Luminescent solar concentrators – reabsorption and fundamental principles of thermodynamics

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Abstract

We report on subject of luminescent solar concentrators as an introductory topic related to education on photovoltaics. Employing of luminescent solar concentrators in any photovoltaic systems possess a plethora of practical and theoretical issues that can be separated into several partial projects and systematically investigated by undergraduate students (without prior knowledge of photovoltaic technologies). Focusing of major mechanism of optical losses, which is phenomena of reabsorption, it is possible to bridge basic functionality and experimental observations of concentrators with theoretical aspects of light conversion and concentration originating in fundamental thermodynamic laws. We show how simplified thermodynamical analysis of radiation flows can lead to estimation of practical parameters of luminescent concentrators.

Keywords: solar cells, photovoltaics, luminescence, fluorescence, concentrators, thermodynamics

INTRODUCTION

Luminescent solar concentrators (LSC) attracted interest for photovoltaic (PV) applications with their potential to reduce costs by concentrating the sunlight onto small area. LSCs were studied extensively already in 1980s [1], however due to the recent interest in new materials and approaches for photovoltaics they are gaining research attention again [2].

From the pedagogical point of view, LSC present an attractive topic for undergraduate (and masters) students of technical fields and can act as an entry topic to the area of photovoltaic research. Moreover, LSC can be used as a demonstrative system of fundamental PV physical principles.

LSC FOR TEACHING AND EDUCATION

Principle of LSC

LSC consist of a plate implanted or covered by luminescent dye molecules. Molecules absorb incident solar radiation from relatively large surface and generate luminescence in all directions. Due to higher refractive index of LSC material, total internal reflection can guide the emitted luminescence towards thin edge of the LSC where solar cell is placed, see schematics on Fig. 1. Although collecting concentrated light from smaller area leads to saving materials, the significant advantage of LSC relies in ability to concentrate diffuse sunlight in contrast to conventional solar concentrators (parabolic mirrors, Fresnel lenses) which can concentrate direct sunlight only.

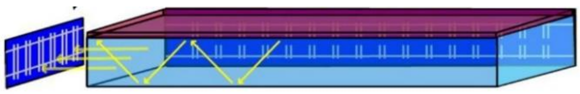

Fig. 1: Schematics of thin dye-layer LSC with solar cell at the edge

Losses in LSC – challenges for improvement

Historically, LSCs are known for low optical efficiencies due to significant losses [3], [2]. There are two critical places for losses – interface of LSC and solar cell, where any inaccuracy results in unwanted outcoupling of the light; losses through escape cone from the front surface, present all over the length of LSC. The latter is mostly a consequence of reabsorption losses which arises from the overlap of absorption and emission spectral bands, see Fig. 2.

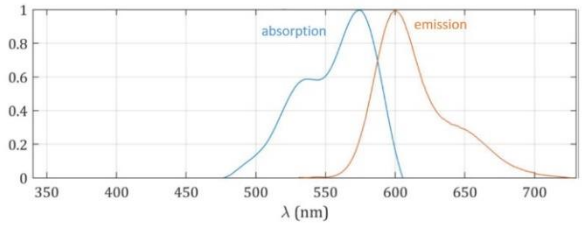

Fig. 2: Normalized absorption and emission spectra of a luminescent dye (BASF R305)

As a part of the LSC research topics, students can decide which of the efficiency issues they aim to tackle, depending on their individual skills. Interface between LSC and solar cell requires focus on coupling optimization by either designing antireflective coatings or index matching layers, as well as optimizing the size and contacting of attached cells and developing convenient opto-electo-mechanical setup for illumination and electrical characterisation of the whole LSC-cell system.

Optimizing reabsorption losses requires deeper understanding of theoretical principles of light conversion and propagating. Students can focus on simulating absorption/emission spectral bands and calculating reabsorption probability along the propagation direction, either with simplified analytical models [4], [5] or by ray-tracing simulations [6]. Moreover, operation of LSC with regards to reabsorption phenomena can act as a demonstrative system for fundamental thermodynamical principles of light conversion.

Reabsorption – linking with fundamentals

Losses of LSC due to escape cone emission are closely related to fundamental laws of thermodynamics. The process of continuous absorption, emission and reabsorption along the propagation of photons within the LSC leads to formation of equilibrium between photons and absorbing molecules. Photons then act as a photon gas and can be described by black body-like distribution with characteristic temperature T and chemical potential μ [7]. This can be directly observed by recording spectra emitted from the edge of LSC and fitting black body curve to the overlapping part of emission spectra with absorption band.

The assumption above leads to the possibility of looking at LSC operation (even without solar cell attached) as of a heat engine – it converts solar black body radiation at fixed temperature to "colder" black body radiation with finite chemical potential. Such an approach then leads to evaluation of limits of LSC operation, e.g., by relating chemical potential to maximum achievable open-circuit voltage [8]. Moreover, limitation of LSC on maximum concentration ratio can be evaluated by considering simple analyses of entropy fluxes related to incident and emitted light, see schematic in Fig. 3. The total entropy change ΔS (which must be non-zero according the second law of thermodynamics) can be expressed in terms:

$$\Delta S = -S_{INC} + S_{EM} + {}^{E_S}/_{T} \tag{1}$$

where S_{INC} and S_{EM} are entropy fluxes of incident and emitted beam respectively and E_S is the Stokes shift, characteristic for used molecular dye. The term E_S/T is then representing heat loss to the reservoir, originating form thermalization processes within molecules. Assuming constant photon fluxes and describing spatial distribution of incident and emitted photons in terms of etendues $\mathcal{E}_{INC}$ and $\mathcal{E}_{EM}$ respectively, we can write equation (1) as:

$$k_B ln\frac{\mathcal{E}_{EM}}{\mathcal{E}_{INC}} + \frac{E_S}{T} \geq 0 \tag{2}$$

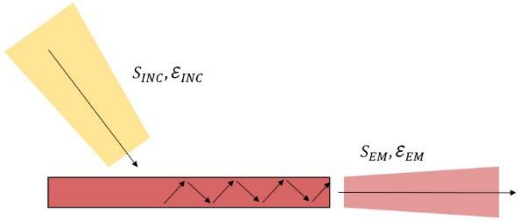

Fig. 3: Schematics of entropy flows in LSC

Equation (2) above can be used to evaluate maximum concentration ratio for two specific cases:

Diffuse incident light – etendues of incident and emitted light are equal (full hemisphere) and C_{MAX} is then given by

$$C_{MAX} = e^{{}^{E_S}/_{k_B T}} \tag{3}$$

Direct incident light – analogous case to conventional geometrical concentration (where C_{MAX} is given by solid angle ratio), we obtain:

$$C_{MAX} = \frac{\pi}{\omega_S} e^{{}^{E_S}/_{k_B T}} \tag{4}$$

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