Modeling a Solar Concentrator using a Complex Photoluminescence Model

S. Gangadhara*, J. Wilde+, B. Mischuck*, Z. Derocher*

*Zemax LLC

+Stanford University

Outline

- What is Photoluminescence (PL)?
- Details of PL model implemented in OpticStudio
- How do Solar Concentrators work?
- OpticStudio model of a Quantum Dot Solar Concentrator (QDSC)
- Summary

Photoluminescence

- Photoluminescence is the absorption and emission of photons through a process of photo-excitation and radiative relaxation
  - From Wikipedia (https://en.wikipedia.org/wiki/Photoluminescence): Time periods between absorption and emission may vary: ranging from short femtosecond-regime for emission involving free-carrier plasma in inorganic semiconductors up to milliseconds for phosphorescent processes in molecular systems; and under special circumstances delay of emission may even span to minutes or hours
- Photoluminescence may be used in several applications
  - Lighting
  - Analytic chemistry
  - Microscopy
  - Semi-conductor characterization
  - Solar concentrators

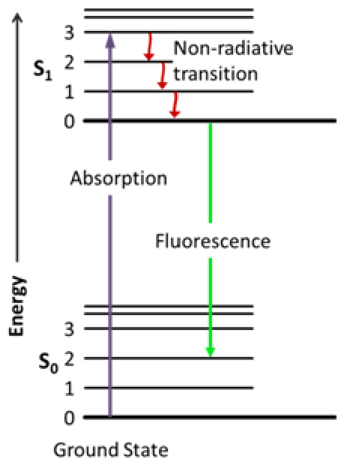

Image taken from: https://www.princetoninstruments.com/applications/fluorescence-phosphorescence-photoluminescence

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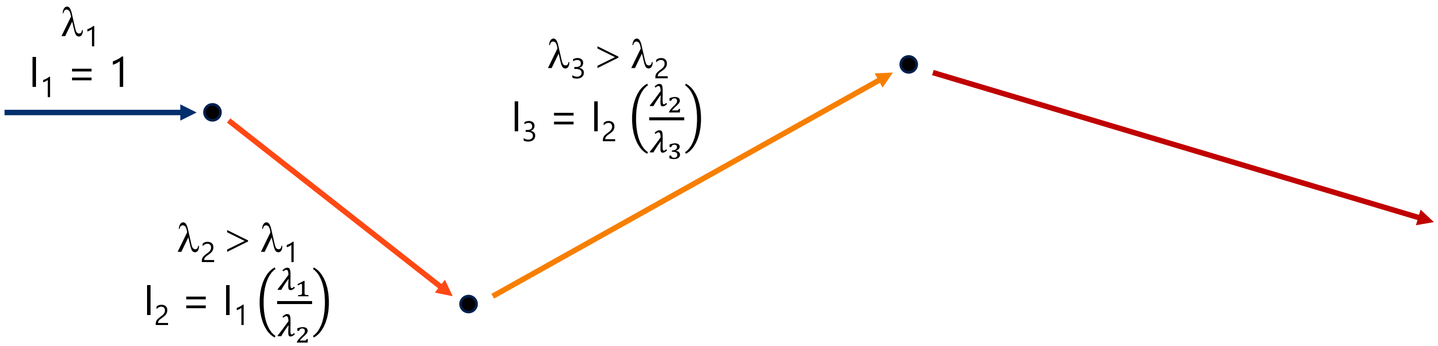
PL Model in OpticStudio

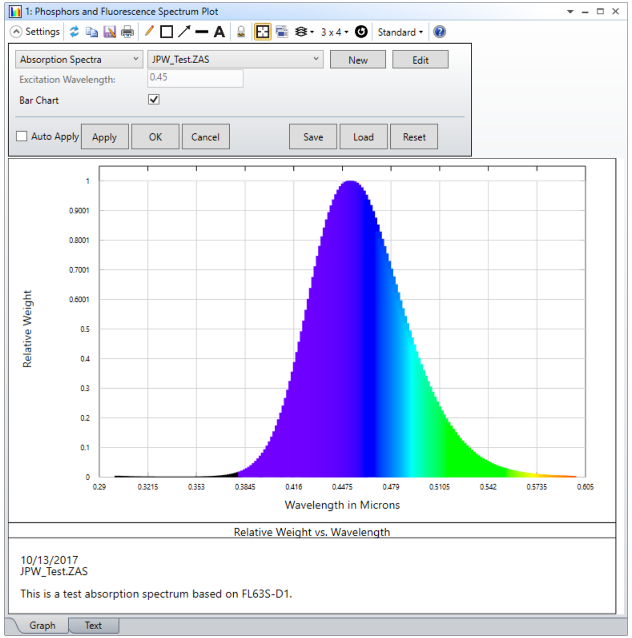
- Photoluminescence is modeled in OpticStudio as an inelastic bulk scattering process:



- Each fluorescent scattering event shifts the ray wavelength further toward the red and reduces its energy or intensity
- The probability for absorption in the material and subsequent re-emission are defined by a mean-free path (L) and a quantum yield (Q)

PL Mean-Free Path: Absorption Spectrum

- The Absorption Spectrum, A(λ,x), represents the likelihood that a photon at an input wavelength λ (in nm) will be absorbed some distance x (in cm) within the PL material
- The Absorption Spectrum is defined to relate the input and transmitted intensities via:
  - $I_T(\lambda) = I_0 10^{-A(\lambda,x)}$
- The input and transmitted intensities can also be defined in terms of a mean-free path (L, in cm):
  - $I_T(\lambda) = I_0 e^{-(x/L(\lambda))}$
- This allows us to write the mean-free path as:
  - $L(\lambda) = x/(A(\lambda,x)*\ln(10))$



PL Mean-Free Path: Extinction Spectrum

- From the Beer-Lambert Law:
  - $A(\lambda,x)= \varepsilon(\lambda)*c*x$
  - $\varepsilon(\lambda)$ = Extinction coefficient ((mole/liter)$^{-1}$cm^{-1})
  - c = Molar concentration (mole/L)
- The molar concentration can be expressed molar in terms of the fluorophore number density (molecules/cm^3):
  - $c = n*(10^3/NA)$, where NA = Avogadro's number (6.022 x 10^{23} molecules/mole)
- The model requires a reference extinction coefficient ($\varepsilon(\lambda_x)$) at the extinction wavelength (λ_x) to convert the absorption spectrum to a wavelength-dependent extinction coefficient
- The extinction coefficient for any input wavelength is calculated according to:
  - $\varepsilon(\lambda) = \varepsilon(\lambda_x)*(A(\lambda)/A(\lambda_x))$
  - *Note that positional dependence of Absorption Spectrum cancels in the ratio*

PL Mean-Free Path: User Inputs

- Combining formulas from the previous slides allows us to calculate the mean-free path in terms of quantities a user can provide:
  - $L(\lambda) = x/(A(\lambda,x)*\ln(10)) = 1/\varepsilon(\lambda)*c*\ln(10) = [(A(\lambda_x)/A(\lambda))/(n*\varepsilon(\lambda_x))]*(NA/10^3*\ln(10))$
- The quantities in square brackets are user inputs to the model:
  - Extinction Wavelength (λ_x)
  - Extinction Coefficient @ Extinction Wavelength ($\varepsilon(\lambda_x)$)
  - Particle Density (n)
  - Absorption Spectrum ($A(\lambda)$), which includes value @ Extinction Wavelength ($A(\lambda_x)$)
- Mie scattering can also be optionally included to model non-fluorescent scattering
  - If a scattering event occurs, the type of event is determined probabilistically, based on the ratio of the photoluminescence and Mie mean free paths

Output Intensity: Quantum Yield

- Probability of absorption determined by the mean-free path (L)
- Probability of re-emission determined by the quantum yield (Q)
- Q generally depends on the input wavelength λ_{in} only (and not on the re-emitted output wavelength λ_{out})
  - Emission spectrum used to define λ_{out}
- Then, the output intensity is given by:
  - $I_{out} = I_{in} * Q(\lambda_{in}) * (\lambda_{in}/\lambda_{out})$
- The output wavelength is restricted so that it cannot exceed the incident wavelength

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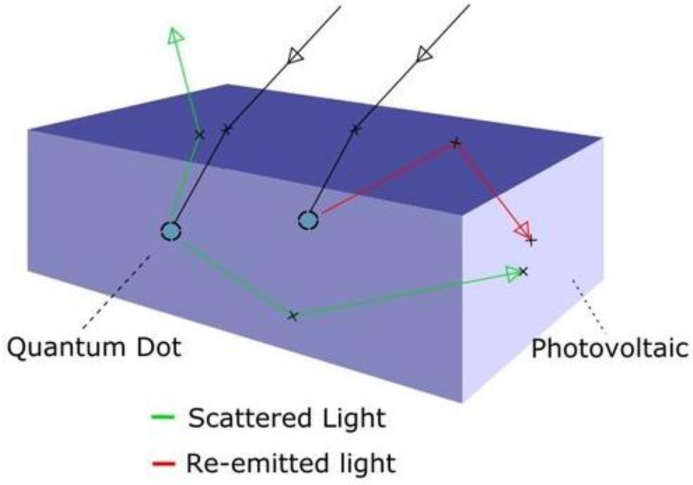
Solar Concentrators

- Solar concentrators are used to take a large area of sunlight and focus it onto a small area, increasing the efficiency of energy conversion
- Traditional concentrators use mirrors or lenses (geometric concentrators)
- Quantum Dot Solar Concentrators (QDSCs) concentrate sun-light using photoluminescence
- QDSCs consist of a transparent rectangular substrate with high index of refraction and high density of semiconducting nanoparticles (quantum dots)
- PV module is placed on one of the small sides of QDSC
- Design results in improved concentration ratio and allows both direct and diffuse sunlight to be collected



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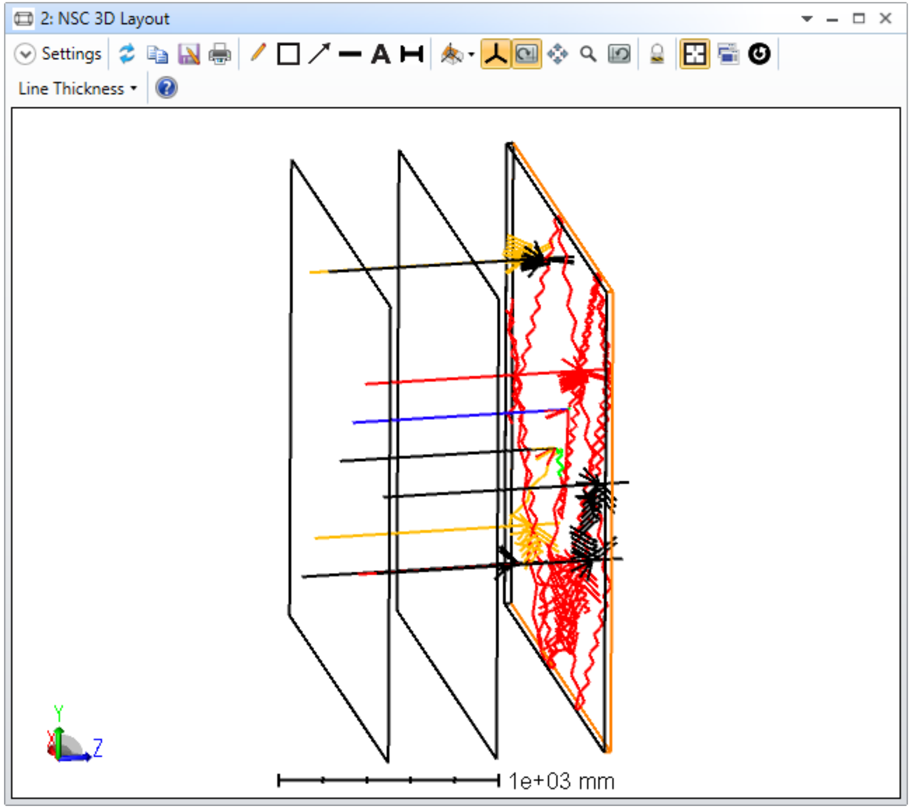
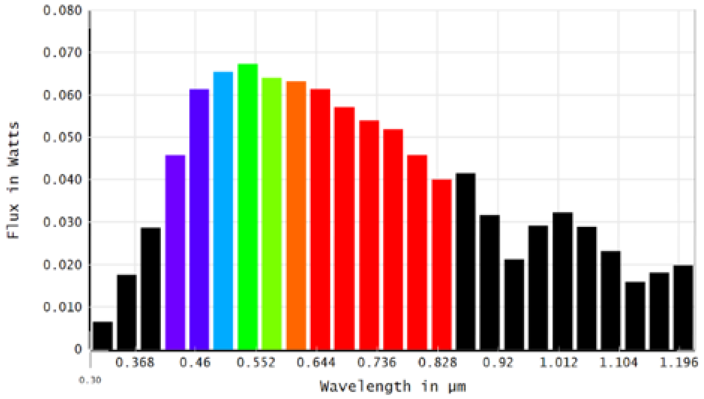
Simulation Model: Geometry

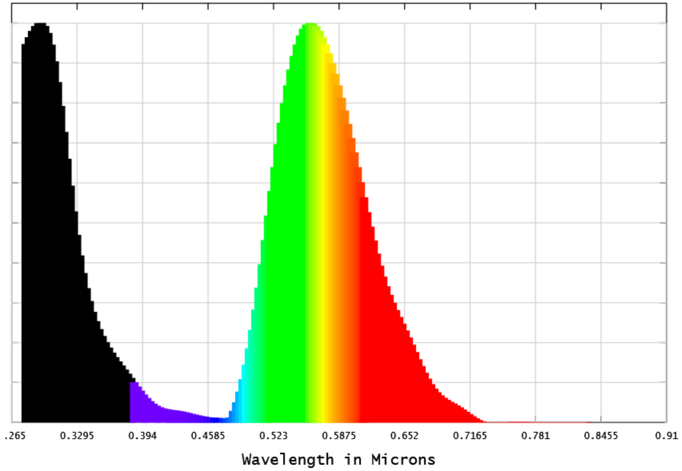
- System consists of a collimated source (unpolarized) and a rectangular volume for the QDSC
  - Material is PMMA
  - Side and back faces have ideal 99.5% reflective coating, and front face is uncoated
- Absorbing Detector Color used to model PV module
- Detector Color objects are used to record the incident and transmitted light
- Lambertian scatter model used to scatter a small percentage of incoming light



Simulation Model: Inputs

- Photoluminescence parameters and spectra taken from research on $CuInS_2/ZnS$ quantum dots
  - Extinction coefficient set to 10^5 at an extinction wavelength (λ_x) of 400 nm
  - Quantum Yield (Q) taken to be 0.81, constant with wavelength
  - Quantum dot density set to $5x10^{16}$ molecules/cm^3
  - Resulting PL mean-free path is 0.523 mm at λ_x
  - Absorption and Emission spectra shown on bottom right
- Input spectrum based on NREL solar data at 1.5 airmass @ sea level (shown on top right)
- Non-fluorescent scattering is also included, with a Mie mean-free path of 5 mm





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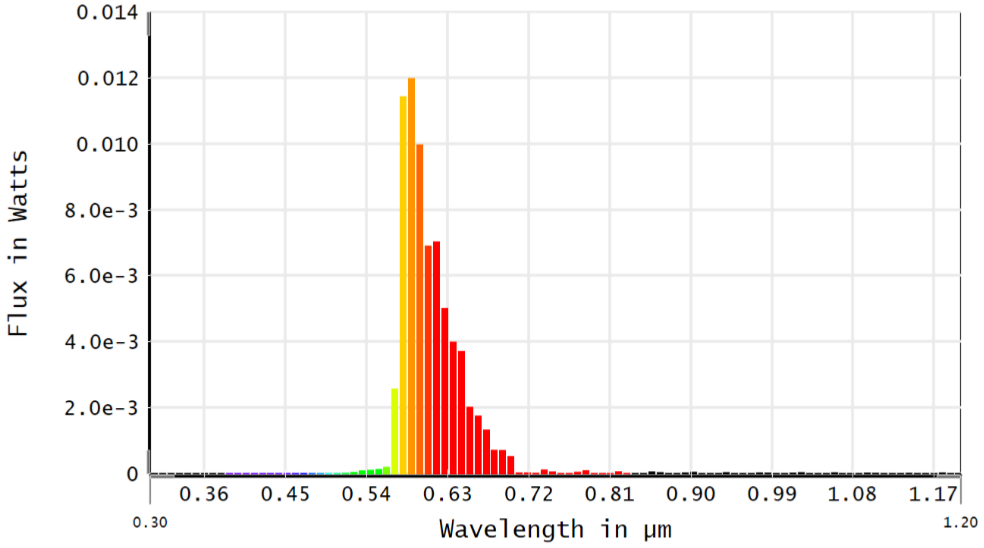
Simulation Model: Results

- Flux vs. Wavelength results for PV module shown on the right
  - Absence of short wavelength light due to short PL mean-free path
  - 550-650 nm range highly peaked, as expected from input absorption and emission spectra
- Folding detector data into a crystalline Si (c-Si) solar cell responsivity curve, approximate cumulative efficiency is estimated
  - Total efficiency is ~6%
  - Efficiency is ~585% larger when including QSDC than without



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- Photoluminescence has many scientific and industrial applications
- A complex model has been added to OpticStudio to support the accurate design of systems that include photoluminescence
  - This model accounts for wavelength-dependence in the mean-free path and for both fluorescent and non-fluorescent scattering
- A model of a photoluminescence-based Quantum Dot Solar Concentrator (QDSC) has been built in OpticStudio
  - Results indicate a significant improvement in collection efficiency when using a QDSC