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Functionalizing the rear scatterer in a luminescent solar concentrator

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Luminescent solar concentrators (LSCs) are presented that use a rear scattering layer made of a phosphorescent material for improving the use of the incident solar light spectrum. Besides simply scattering incident light that passes through the waveguide proper, the phosphor can absorb blue light and emit this light at a wavelength more amenable to absorption by the fluorescent dye. Integrated emission energies from the LSCs may be increased using the phosphor scatterer 4%–40% depending on the concentration of dye in the waveguide when compared to standard white scatterers.

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I. BACKGROUND

The potential of the luminescent solar concentrator (LSC), a device well-suited for generating electricity from sunlight in the built environment, has been extensively studied.^{1–4} In its most basic form, the LSC consists of a plastic plate either filled or topped with fluorescent dye. Sunlight incident on the top surface is absorbed by the dye molecules and emitted at a longer wavelength; a fraction of this light is trapped by total internal reflection (TIR) within the waveguide and is transported to the edges of the device where one may place one or more small photovoltaics for conversion of the light energy to electrical current. The LSC demonstrates the promise of being both low in cost and weight and adaptable in its coloration, shape and size, providing many advantages for architectural integration not afforded by other solar systems.

Widespread adoption of these devices has been curtailed by several factors. One of the key drawbacks of the LSC is incomplete usage of the solar spectrum. The most widely used fluorescent materials for the LSCs to date have been the Lumogen series of dyes produced by BASF.^{5,6} We have also presented a new perylene perinone dye that extended the absorption range of the LSC with reasonable fluorescent quantum yield.⁷ However, no dyes are foreseen that could uniformly cover the solar spectrum. A second prominent loss is due to re-absorption events.^{8–10} Re-absorption results from the absorption of emitted light by subsequent dye molecules, owing to the generally limited Stokes shift, or separation between the absorption and emission spectra, of most organic dyes. In addition to losses associated with non-emission due to limited fluorescence quantum yields of the dyes, there are additional losses from the reabsorbed light again emitted but in such a direction as to escape the waveguide surface(s). Re-absorption in LSC samples is often seen as a distinct red-shift of the emission spectrum from the waveguide edge as compared to the direct emission spectrum of the dye.

In order to make better use of incident sunlight, rear reflecting layers have been applied to the LSC. In particular, white scattering layers have been used with twofold purpose.^{2,6,11–16} The first is to redirect light that has passed through the waveguide without being absorbed in such a direction as to allow this light to directly illuminate the edge mounted photovoltaic. This feature demonstrates a dependence on distance, and the impact of the scatterer decreases as the

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waveguide size increases.¹⁶ The second role of the scatterer is to allow light that has not been absorbed but is within the absorption band of the dye to be returned for a second passage through the dye, effectively doubling (or more) the pathlength of the light through the absorbing material.

In this paper, we demonstrate the concept of using a rear scatterer incorporating a phosphor in combination with an LSC waveguide. The phosphor in this configuration plays a double role. It acts similarly to a standard white scatterer for light outside the absorption band of the phosphor, but for wavelengths within the absorption band of the phosphor, it acts as a spectral down shifter, emitting light at a wavelength much closer to the optimal absorption wavelength of the fluorescent dye (see Figure 1 for the functionality of the phosphor layer). Previous work suggested using a separate dye layer on top of a scatterer to provide a spectral shift.¹² In this work, the luminophore is located within the scattering layer itself, so in practice should be easier to produce. We demonstrate that the enhancement of LSC total energy output is possible when using the phosphor-containing scattering layer as compared to a standard white scattering layer.

II. MATERIALS AND METHODS

Thin glass slides were coated with a dispersion of 4.001 g cerium-doped yttrium aluminium garnet (YAG:Ce) phosphor in 0.661 g acrylate binder (which contained ethylacetate, ethyllactate, and isopropyl alcohol) and 1.322 g 2-(2-ethoxyethoxy)ethylacetate by bar coating at 5 mm/s. The dried samples were nearly opaque. The wet layer was deposited with a fixed bar doctor blade with gap thickness of 80 μm and the dry thickness was assumed to be about 40 μm . The phosphor particle size was determined by laser diffraction particle size analysis (Sympatec) to be $D_{50} = 4.1 \pm 0.5 \mu\text{m}$. The quantum yield was determined to be $>90\%$.

Injection moulded $5 \times 5 \times 0.3 \text{ cm}^3$ poly(carbonate) waveguides filled with 4-500 ppm of the dye Lumogen Red305 (BASF)¹⁷ or a perylene nonyl-perinone⁷ were provided by Sabic Innovative Plastics and used as waveguides. The top surfaces of the samples were exposed to the light from a 300 W solar simulator with filters to approximate the 1.5 air mass (global) solar spectrum (Lot-Oriel) producing an integrated output of 401 W/m^2 over the spectral range 350-800 nm. The waveguides were placed on three different backgrounds separated by an air gap: a white scatterer of thick white paper, a white scatterer made by spray painting a glass slide with white paint, and a similar slide with the phosphor-containing scattering layer deposited on top. Single edge emission spectra and intensity were determined using a Labsphere

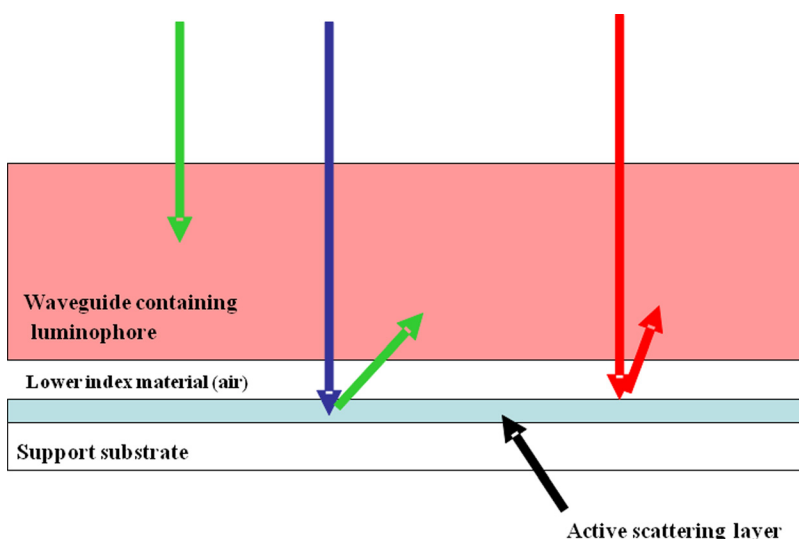


FIG. 1. Depiction of an LSC waveguide which uses a scattering layer containing a phosphor. For this work, the lower index layer was air.

spectral light measurement system (SLMS) LED 1050 integrating sphere, and total edge outputs were determined by integrating the measured spectra from 350 to 800 nm.

III. RESULTS

The YAG:Ce phosphor has a peak absorbance at ~ 450 nm and emits around 525 nm.¹⁸ Both the Red305 and perylene perinone also have a secondary absorption peak around this emission wavelength (see Figure 2 for representative absorption and emission spectra for the materials used in this work). The emission spectra from one edge of a polycarbonate plate containing 15.5 ppm Red 305 (peak absorbance 0.2) using a rear white scatterer and a YAG:Ce rear scatterer are shown in Figure 3(a).

With higher absorbance of the waveguide, the relative impact of the YAG:Ce rear phosphor is lower. Consider the sample containing 127 ppm of the Red 305 dye with peak absorbance 1.7, shown in Figure 3(b), and the integrated emission spectra from 350 to 800 nm are found in Figure 4 as well as the increase in output using the phosphor scatterer compared with using the white scattering backgrounds.

Similar experiments were done using the perylene perinone waveguides. As seen in Figure 5, there is also an enhancement of the output upon application of the phosphor to the rear of the waveguide.

IV. DISCUSSION AND OUTLOOK

In the configuration using a luminescent phosphor in the rear scattering layer, one may make better use of the incident spectrum. One maintains the ability to scatter light that is outside the phosphor absorption range, but also additionally absorb light that passes through the waveguide, or outside the absorption band of the dye and emit it at a wavelength closer to the absorption peak of the dye in the waveguide. In Figures 3(a) and 5, it is clear to see the influence of the phosphor on the system absorption and emission. Light that normally was directly scattered to the emission edge has been absorbed by the phosphor, resulting in the drop in emission around 450 nm (the peak of the phosphor absorption). This light has been emitted by the phosphor at 525 nm. Some of this emitted light passes directly to the edge, as seen in Figures 3(a) and 5 by the additional output at 525 nm. Given the relatively short influence of the scatterer towards assisting in edge output, returning light to the waveguide within the absorption band of the fluorescent dye would allow light normally outside the angles of total internal reflection to be trapped by TIR, effectively increasing the potential transfer distance of these photons.

There is an appreciable increase in the integrated edge emission in both the Red 305 and perylene perinone waveguides, especially where the dye content is less. For example, as seen in

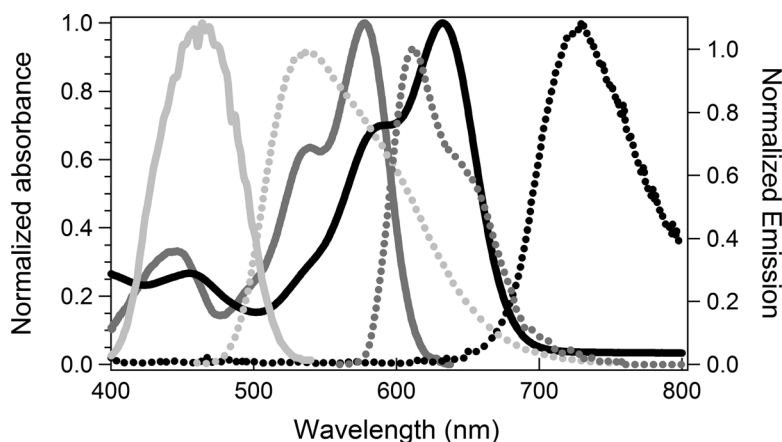


FIG. 2. Normalized absorbance (solid lines) and emission (dotted lines) spectra for YAG:Ce phosphor in an acrylate host (light gray), and Red 305 (dark gray) and the perylene perinone (black) in polycarbonate waveguides.

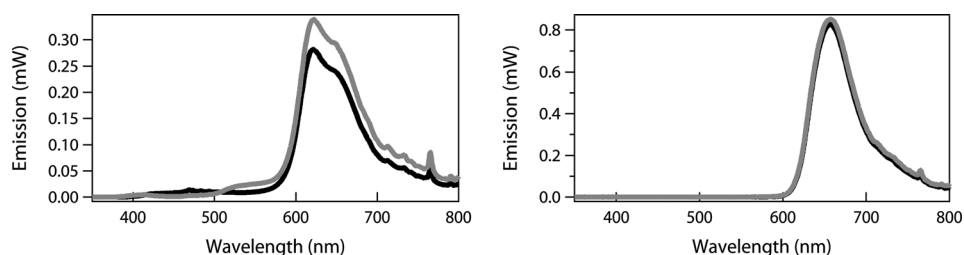


FIG. 3. (a) Emission spectra of a Red305 polycarbonate waveguide with absorbance 0.2 at the main absorption peak on a white scatterer (black line), and the same waveguide on the phosphor-containing scattering layer (gray line). The use of the phosphor-containing scattering layer resulted in a 27.1% increase number of edge emitted photons. (b) Emission spectra of a Red 305 polycarbonate waveguide with absorbance 1.7 at the main absorption peak on a white scatterer (black line) and the same waveguide on the phosphor-containing scattering layer (gray line). The use of the phosphor-containing scattering layer resulted in a 5.7% increase in number of edge emitted photons.

Figure 4, the output of even the 0.5 peak absorbance Red 305 plate is 15% greater when using the rear phosphor scatterer than the white scatterers. The enhancement in the perylene perinone plates is less, ranging from 4% to 8% over the range of peak absorbance 0.4 to 3.5, but is still appreciable.

It appears that most of this additional phosphor-emitted 525 nm light has been absorbed by the dyes in the waveguide and further converted to longer emissions by both the Red 305 and perylene perinone dyes. By downshifting the solar spectrum in this way, we gain the additional benefit of improved matching to the spectral response of the attached silicon-based photovoltaic cells. The emission of the Red 305 at 630 nm and of the perylene perinone at 670 nm could allow for more efficient conversion to current in the external cell than the original 450 nm solar light or the 525 nm phosphor-emitted light.

Since the phosphor is located within the rear scatterer rather than in the waveguide itself, one could even use phosphors with significantly lower quantum efficiency than YAG:Ce (measured at >90% in our samples). One can thus concentrate on selecting a phosphor to absorb in parts of the spectrum less well-covered by the organic fluorophores with less concern over the emission efficiency. Using lower quantum efficiency phosphors within the waveguide itself would be prohibitive: not only would there be energy losses from the lower quantum yield but the doping concentrations required to get enough light absorbed would be such that there would be significant additional scattering of light out of the waveguide modes.

The use of a rear scatterer incorporating a phosphor could be of particular use in applications where simple increased dye loading is not a desirable solution for increasing performance. One such situation are devices where aesthetics are as or more important than absolute

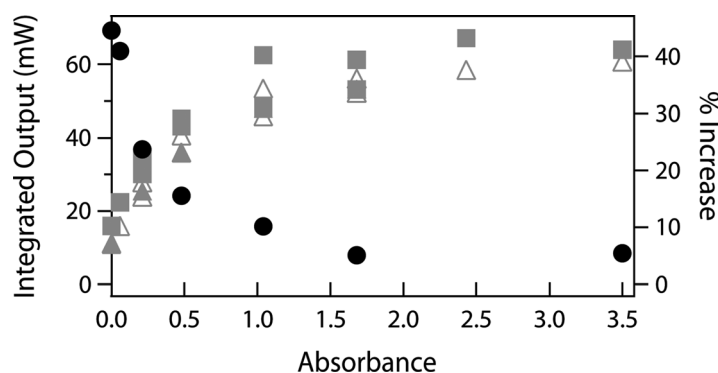


FIG. 4. Integrated emission (left axis) from Red 305 filled waveguides on top of white paper (solid gray triangles) and white painted glass (open gray triangles) scatterers, and on the phosphor-containing (gray squares) scattering layer, and averaged percentage increase of edge energy output using phosphor-containing rear layer (black circles, right axis) as a function of the measured absorbance of the waveguide.

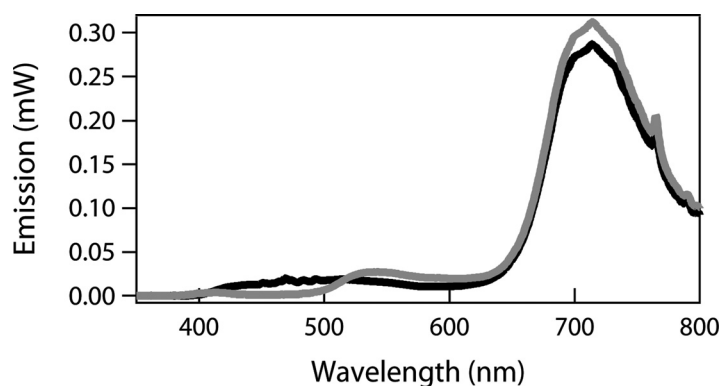


FIG. 5. Emission spectra of a perylene perinone polycarbonate waveguide with peak absorbance 0.37 on a white scatterer (black line) and the same waveguide on the phosphor-containing scattering layer (gray line). The use of the phosphor-containing scattering layer resulted in an 8.4% increase in number of edge emitted photons.

performance. For example, if the LSC is to be applied as a building tile where a pale orange color is required by the designer there is a limited choice of dyes that may be used, and portions of the solar spectrum may not be adequately absorbed. In this situation, the luminophore will be added to the plate in reduced amounts and is very likely unable to efficiently process the complete short wavelength spectrum; the addition of the rear scatterer described above could enhance the power output. A second application would be in situations where the dye solubility becomes an issue, such as in systems that employ dye layers applied only to the top of a clear waveguide as thin films (for example, Ref. 19). In these latter systems, the dye layer is often $<30\ \mu\text{m}$ thick and prevention of dye agglomeration and resultant fluorescence quenching is more difficult, so lower dye concentrations are often necessary, which normally limits light absorption. The use of the rear luminescent scattering system could again enhance performance in an easy way.

V. CONCLUSION

In summary, if the cost is relatively low, phosphors could be included in a luminescent solar concentrator device within the rear scattering layer to enhance light absorption by the dye molecules in the waveguide through shifting the spectrum of incoming, unabsorbed light to a wavelength more amenable to absorption by the dye, while still providing the role of a scatterer for light outside the absorption band of the phosphor. This would be an opportunity to introduce functionality into the scattering layer beyond simply dispersing the direction of the returned light.

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¹W. G. J. H. M. van Sark, K. W. J. Barnham, L. H. Slooff, A. J. Chatten, A. Büchtemann, A. Meyer, S. J. McCormack, R. Koole, D. J. Farrell, R. Bose, E. E. Bende, A. R. Burgers, T. Budel, J. Quilitz, M. Kennedy, T. Meyer, C. d. M. Donega, A. Meijerink, and D. Vanmaekelbergh, *Opt. Express* **16**, 21773 (2008).

²J. C. Goldschmidt, M. Peters, A. Bösch, H. Helmers, F. Dimroth, S. W. Glunz, and G. P. Willeke, *Sol. Energy Mater. Sol. Cells* **93**, 176 (2009).

³L. R. Wilson, B. C. Rowan, N. Robertson, O. Moudam, A. C. Jones, and B. S. Richards, *Appl. Opt.* **49**, 1651 (2010).

⁴M. G. Debije and P. P. C. Verbunt, *Adv. Energ. Mater.* **2**, 12 (2012).

⁵L. R. Wilson and B. S. Richards, *Appl. Opt.* **48**, 212 (2009).

⁶L. H. Slooff, E. E. Bende, A. R. Burgers, T. Budel, M. Pravettoni, R. P. Kenny, E. D. Dunlop, and A. Büchtemann, *Phys. Status Solidi (RRL)* **2**, 257 (2008).

⁷M. G. Debije, P. P. C. Verbunt, P. J. Nadkarni, S. Velate, K. Bhaumik, S. Nedumbamana, B. C. Rowan, B. S. Richards, and T. Hoeks, *Appl. Opt.* **50**, 16 (2011).

- ⁸R. W. Olson, R. F. Loring, and M. D. Fayer, *Appl. Opt.* **20**, 2934 (1981).
- ⁹K. Geetha, M. Rajesh, V. P. N. Nampoori, C. P. G. Vallabhan, and P. Radhakrishnan, *J. Opt. A, Pure Appl. Opt.* **6**, 379 (2004).
- ¹⁰L. R. Wilson, B. C. Rowan, N. Robertson, O. Moudam, A. C. Jones, and B. S. Richards, *Appl. Opt.* **49**, 1651 (2010).
- ¹¹K. Heidler, *Appl. Opt.* **20**, 773 (1981).
- ¹²J. Roncali and F. Garnier, *Sol. Cells* **13**, 133 (1984).
- ¹³J. Mugnier, Y. Dordet, J. Pouget, and B. Valeur, *Rev. Phys. Appl.* **22**, 89 (1987).
- ¹⁴A. A. Earp, G. B. Smith, J. Franklin, and P. D. Swift, *Sol. Energy Mater. Sol. Cells* **84**, 411 (2004).
- ¹⁵S. T. Bailey, G. E. Lokey, M. S. Hanes, J. D. M. Shearer, J. B. McLafferty, G. T. Beaumont, T. T. Baseler, J. M. Layhue, D. R. Broussard, Y.-Z. Zhang, and B. P. Wittmershaus, *Sol. Energy Mater. Sol. Cells* **91**, 67 (2007).
- ¹⁶M. G. Debije, J.-P. Teunissen, M. J. Kastelijn, P. P. C. Verbunt, and C. W. M. Bastiaansen, *Sol. Energy Mater. Sol. Cells* **93**, 1345 (2009).
- ¹⁷G. Seybold and G. Wagenblast, *Dyes Pigm.* **11**, 303 (1989).
- ¹⁸Y. Dong, G. Zhou, J. Xu, G. Zhao, F. Su, L. Su, G. Zhang, D. Zhang, H. Li, and J. Si, *Mater. Res. Bull.* **41**, 1959 (2006).
- ¹⁹P. P. C. Verbunt, A. Kaiser, K. Hermans, C. W. M. Bastiaansen, D. J. Broer, and M. G. Debije, *Adv. Funct. Mater.* **19**, 2714 (2009).