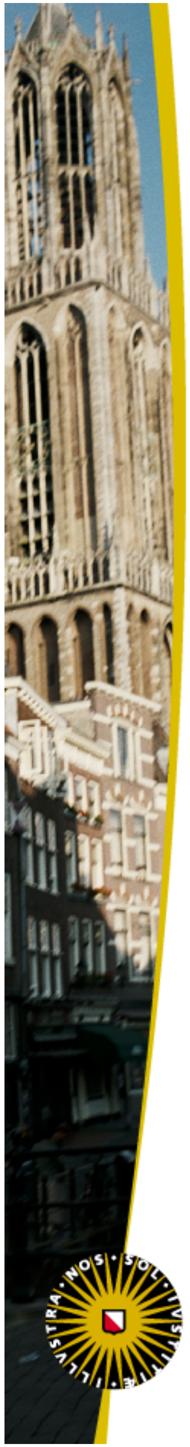
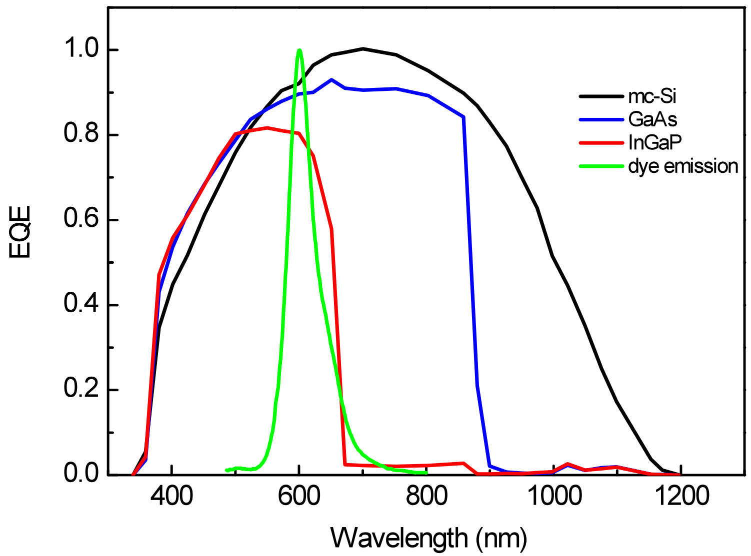


Conclusion

- LSC present drawbacks
  - Spectral sensitivity
    - Organic dyes available with high QE only for wavelengths < 600 nm (2 eV)
    - Using c-Si (Eg=1.1 eV) leaves large part of spectral range (600-1100 nm) unused
  - Stability
  - Absorption matrix
  - Nanoparticles too expensive



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Conclusion

- LSC challenges
  - Need of full spectrum absorbers and NIR emitters, perhaps cascaded
  - Stability of luminescent species in matrix
  - Very low absorption matrix
  - Low cost (nano) materials
  - Abundant materials

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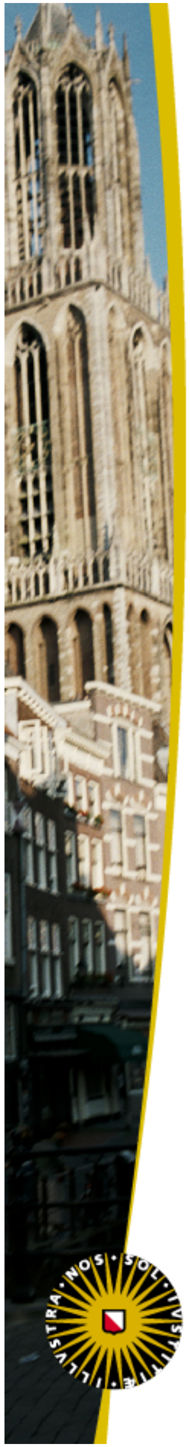

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FULLSPECTRUM

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- FULLSPECTRUM partners
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  - Solaronix: Andy Meier, Toby Meier

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Further reading

- Van Sark *et al.* Optics Express 16 (2008) 21773.
- Barnham *et al.* Luminescent Solar Concentrators, in "*Nanoparticles for Solar Spectrum Conversion*", Tsakalakos (Ed.) Taylor&Francis, Spring 2010.
- Van Sark *et al.* Nanoparticles for Solar Spectrum Conversion, in "*Nanotechnology for Photovoltaics*", Tsakalakos (Ed.) Taylor&Francis, Spring 2010.
- Van Sark *et al.* Luminescent Solar Concentrator, in "*Physics of Nanostructured Solar Cells*", Badescu, Paulescu (Eds.) Nova Science, Spring 2010.

THANK YOU