LUMINESCENT SPECTRAL SPLITTING: A NEW APPROACH TOWARD CONSTRUCTING HIGH-EFFICIENCY SOLAR CELLS

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We consider an approach, which we call luminescent spectrum splitting (LSS), for efficiently dividing solar radiation into several spatially divided spectral components. These spectral components separately illuminate photovoltaic cells of different band gaps using a simple optical design that is easy to manufacture and easily extensible to an arbitrarily large number of spectral channels. Because of this extensibility, the number of junctions in the system is limited only by the availability of photovoltaic cells with appropriate band gaps. As a result, significantly high system efficiencies should be accessible. In our analysis of this concept, we find that optical quantum efficiencies as high as 95 percent can be achieved.

We have introduced a spectral-splitting concept that opens up a new design space for constructing high-efficiency PV systems. Although our results show high quantum efficiency at the expense of solar concentration, we have only examined a small portion of the design space in the report. A number of possible extensions are worth further investigation.

For typical solid-state solar cells, a natural tradeoff occurs between current (the number of photons converted to electrical energy) and voltage (the amount of energy converted per photon) that limits the overall solar-to-electric conversion efficiency that can be achieved. This tradeoff, known as the Shockley–Queisser limit, is a consequence of the broadband spectrum of the incident solar power density and the electronic structure of semiconductor p-n junctions. The most common approach to overcoming this limitation is to construct a "multi-junction" photovoltaic (PV) system where each junction is "tuned" to a separate portion of the solar spectrum (Imenes and Mills 2004). A well-known example of such a design is the "tandem" solar cell, where p-n junctions are stacked on top of each other in optical series by epitaxial growth of different layers of material. Very high power efficiencies have been reported with tandem cells; however, the stacked design requires current matching across the p-n junctions.

This current-matching requirement limits the practical efficiency gains when seasonal and diurnal variations in the solar spectrum are considered. A promising alternative to the tandem approach is the use of optical elements to spatially separate portions of the solar spectrum and deliver them to separate, single-junction solar cells. This spatial separation of the solar spectrum avoids the lattice-matching constraints of epitaxial growth and the current-matching requirement that constrains robustness in tandem cells. Some examples of efforts to optically split the solar spectrum include the RAINBOW multi-junction design from the National Aeronautics and Space Administration (NASA) (Lewis et al. 1997; Smith et al. 2000), holographic splitting

(Ludman et al. 1992), and a Defense Advanced Research Projects Agency (DARPA)-funded concentrated PV project (Barnett et al. 2006; Barnett et al. 2009).

A variety of optical designs have been proposed and built to spatially divide the solar spectrum. The design employed by the DARPA-funded PV project, for example, made use of dichroic mirrors (wavelength-dependent reflective surfaces) and tandem solar cells. Dichroic mirrors, however, have proven to be difficult to work with practically in solar cell designs because (1) their reflective properties are sensitive to the angle of the incident light, which is problematic in cases where the light is concentrated; (2) designs based on dichroic mirrors are difficult to extend; and (3) dichroic materials are cost prohibitive.

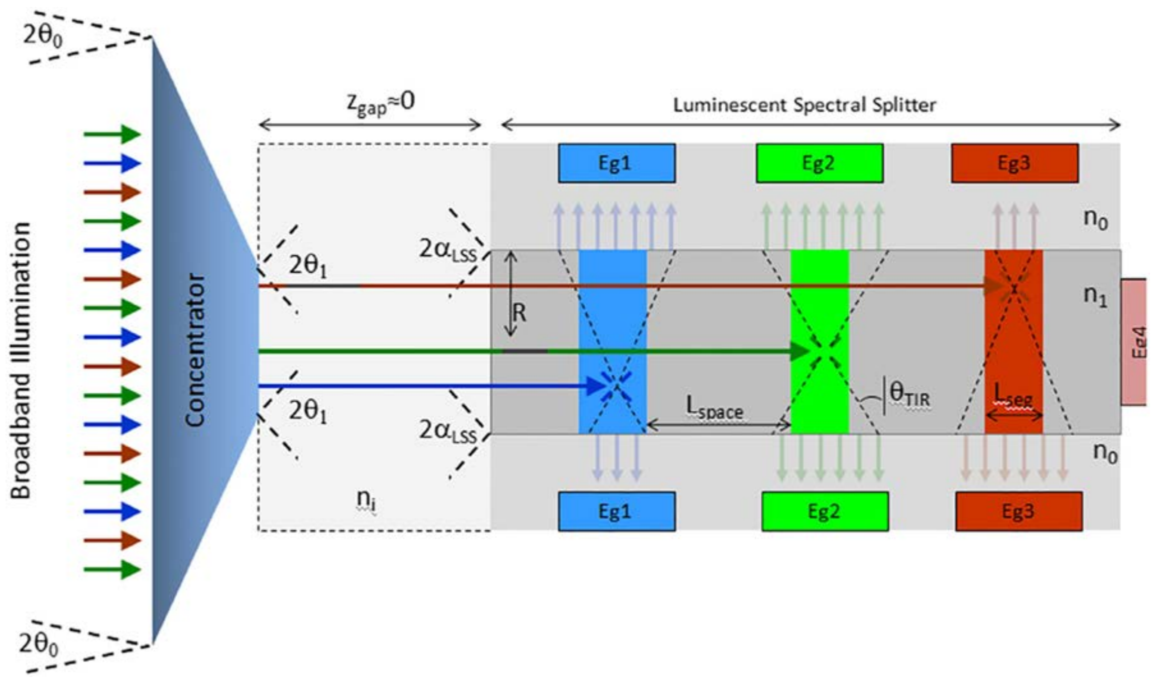
An alternative approach to dichroic mirrors makes uses of stacked arrays of luminescent solar concentrators (LSCs)—waveguides doped with luminescent materials. Stacked LSCs can achieve both spectral division and high concentration of light, which lower the amount of PV material needed. However, the optical efficiencies of LSCs are severely constrained due to reabsorption. In our report, we considered a similar approach, which we call luminescent spectrum splitting (LSS), that aims to split the solar spectrum with maximum optical efficiency by using a simple design that is easy to manufacture and easily extensible to an arbitrary number of subcells.

Although our concept is similar to LSCs, we focus first on high efficiency and good spectral splitting, in contrast to LSCs, where the primary objective is to achieve high light-concentration ratios. This change in focus provides new opportunities in the spectral-splitting design space. In our analysis of this concept, we find that optical quantum efficiencies as high as 95% can be achieved.

THE LSS CONCEPT

The LSS concept is illustrated in Figure 1. Broadband solar illumination is first concentrated by a non-imaging concentrator optic, such as a compound parabolic concentrator. The concentrated solar flux is then fed into an optical waveguide, where light is propagated by total internal reflection (TIR). To achieve spectral splitting, parts of the waveguide are doped with tunable flurophores with very high luminescent quantum yield. This yield can be achieved by embedding semiconductor nanocrystals inside polymer matrices via polymerization or similar methods (Lee et al. 2000; Reisfeld 2001; Lee 2002; Sheng et al. 2006; Olsson et al. 2004; Sundar et al. 2004). With this setup, each ray propagates through the waveguide until it encounters a segment that is doped with nanocrystals whose band gap is lower in energy than the ray's wavelength.

Rays absorbed by the fluorophores are then reemitted isotropically at a lower frequency depending on the nanocrystal's emission profile. Some of the reemitted rays will not meet the TIR condition and will exit the waveguide along the sides, where they can be collected by single-junction PV materials. In the report, we focused on a cylindrical design with rotational symmetry about the z-axis, but rectilinear or other designs are also possible and are worth investigating in future studies.



The gap between primary concentrator and the LSS is inflated so that angle definitions can be illustrated. The diagram is not to scale.

Figure 1. Diagram of LSS Concept.

ANALYSIS

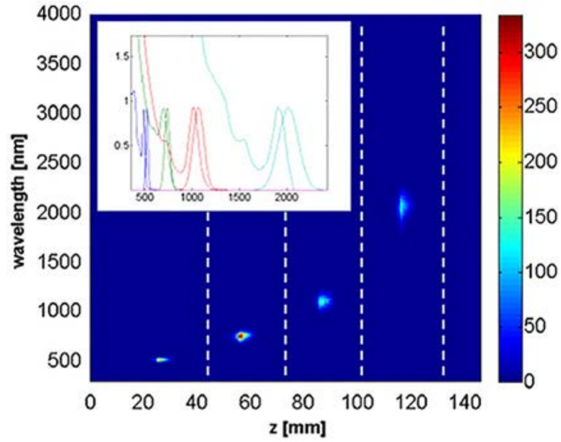
In our analysis of the LSS concept, we identified the following relevant design parameters (some of which are illustrated in Figure 1):

- C_1: Input concentration (not illustrated in figure)
- n_0: Refractive index of cladding on LSS
- n_1: Refractive index of LSS interior
- n_i: Refractive index at input to LSS and exit of primary optic
- L_{seg}/R: Unitless ratio between length of color segment and radius of LSS
- P_{trans}: Probability of a photon to traverse a color segment without absorption when traveling on axis and with wavelength at the color segment's absorption peak(not illustrated in figure)
- L_{space}/R: Unitless ratio of the length of spacing between color segments and the radius of LSS
- θ_0: Acceptance half angle of primary concentrator.

To assess the performance of the LSS concept as a function of these parameters, we constructed a Monte Carlo ray-tracing model to simulate photon propagation through the LSS waveguide. With this simulation, we can examine the optical and power efficiency of the LSS as a function of the design parameters given previously. For our study, we sought to simulate a system that is realistically feasible using present technology. We selected a refractive index of $n_1 = 1.62$ for the LSS, corresponding to optical glass. The cladding index n_0 was a varied parameter between 1.4 and 1.65. We also varied P_{trans} between 0.0001 and 0.02 and L_{seg}/R between 0.1 and 10 and assumed the ideal case where the quantum yield is 1. For the primary concentrator, we assumed an input concentration $C_1 = 94X$.

With the aforementioned constraints, a number of parameter combinations were identified through the simulation for which the optical quantum efficiency exceeded 90%. Figure 2 shows the output spectrum of one of these combinations ($L_{seg}/R = 5.0$, $n_0 = 1.60$, $P_{trans} = 0.01$). In this figure, we see that the LSS concept accomplishes the main goal of splitting the broadband solar spectrum into four spatially separated narrowband outputs that do not overlap significantly. For this case in particular, we obtained a quantum efficiency (QE) of 94% and a power efficiency (PE) of 75%. (QE = 80% and PE = 70% when only side walls are counted.) The probability of reabsorption inside the same color segment was 0.35 in this run, which is much lower than typical LSC designs.

The caveat to the high QE results is that the color segments deconcentrate the input optical flux. This concern is illustrated in Figure 3. Because of this deconcentration, we need to cover large portions of the waveguide with PV material to fully use the output spectrum, which can be problematic if the costs of the PV materials are high. In Figure 3, net concentration is defined as the ratio of the area of the input primary concentrator to that of the total collection areas covered by the PV materials, or C1 × input area/coverage area. Here, we see that we can obtain reasonable QEs (>90%) for net concentrations less than 10X, which is much lower than the input concentration (94X). Thus, the LSS



Absorption and emission spectra for each color segment are shown in the inset.

Figure 2. Output Spectrum of the LSS Waveguide Monte Carlo Simulation as a Function of Axial Length z and Wavelength for the Case $L_{seg}/R = 5.0$, $n_0 = 1.60$, $P_{trans} = 0.01$, $L_{space}/R = 5.04$, $N = 10^5$.

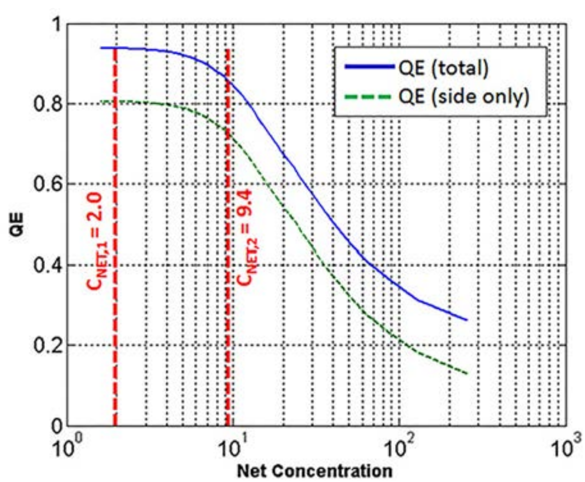


Figure 3. Tradeoff between QE and Net Concentration.

concept can be seen as sacrificing the input concentration to achieve spectral splitting at high QE.

Using these outputs from the Monte-Carlo simulation, we calculated the expected solar-to-electric conversion efficiency if PV cells with band gaps matched to these optical spectra (e.g., aluminum gallium indium phosphide (AlGaInP), indium gallium arsenide (InGaAs), silicon (Si), and germanium (Ge)) were coupled to each of our LSS designs. Based on reported external quantum efficiencies and other relevant PV parameters, we computed the expected current generation in each PV cell and found an overall solar-to-electric conversion efficiency in the neighborhood of 30%. The individual efficiencies of each channel were 58%, 56%, 30%, and 11% (high to low band gap). The lower band gap cells exhibited very high dark currents, which limited their efficiencies.

CONCLUSIONS

We have introduced a spectral-splitting concept that opens up a new design space for constructing high-efficiency PV systems. Although our results show high quantum efficiency at the expense of solar concentration, we have only examined a small portion of the design space in the report. A number of possible extensions are worth further investigation. Non-symmetrical geometries, such as rectangular or hexagonal cross-sections, for example, would permit the tiling of many units into arrays, which could leverage recent developments in the field of solid-state lighting.

The addition of secondary concentrators may also lead to higher net concentration designs. Another possibility is the use of aligned anisotropic luminescence, where flurophores preferentially readmit toward the sides of the waveguide. In addition, future development of inexpensive PV materials may also make the LSS approach more commercially interesting. Regardless of these possibilities, the LSS approach offers a design that is inherently simple, robust, and extensible and that should be relatively inexpensive to manufacture.

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Luminescent Spectral Splitting: Efficient Spatial Division of Solar Spectrum at Low Concentration

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