

Luminescent solar concentrators – the solar waveguides

Brindha V. G. Mohan^{1,*}, V. Vasu², A. Robson Benjamin¹ and M. Kottaisamy³

¹Department of Physics, The American College, Madurai 625 002, India

²School of Physics, Madurai Kamaraj University, Madurai 625 021, India

³Department of Chemistry, Thiagarajar College of Engineering, Madurai 625 002, India

This study aims at giving a prologue to the non-tracking, concentrating solar waveguides called luminescent solar concentrators. It deliberates the major factors of loss in such systems that limit photon collection and conversion efficiency. Identifying fluorescent molecules possessing a larger Stokes shift value with a broad degree of absorption in the UV-Vis continuum, with sharper and narrower near infra-red emission spectra at a higher quantum yield that achieves a perpetual total internal reflection, remains a challenge now. Geometrical and material properties also play a strategic role in accomplishing waveguides, with minimal loss, through total internal reflection of trapped photons for photovoltaic conversion.

Keywords: Fluorescence, luminescent solar concentrator, poly(methyl methacrylate), total internal reflection.

At the turn of every decade, a new solar innovation manifests itself with its own pros and cons. In this respect, the idea of a luminescent solar concentrator (LSC), though sounds unfamiliar, is rather an old technology, with its prototypes proposed in the late 1970 (refs 1, 2). LSCs are planar waveguides that capture the incident solar radiation from a broad absorption range (UV-Visible) by means of fluorescent molecules embedded typically in a plastic/glass sheet and re-emit at a longer wavelength (NIR) which is then waveguided by total internal reflection (TIR) to a photovoltaic cell at the other edge(s) (Figure 1).

The study begins with questions, like how to achieve the isotropic emission for TIR, what are the techniques to reduce waveguide losses, how to ensure uniform aligning of the embedded molecules, how to rectify losses of reflection and such varied interrogations. The foremost challenge has been in identifying a pertinent fluorescent molecule (fluorophore) and a propagating medium for the crucial mechanism of TIR to occur. Hence, this presently active field of research has stayed stunted for nearly three decades principally in pursuit of a photostable fluorescent molecule. Conventionally, the molecule is an organic dye having a high photoluminescent quantum yield (PLQY) with a broad absorption and sharp emission peak. Although organic dyes such as rhodamine and coumarin

showed some noteworthy results in the rudimentary stages, because of their overlapped excitation–emission peaks and drastic photobleaching nature, they limited the optical efficiency as well as the life time of LSC modules³.

At the start of the millennium, with the advent of tailored materials, quantum dots and organic–inorganic hybrid molecules, a plethora of efforts are being made in optimizing an ideal LSC device^{4–7}. A very elaborate review of LSCs has been documented by Debije *et al.*⁸. Hence, the objective of this review is to introduce to Indian readers an overview of some of the chief theoretical and experimental implications that have been made in single plate LSCs, doped with single fluorophores.

Why LSC?

To begin with, LSCs are not photovoltaic (PV) systems; rather they are sub-devices that would subsidize the present PV systems, mainly, in urban settings. They are thus appropriate for densely populated and economically deprived countries, where the foremost problem in executing PV grid systems, on a domestic scale, is the initial cost of installation and maintenance. In India, although solar farms are being implemented on a large scale, harvesting this abundant solar energy in cities is unachievable due to space constraints and the size of modules. As an inexpensive, compact, adaptable, durable, non-tracking and light-weight alternative to heavy PV modules, LSCs could be the key in making energy-efficient buildings closer to reality.

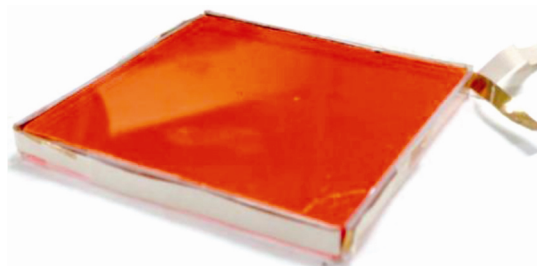
The intriguing fact about LSCs is their potential in providing equivalent theoretical conversion efficiency as high as that of single-junction Si-based PV cells⁹. Due to the diminished interest in this research over the past decades, numerous challenges in achieving an effective LSC remain quiescent, with a highest achieved efficiency of only 7.1% (Table 1). Nevertheless, practical efficiencies up to 10% are achievable with collector configurations like multiple stacks, multi-dye system, thin films, multi-layered films, cascaded stacks, etc.^{10–13}.

Until now, the approach to overcome major hindrances in LSC designs like surface loss, re-absorption loss, probability of total internal reflection, large emission

*For correspondence. (e-mail: brindhakrithika@gmail.com)

Table 1. Reported LSC efficiency⁵

Fluorophore	PV at edge(s)	LSC size (cm)	Reported efficiency (%)
Red305	Si (1)	5 × 5 × 0.3 Perspex	3.3
Red305, CRS040	GaAs (1)	5 × 5 × 0.5	4.6
Red305, CRS040	GaAs (4)	5 × 5 × 0.5	7.1
BA241	GaInP (4)	2 × 2 × 0.3	5.1
CdSe/CdS QD	Si (1)	5 × 5 × 0.3 Perspex	2.1

**Figure 1.** A luminescent solar concentrator⁵⁹.

range, are under rigorous investigation^{14–16}. However, the concentration ratio of LSCs stays much higher (typically 1–10 suns) than other concentrator sub-devices or their geometric counterparts.

When compared to an equivalent area of PV, LSCs exhibit lower efficiency due to the existing loss factors but are viable candidates for constructed environments in cities by creating more than five-fold decrease in cost as well as by reducing 90% of the size and weight of PV panels¹⁷. With the growing number of high-rise buildings in urban localities, most of the solar irradiance is obstructed whence much of this diffuse radiation is lost unused¹⁸ (Figure 2). Since LSCs have larger acceptance angles ($\theta_{\text{LSC}} \sim 65^\circ$) compared to geometric solar concentrators (GSCs) ($\theta_{\text{GSC}} \sim 27^\circ$), they are appropriate for trapping diffused solar flux without employing complex heliostatic tracking. In fact, the ease in their fabrication and integration is provoking renewed interests among architects as well. Furthermore, these sub-devices have alternate applications such as smart windows for day-lighting with proved thermal efficiency in converting the incoming solar energy into thermal energy, or electric energy or both^{2,19}. This additional benefit makes them an elegant choice for indoor heating devices.

Challenges in design

Figure 3 shows a single plate rectangular LSC, highlighting the chief photon transport processes involved in a glass-like host. When the incident photons hit the surface of LSC, there is a definite chance of a tiny proportion being reflected due to Fresnel reflection ($\sim 4\%$). Rear reflections can be guarded by using diffuse reflectors or suitable filter mirrors. Only the remaining 96% of radia-

tion that enter LSC has a fixed probability of being absorbed by the embedded molecules/fluorophores.

As shown in Figure 3, only the incoming radiation with incident angle larger than the critical angle (1), enters the LSC host.

$$\theta_c = \sin^{-1}\left(\frac{1}{n}\right) \text{ (Snell's law),} \quad (1)$$

where n is the refractive index of the waveguide. In this way, for a given host, those photons that strike the surface outside the trapping cone will be lost in an escape cone loss (ECL). In effect, while assuming an isotropic alignment of dye molecules, nearly 25% of the trapped photons are lost at the surface due to ECL²⁰. In the cases of imperfect waveguide with fabrication defects, dust/bubbles or the selection of a short- λ absorbing polymer, the host may also absorb or scatter a small fraction ($\sim 0.05\%$) of the inward bound radiation.

After entering the LSC host, depending on their absorption coefficient, the trapped photons are absorbed by fluorophores leading to luminescence. On the contrary, by choosing a fluorophore with a narrow absorption range, most of the incoming solar photons leave the LSC unabsorbed ($\sim 75\%$ for absorptions less than 550 nm) through the rear. Those that are absorbed undergo luminescence and are re-emitted at a longer wavelength; after which they may undergo any one of the three possible transport pathways as indicated in Figure 4.

These second-generation of photons may be (a) absorbed again by a neighbouring molecule due to the spectral overlap; (b) lost through non-radiative decay; (c) lost due to ECL, or; (d) trapped through TIR and reach the edge of the LSC.

Usually the second generation photons have lower energy and emission intensity as a result of luminescence; thus it has a reduced probability (to nearly 25%) of exciting another molecule²¹. It has been calculated through simulation studies that a minimum of only two re-absorption events are possible in a square module ($5 \times 5 \text{ cm}^2$) which may vary with the dye concentration. However, fluorophores (e.g. organic dyes) with overlapped excitation–emission spectra, i.e. those with smaller Stokes shift facilitates re-absorption (a). Even at these conditions, such an excitation may end as a non-radiative decay process instead of luminescence for dyes with

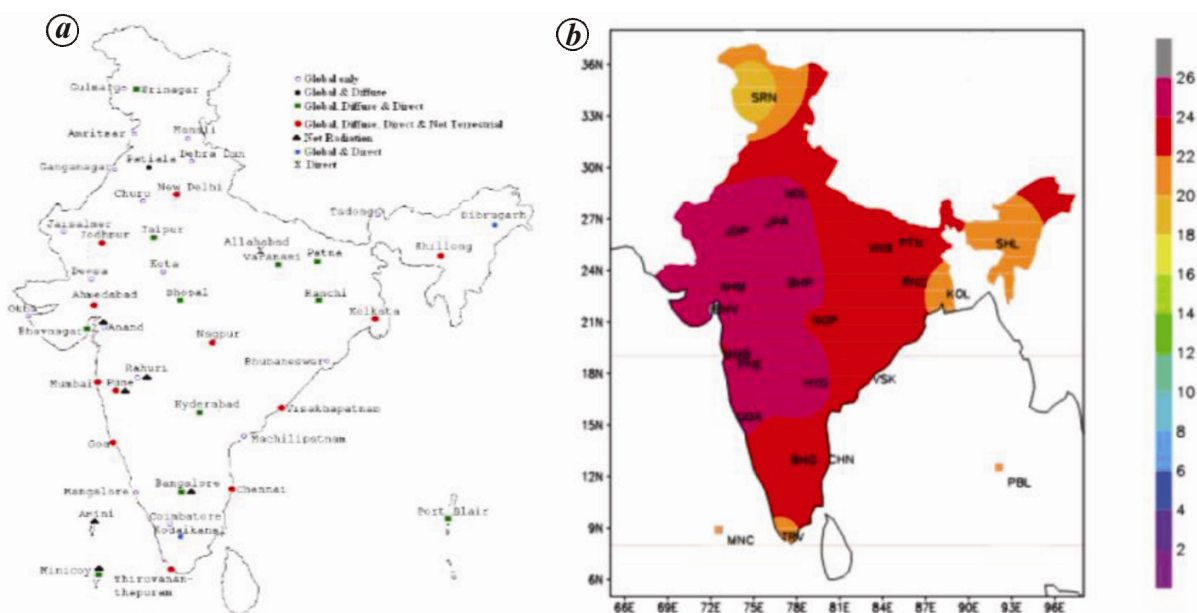


Figure 2. Radiation network in India (a); Global solar irradiance in April (b).

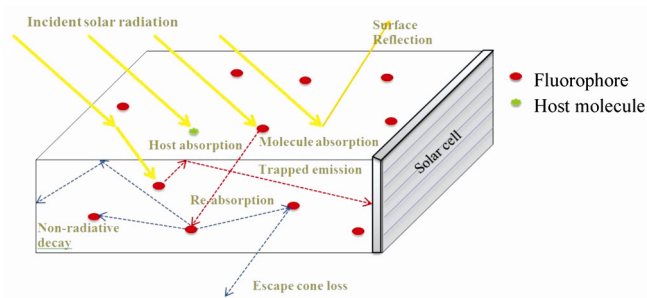


Figure 3. Schematic of light trapping in an LSC; reflection loss (orange); trapped radiation (red); radiation lost by re-absorption, ECL and non-radiative decay (blue).

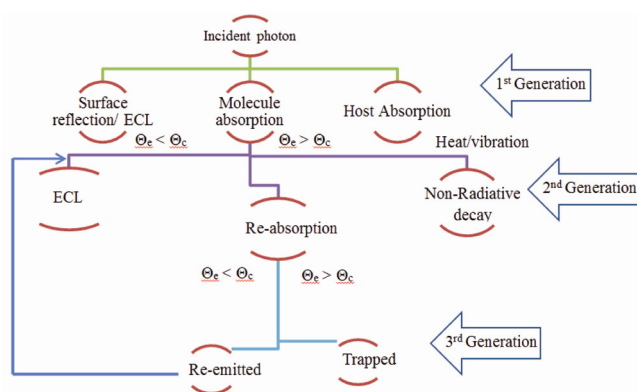


Figure 4. Photon recycling pathways in an LSC.

non-unity/near-unity PLQY (b), which ceases the photon transport. On the other hand, for dyes with near-unity PLQY, the re-emitted luminescent photons are scattered at all angles which is more likely (about 25%) to suffer

ECL (c). As a consequence, re-absorption always leads to a loss (about 20–40%) of the absorbed photons (Figure 4), thereby drastically reducing the optical efficiency of an LSC.

To sum up, in the absence of re-absorption, ECL and absorption losses, more than 50% of design losses can be eliminated. It is for this reason that the choice of fluorophore and host medium plays a critical role in a lossless propagation of captured photon through LSC^{22,23}. On successful trapping, the photon reaches the edges of LSC by TIR (d) where it is absorbed by a solar cell with appropriate bandgap for initiating charge generation.

LSC theory

In general, the performance of LSC is a measure of the efficiency of optical conversion, η_{opt} which is defined as the ratio of the power output at the edge (P_{out}) to the incident optical power (P_{in}).

$$\eta_{opt} = \frac{R_{out}}{P_{in}} \quad (2)$$

Considering the loss factors, the efficiency of a practical LSC is written as the product of the factors such as

$$\eta_{opt} = (1 - R)P_{TIR} \cdot \eta_{abs} \cdot \eta_{PLQY} \cdot \eta_{Stokes} \cdot \eta_{host} \cdot \eta_{TIR} \cdot \eta_{self} \quad (3)$$

where R is the reflected radiation from the surface due to Fresnel reflection $= (n - 1)^2 / (n + 1)^2$, n the refractive index of the waveguide, P_{TIR} the probability of total

Table 2. Cause and solution for loss factors in an LSC

Loss factor	Dependence	Solution
η_{TIR}	Photons emitted inside the trapping cone.	Polymer of suitable refractive index, in the range $1.3 < n < 2$ as waveguides Choice: PMMA and PC.
η_{abs}	Broad absorption spectra and narrow emission spectra of the fluorophore	Fluorophores with $\lambda_{\text{abs}} < 950$ nm and $\lambda_{\text{em}} \sim 950$ nm suitable for PV operation. Choice: organic dyes, quantum dots (CdSe/ZnS, PbS, PbSe) and Rare-earth ions (Nd^{3+} , Yb^{3+} , Eu^{3+}).
η_{PLQY}	The probability of an excited fluorophore decaying by emission of a photon undergoing non-radiative transfers.	Near-unity PLQY fluorophores. Choice: organic dyes, quantum dots, rare-earth ions.
η_{Stokes}	Broad separation between the peak absorption and peak emission wavelengths of the fluorophore.	Quantum dots and rare-earth/complexes.
η_{host}	Host absorption of re-emitted photons.	Non-absorbing host. Choice: PMMA, epoxy resin and glass.
η_{TIR}	Presence of impurities, unsmooth surfaces and scratches.	Defect-free waveguides.
η_{self}	Fluorophore concentration and PLQY.	Limited concentration.

internal reflection $= \sqrt{(n^2 - 1)/n}$, η_{abs} the spectral range absorbed by the fluorophore, η_{PLQY} the photoluminescent quantum yield of the fluorophore, η_{Stokes} the non-overlapping absorption–emission peaks of the fluorophore, η_{host} the absorption of luminescent photons by host polymer, η_{TIR} the efficient trapping of reflected photons by waveguide and η_{self} is the re-absorption of re-emitted photons by other fluorophores.

Table 2 comprehends the cause and solution of each of these losses from which the choice of design and materials is conferred. Besides these tabulated parameters, the performance of LSC also depends on geometrical design. For instance, for a planar concentrator, the photon flux at the edge is given as

$$\frac{(\text{Absorbed photons}) \times (\text{Geometric gain of exposed surface}) \times (\text{Fraction of trapped luminescent photons})}{\text{Area covered by PVC}},$$

where the geometric gain is arrived through the formula

$$G_{\text{geo}} = \frac{\text{Surface area of LSC}}{\text{Edge area of PV}} = \frac{A_{\text{sf}}}{A_e}, \quad (4)$$

with A_{sf} being the surface area and A_e the area of the plate edges. The value of G is typically higher than the concentration of any other non-tracking solar collector. For a square planar waveguide of thickness in the range of few millimetres, the geometric gain is simply the ratio of the length to thickness of the plate for which a gain of over 300 can be achieved³. Then the overall concentration ratio of the LSC is given as

$$C = G \cdot \eta_{\text{opt}}. \quad (5)$$

However, while improvising a LSC, enhancing the external quantum efficiency is of primary importance. The external quantum efficiency (η_{EQE}) is given as

$$\eta_{\text{EQE}}(\lambda, 90^\circ) = \frac{\text{Electron hole pairs collected by a device}}{\text{No. of incident photons incident on the device}}, \quad (6)$$

which is a function of input spectral wavelength and therefore responds to the entire spectrum; η_{EQE} provides the overall information about both spectral responsivity and reflectance of a PV device. In LSCs, as a result of luminescence, the trapped photons undergo down shifting where shorter wavelengths are made available to solar cells for charge generation. In general, the external quantum efficiency curve plots the spectral response of a PV device based on the number of e^-h^+ pairs generated for every trapped photon. Therefore, by enhancing η_{EQE} at short- λ region, the short-circuit current and the conversion efficiency are improved in a LSC without altering any other electronic properties of the edge solar cell itself²⁴. The overall power conversion efficiency of an LSC is given by

$$\text{PCE} = \frac{I_{\text{sc}} V_0}{S \cdot A_{\text{sf}}} \times \text{FF}, \quad (7)$$

where S is the intensity of incident radiation and I_{sc}^L and V_0^L being the short circuit current and the open voltage of the PV attached to LSC. FF is the fill factor corresponding to the PV.

Design improvement

As discussed earlier, the maximum percentage losses are due to ECL, re-absorption and absorption loss. This

section provides a brief description on some of the proposed cell design and material properties to overcome the aforementioned losses.

Module geometry

Most of the LSCs are of square or rectangular geometry of only a few millimetres thickness. But the problem with planar LSCs is the non-uniform light output received at the edge, especially for large aspect ratios which reduces the overall efficiency²⁵. Hence, adequate efforts have also been made on other possible geometrical shapes such as cylindrical and hexagonal hosts for LSC²⁶ as well as daylighting applications²⁷. In view of a cylindrical LSC, which in principle has a close correlation with a scintillating fibre, a ray tracing study has been reported for surface emission events. As for solid cylindrical geometry (single as well as multiple cylinders), the optical concentration is greater (1–1.9 times) than an equivalent area of square LSC with polymethyl methacrylate (PMMA) host²⁸. Although the cylindrical shape considerably increases the geometrical concentration ratio, a solid cylindrical LSC does not significantly reduce the major loss factors like ECL and host absorption. Hollow cylindrical LSCs, on the other hand, with imbedded NIR-emitting quantum dots in PMMA matrices have shown improved light absorption and less self-absorption, thereby improving the optical efficiency compared to their flat and solid cylindrical counterparts²⁹.

A comparative study between flat and cylindrically bent LSCs gives an insight on planar versus non-planar

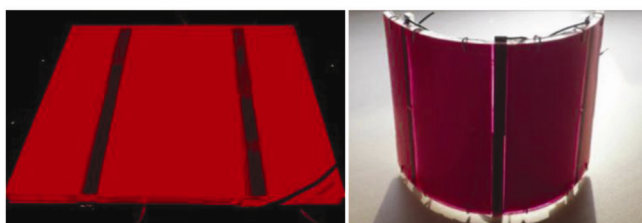


Figure 5. Flat and bent LSCs³⁰.

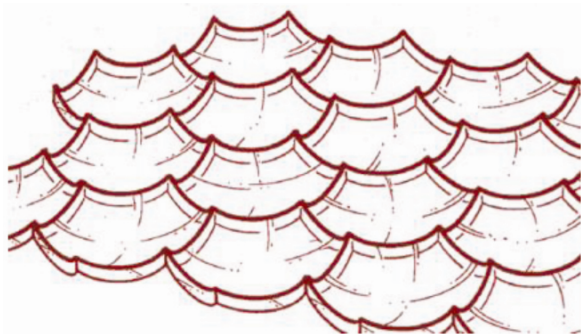


Figure 6. Hexagonal concave LSC design²⁶.

LSCs to both direct and diffuse solar radiation³⁰. Though the design differs slightly from conventional LSCs in the manner of attachment of solar cell (in front instead of edge, as demonstrated by Corrado *et al.*³¹) (Figure 5), the results clearly indicate a reduced angular dependence of incoming radiation in case of a bent LSC. Likewise Zewail *et al.*²⁶ proposed a non-planar design with two-dimensional array of close-packed concave, hexagonal elements with curved elliptical edges featuring mirrors and PVs on alternate sides (Figure 6). This in effect reduces the escape cone loss to almost 30% and also overcomes PV connectivity issues in arrays²⁶. Non-planar LSCs (like the ones discussed and many proposed designs)³² in general provide increased light output by narrowing the critical cone but poses issues in fixture of solar cells at the edges. However, considering the commercial feasibility and ease of comparison, research analysis are confined to planar LSCs.

In a spectral-based modelling for fluorophores with high extinction coefficient by Adam Green *et al.*³³, thinner modules are preferred to eliminate re-absorption losses, whereas for those with low absorption coefficient, a thicker plate is suggested. A convenient choice for most organic dyes would be thin sheets, of about 1 mm on a PMMA host with a large surface area as sheets with larger surface area reduces ECL due to their smaller optical density ($OD = \log_{10}(T)$, where T is the internal transmittance)²⁴. In case of particles with lower optical coefficients like RE ions, it has been suggested that absorption properties can be improved by creating chelates of ions or antenna structures to facilitate better absorption. Although the losses due to reflection become inevitable for larger sheets, it can be rectified with specular back reflectors or lambertian reflectors like polytetrafluoroethylene (PTFE)³⁴. By reducing the thickness, the geometric gain is also increased in addition to reducing the optical path-length. Conventionally, short, broad plates reduce absorption losses over long, narrow plates of the same geometric gain³⁵. Additionally, by making use of selective filters and photonic crystals for loss-less photon collection, the particle concentration can be reduced effectively^{36,37}.

Particle concentration

In general, the number of recycle events within a LSC module is directly proportional to the concentration of fluorophore. Although the particle concentration and plate dimension are inter-dependant, lower particle concentration is always preferred, in the range of 10^{-4} – 10^{-3} M to reduce losses caused by re-absorption. While organic dyes possess high PLQY, single dye systems undergo severe photo-sensitive reactions over long exposures and also suffer re-absorption losses due to smaller Stokes shift^{38,39}. Whereas in mixed dye systems, the concentration is increased causing photon transport to occur

through non-radiative means, FRET (Förster Resonance Energy Transfer) than radiative transfers⁴⁰. Although mixed dye systems can absorb nearly 70% of the incident radiation, FRET effects contribute to reduction of quantum yield beyond a certain concentration limit and may also contribute to losses due to clustering and agglomeration of particles in reabsorption. In case of isotropic emitters like inorganic phosphor or dichroic dyes with near unity PLQY, ECL is sufficed leading to effective photon trapping²¹ at limited particle concentration. As mentioned in the previous section, with such emerging fluorophores, an increase in particle concentration can be compensated by altering the geometric gain without losing the collected photons. In search of a fluorophore with broad Stokes shift with high PLQY and durability, RE ions/chelates, inorganic phosphor and quantum dots are pertinent choices that show a major axis of development in this respect^{40,41}.

Fluorophore-spectral properties

It is self-evident that fluorophores, whether organic or inorganic, must show a near-unity fluorescence quantum yield with well-separated λ_{abs} and λ_{em} for the subsequent emission-absorption events to cascade without particle self-absorption. Generally in LSC, although the concentration ratio can reach as high as 10^4 , the achieved concentration ratio is much lower than that predicted thermodynamically⁴²⁻⁴⁴.

$$C_{\text{lim}} \approx \left(\frac{E_{\text{em}}^3}{E_{\text{abs}}} \right) \exp\left(\frac{\Delta E}{kT} \right). \quad (7)$$

This discrepancy lies in the fact that in LSCs, the concentration ratio and photon collection stand as two different factors since the collected photons are lowered in energy due to re-absorption and non-unity quantum yields thereby reducing the photon recycle events before reaching the solar edge for charge collection⁴⁵. By considering the absorption and collection efficiency as two parameters, Markvart *et al.*⁴⁶ analysed the spectral response of an LSC under uniform emission conditions. According to this model, at the short-wavelength region, multiple absorption-emission events are possible since optical pathlength of photons is shorter than re-absorption length. Therefore, collection efficiency is greater at this region, since spectral transitions are independent of particle concentration. At longer wavelengths, the optical pathlength becomes longer than absorption length indicating less probability for re-absorption.

Such an analysis infers that it is possible to reach an LSC conversion efficiency of up to 90% with the choice of fluorophore whose Stokes shift is slightly above the energy gap of the solar cell in order to obtain efficient photon transport with minimal re-absorption

losses (Figure 7). Such a condition can be attained by choosing the optical coefficients that would satisfy the conditions

$$\alpha_{\text{abs}} \geq 1/d \text{ and } \alpha_{\text{em}} \ll 1/L \text{ at appropriate wavelengths,}$$

where L is the width of waveguide and d is the thickness of waveguide. Besides these spectral properties, the molecules must be smaller, preferably in nano scale and must be completely miscible in the host matrix to avoid scattering.

Host material

As emphasized in the earlier section, the important criterion in choosing an LSC host matrix is its refractive index, n which determines the primary loss due to ECL. Typically hosts with small refractive index show minimal reflection loss at the top surface whereas those with larger refractive index minimize front surface ECL⁶. As a compromise between the two factors, a host matrix with refractive index in the range $1.5 < n < 2$ is preferred widely to eliminate ECL to the maximum at the top surface instead of reflection since the latter can be controlled by mirrors/reflectors⁴⁷. In addition to refractive index, the photostability of the host is an important concern for long time cell exposure⁴⁸. Also, to eliminate loss due to host absorption, the host must be crack and defect-free, devoid

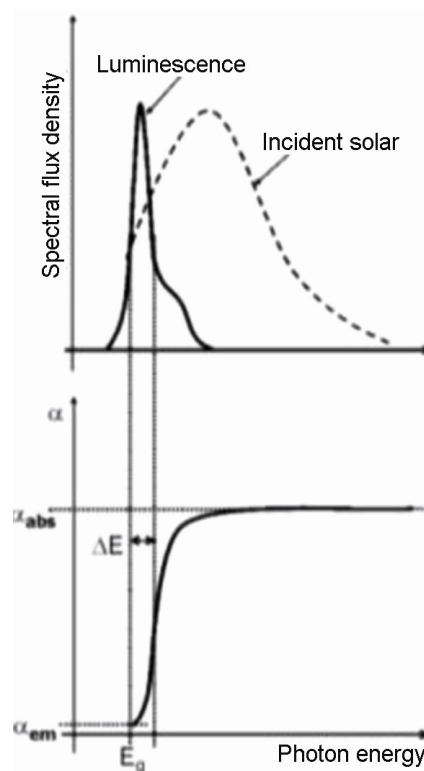


Figure 7. Spectral characteristics of collector⁴⁶.

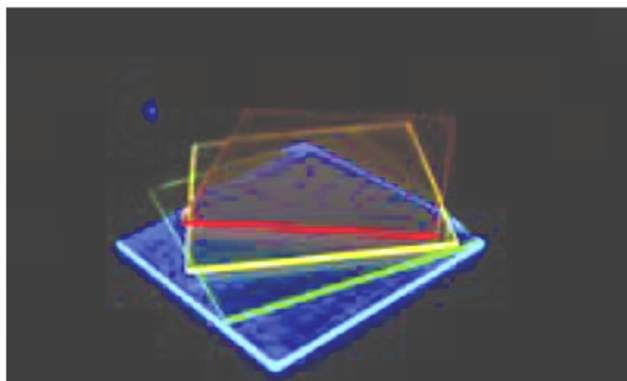


Figure 8. Total internal reflection in doped polymer sheet under UV light; <http://science.howstuffworks.com/environmental/green-science/luminescent-solar-concentrator1.html>

of impurities and optically transparent at the cell's operating wavelength. Although glasses doped with inorganic molecules, phosphor and rare-earth ions have been reported to subtly reduce re-absorption losses, such substrates are not commendable⁴⁹⁻⁵¹ for the above reasons. Hence polymers are opted over glasses to avoid breakage and ease of fabrication. Based on a very recent study on optical properties and edge emission of six pertinent polymers⁵², PMMA and PC are recommended as the most suitable LSC hosts. As suggested in Table 2, PMMA (also known as acrylics/plexiglass) is the most preferred host for LSC waveguides due to their photostability³, availability, thermal resistance and optimal refractive index ($n = 1.49$) which is favourable for uninhibited TIR (Figure 8). Moreover, PMMA hosts a broad range of soluble luminescent particles including organic dyes⁵³, rare-earth complexes⁵⁴, inorganic phosphor⁵⁵ and quantum dots⁵⁶ for LSC fabrication thus befitting for experimental studies of diverse fluorophores at various concentrations.

Polymers or copolymer combinations with refractive index values, $n \sim 2$ are in the quest for effective photon trapping. Flexible LSC sheets have also been explored with polymers such as polysiloxane ($n = 1.40$) and polydimethyl siloxane ($n = 1.43$) which exhibit efficiencies similar to polycarbonate hosts but suffer luminescence quenching at practical particle concentrations^{13,57}.

Solar cell

Although it might look trivial, the attachment of a solar cell to an LSC sheet is a very subtle task which may have an immediate consequence on LSC performance and therefore requires utmost care and precision. The first step is to choose a solar cell with appropriate band gap matching spectroscopic profile of the embedded fluorophore. For example, a fluorophore with emission wavelength ~ 750 nm provides the best photoresponse for a

mono-Si solar cell. Secondly, the solar cell to be attached to an LSC must be free from encapsulants, like ethylene vinyl acetate (EVA) to enhance photon absorption without any obscuring at the sheet-PV interface⁵⁸. Thirdly, while attaching a PV cell, choosing an adhesive with perfectly matched refractive index with that of the host material is necessary; mostly epoxy resin or araldite is preferred for PMMA sheets of not more than $50 \mu\text{m}$ thickness⁵⁹. Finally, while measuring the power output of an LSC under a solar simulator, in order to analyse performance under both diffuse and direct sunlight and to maintain a monotonous research protocol, air mass AM 1.5 g spectrum at one sun intensity is recommended²⁴. Newer designs are also being experimented with front attachment of solar cells as shown in Figure 5, for minimizing design loss where the gain and PCE varies with area of cell coverage.

Conclusion

As it is clear by now, LSCs belong to the class of fourth generation PVs where the outcome is low-cost and low-efficiency solar cells that are specifically suited for self-sustained buildings. This turns our attention towards radiation mapping in India, where the global solar irradiance (both direct as well as diffuse components) is most abundant in the metropolitan and industrial cities (Figure 2). Unfortunately, the utilization of this radiation is insignificant as compared to Germany and Sweden where the measure of specular insolation is ineffectual. Yet, the concept of LSCs became predominant in these regions as an endeavour to harvest the obtainable diffuse radiation. But the quintessence of this technology becomes relevant for India with colossal solar irradiance. Particularly in metro-cities, with the growing demand for fossil fuels, the need for an alternate clean energy technology which is both economically feasible and structurally commendable is alarming. By taking advantage of the concept of LSC, potential utilization of renewable solar energy can be accomplished in the form of compact smart windows, facades and rooftops of multi-storied buildings in city centres at a rational cost. An LSC can be designed to utilize the entire solar spectrum partly for electric energy conversion and for thermal energy conversion as a day-lighting/indoor heating system at the same time, which is an added advantage.

Recently, the encouraging prospect in LSC research is that the technology is on the verge of commercialization by the 'Ubiquitous Quantum Dot (UbiQD)' that has licensed an optimal LSC design using non-toxic quantum dots ($\text{CuInSe}_x\text{S}_{2-x}$) for industrial scale-up in August 2017 (ref. 60). As the challenges are being unveiled, a pool of innovative ideas is intended to achieve an ideal LSC design.

Positively, many new techniques are being executed, like applying phosphor nanoclusters⁶¹, recyclable cellulose

nanocrystal host⁶², etc. The authors hope that this article will help in sprouting innovative ideas, methods and systems conferring to luminescent solar concentrators among Indian energy researchers.

- Weber, W. H. and Lambe, J., Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells. *Appl. Opt.*, 1976, **15**, 2299–2300.
- Goetzberger, A. and Greubel, W., Solar energy conversion with fluorescent collectors. *Appl. Phys.*, 1977, **14**, 123–129.
- Batchelder, J. S., Zewail, A. H. and Cole, T., Luminescent solar concentrators: theory of operation and techniques for performance evaluation. *Appl. Opt.*, 1979, **18**(18), 3090–3110.
- Klimov, V. I., Baker, T. A., Lim, J., Velizhanin, K. A. and McDaniel, H., Quality factor of luminescent solar concentrators and practical concentration limits attainable with semiconductor quantum dots. *ACS Photonics*, 2016; doi:10.1021/acsp Photonics. 6b00307.
- Sark, W. G. J. H. M. V., Luminescent solar concentrators – a low cost photovoltaics alternative. In EPJ Web of Conferences, Copernicus Institute, The Netherlands, 2012.
- Gallagher, S. J., Rowan, B. C., Doran, J. and Norton, B., Quantum dot solar concentrator: Device optimisation using spectroscopic techniques. *Solar Energy*, 2007, **81**, 540–547.
- Roondão, R. *et al.*, High-performance near-infrared luminescent solar concentrators. *ACS Appl. Mater. Interf.*, 2017, **9**, 12540–12546.
- Debije, M. J. and Verbunt, P. P. C., Thirty years of luminescent solar concentrator research: solar energy for the built environment. *Adv. Energy Mater.*, 2012, **2**, 12–35.
- Goetzberger, A., Fluorescent solar energy collectors: operating conditions with diffuse light. *Appl. Phys.*, 1978, **16**, 399–404.
- Friedman, P. S., Luminescent solar concentrators. *Opt. Eng.*, 1981, **20**(6), 887–892.
- Daorta, S. F., Proto, A., Fusco, R. Andreani, L. C. and Liscidini, M., Cascade luminescent solar concentrators. *Appl. Phys. Lett.*, 2014, **104**, 153901–153904.
- Earp, A. A., Smith, G. B., Franklin, J. and Swift, P., Optimisation of a three-colour luminescent solar concentrator daylighting system. *Sol. Energy Mater. Sol. Cells*, 2004, **84**, 411–426.
- Buffà, M., Carturan, S., Debije, M. G., Quaranta, A. and Maggioni, G., Dye-doped polysiloxane rubbers for luminescent solar concentrator systems. *Sol. Energy Mater. Sol. Cells*, 2012, **103**, 114–118.
- Moudam, O., Rowan, B. C., Alamiry, M., Richardson, P., Richards, B. S., Jones, A. C. and Robertson, N., Europium complexes with high total photoluminescence quantum yields in solution and in PMMA. *Chem. Commun.*, 2009, **43**, 6649–6651.
- Krumer, Z., Sark, W. G. J. H. M. V., Schropp, R. E. I. and Donegá, C. D. M., Compensation of self-absorption losses in luminescent solar concentrators by increasing luminophore concentration. *Sol. Energy Mater. Sol. Cells*, 2017, **167**, 133–139.
- Sloof, L. H. *et al.*, A luminescent solar concentrator with 7.1% power conversion efficiency, *Phys. Stat. Sol. (RRL)*, 2008, **2**(6), 257–259.
- Sark, W. G. J. H. M. V., Luminescent solar concentrators – A low cost photovoltaics alternative. *Renew. Energy*, 2013, **49**, 207.
- Typical Climatic Data for Selected Radiation Stations (The Data Period Covered: 1986–2000), Solar Radiation Hand Book-A joint Project of Solar Energy Centre, MNRE, Indian Metrological Department, 2008.
- Nair, M. G., Ramamurthy, K. and Ganesan, A. R., Classification of indoor daylight enhancement systems. *Lighting Res. Technol.*, 2014, **46**, 245–267.
- Erickson, C. S., Bradshaw, L. R., McDowall, S., Gilbertson, J. D., Gamelin D. R. and Patrick, D. L., Zero-reabsorption doped-nanocrystal luminescent solar concentrators. *ACS Nano*, 2014, **8**(4), 3461–3467.
- Verbunt, P. P. C., Somolinos, C. S., Broer, D. J. and Debije, M. G., Anisotropic light emissions in luminescent solar concentrators-isotropic systems. *Opt. Exp.*, 2013, **21**(S3), A485–A493.
- Swartz, B. A., Cole, T. and Zewail, A. H., Photon trapping and energy transfer in multiple-dye plastic matrices: an efficient solar-energy concentrator. *Opt. Lett.*, 1977, **1**(2), 73–75.
- Bailea, S. T. *et al.*, Optimized excitation energy transfer in a three-dye luminescent solar concentrator. *Sol. Energy Mater. Sol. Cells*, 2007, **91**, 67–75.
- Klampafits, E., Ross, D., McIntosh, K. R. and Richards, B. S., Enhancing the performance of solar cells via luminescent downshifting of the incident spectrum: A review. *Sol. Energy Mater. Sol. Cells*, 2009, **93**, 1182–1194.
- Loh, E. and Scalapino, D. J., Luminescent solar concentrators: effects of shape on efficiency. *Appl. Opt.*, 1986, **25**(2), 1901–1907.
- Zewail, A. H. and Batchelder, J. S., Luminescent solar energy concentrator devices, US Patent 4227939, 1980.
- Smith *et al.*, Sunlight collecting and Transmitting system, US Patent 5548490, 1996.
- McIntosh, K. R., Yamada N. and Richards, B. S., Theoretical comparison of cylindrical and square-planar luminescent solar concentrators. *Appl. Phys. B*, 2007, **88**, 285–290.
- Inman, R. H., Shcherbatyuk, G. V., Medvedko, D., Gopinathan, A. and Ghosh, S., Cylindrical luminescent solar concentrators with near-infrared quantum dots. *Opt. Exp.*, 2011, **19**(24), 24308–24313.
- Viswanathan, B., Reinders, A., de Boer, D. K. G., Ras, A., Zahn, H. and Desmet, L., System engineering and design of LSC-PV for outdoor lighting applications, In 7th European Photovoltaic Solar Energy Conference and Exhibition, 5BV.1.38.
- Corrado, C., Leow, S. W., Osborn, M., Chan, E., Balaban, B. and Carter, S. A., Optimization of gain and energy conversion efficiency using front-facing photovoltaic cell luminescent solar concentrator design. *Sol. Energy Mater. Sol. Cells*, 2013, **111**, 74–81.
- Smith *et al.*, Sunlight collecting and Transmitting system, US Patent 5709456, 1998.
- Green, A. P., Optical Properties of Luminescent Solar Concentrators, PhD Dissertation, Department of Physics and Astronomy, University of Sheffield, England, 2014, Ch. 2.
- Wilson, L. R., Luminescent solar concentrators: a study of optical properties, re-absorption and device optimisation, PhD dissertation, Eriot-Watt Univ., Edinburgh, 2010.
- Sloof, L. H., Burgers, A. R. and Bende, E., The luminescent solar concentrator: a parameter study towards maximum efficiency. *Photonics for Solar Energy Systems II, Proc. SPIE*, 2008, **7002**, 700209-1-700209-7.
- de Boer, D. K. G., Broer, D. J., Debije, M. G., Keur, W., Meijerink, A., Ronda, C. R. and Verbunt, P. P. C., Progress in phosphors and filters for luminescent solar concentrators. *Opt. Exp.*, 2012, **20**(S3), A395–A405.
- Peters, M. *et al.*, *Energies*, 2010, **3**, 171–193.
- Seybold, G., and Wagenblast, G., New perylene and violanthrone dyestuffs for fluorescent collectors. *Dyes Pigments*, 1989, **11**, 303–317.
- Sloof, L. H., Burgers, A. R., Danz, R. and Roosemalen, J. A. M. V., IV performance and stability of dyes for luminescent plate concentrators. *J. Solar Energy Eng.*, 2007, **129**, 277–282.
- Wilson, L. R., Rowan, B. C., Robertson, N., Moudam, O., Jones, A. C. and Richards, B. S., Characterization and reduction of re-absorption losses in luminescent solar concentrators. *Appl. Opt.*, 2010, **49**(9), 1651–1656.
- Chatten, A. J., Barnham, K. W. J., Buxton, B. F., Daukes, N. J. E. and Malik, M. A., A new approach to modelling quantum dot concentrators. *Sol. Energy Mater. Sol. Cells*, 2003, **75**, 363–371.

42. Ries, H., Thermodynamic limitations of the concentration of electromagnetic radiation. *J. Opt. Soc., Am.*, 1982, **A72**, 380–385.
43. Yablonovitch, E., Statistical ray optics. *J. Opt. Soc., Am.*, 1982, **72**, 899–907.
44. Smestad, G., Ries, H., Winston, R. and Yablonovitch, E., The thermodynamic limits of light concentrators, *Solar Energy Mater.*, 1990, **21**, 99–111.
45. Papakonstantinou, I. and Tummeltshammer, C., Fundamental limits of concentration in luminescent solar concentrators revised: the effect of re-absorption and nonunity quantum yield. *Optica*, 2015, **2**(10), 841–849.
46. Kittidachachan, P., Danos, L., Meyer, T. J. J., Alderman, N. and Markvart, T., Photon collection efficiency of fluorescent solar collectors. *CHIMIA*, 2007, **61**(12), 780–786.
47. Debijs, M. G., Verbunt, P. P. C., Rowan, B. C. Richards, B. S. and Hoeks, T. L., Measured surface loss from luminescent solar concentrator waveguides. *Appl. Opt.*, 2008, **47**(36), 6763–6768.
48. Hermann, A. M., Luminescent solar concentrators – a review. *Solar Energy*, 1982, **29**(4), 323–329.
49. Pandey, K. K. and Pant, T. C., Solar energy concentrator based on uranyl-doped PMMA, *Solar Energy Mater.*, 1991, **21**, 327–334.
50. Correia, S. F. H., Bermudez, V. Z., Ribeiro, S. J. L., André P. S., Ferreira, R. A. S. and Carlos, L. D., Luminescent solar concentrators: challenges for lanthanide-based organic–inorganic hybrid materials. *J. Mater. Chem. A*, 2014, **2**, 5580–5596.
51. Reisfeld, R. and Kaliski, Y., Nd^{3+} and Yb^{3+} germanate and tellurite glasses for fluorescent solar energy collectors. *Chem. Phys. Lett.*, 1981, **80**, 178.
52. Zettl, M., Mayer, O., Klampaftis, E. and Richards, B. S., Host polymer investigation for luminescent solar concentrators. *Energy Technol.*, 2016; doi:10.1002/ente.201600498.
53. Slooff, L. H., Bakker, N. J., Sommeling, P. M., Büchtemann, A., Wedel, A. and Sark, W. G. J. H. M. V., Long-term optical stability of fluorescent solar concentrator plates. *Phys. Status Solidi A*, 2014, **211**(5), 1150–1154.
54. Wilson, L. R., Rowan, B. C., Robertson, N., Moudam, O., Jones, A. C. and Richards, B. S., Characterization and reduction of re-absorption losses in luminescent solar concentrators. *Appl. Opt.*, 2010, **49**(9), 1651–1656.
55. Liu, C., Deng, R., Gong, Y., Zou, C., Liu, Y., Zhou, X. and Li, B., Luminescent solar concentrators fabricated by dispersing rare earth particles in PMMA waveguide. *Int. J. Photoenergy*, 2014, 1–5.
56. Li, C. *et al.*, Large Stokes shift and high efficiency luminescent solar concentrator incorporated with $\text{CuInS}_2/\text{ZnS}$ quantum dots. *Scientific Rep.*, 2015, **5**, 17777, 1–5.
57. Chou, C. H., Chuang, J. K. and Chen, F. C., High-performance flexible waveguiding photovoltaics. *Scientific Rep.*, **3**, 2244; doi:10.1038/srep02244.
58. McIntosh, K. R., Lau, G., Cotsell, J. N., Hanton, K., Batzner, D. L., Bettiol, F. and Richards, B. S., Increase in external quantum efficiency of encapsulated silicon solar cells from a luminescent down-shifting layer. *Prog. Photovoltaics: Res. Appl.*, 2009, **17**, 191–197.
59. Martínez, A. L. and Gómez, D., Design, fabrication, and characterization of a luminescent solar concentrator with optimized optical concentration through minimization of optical losses. *J. Photon Energy*, 2016, **6**(4), 045504-1-045504-11.
60. Schlosser, K., New Mexico company licenses innovative solar panel technology from two Washington universities. *In Geekwire*, August 2017.
61. Zhao, Y. and Lunt, R. R., Transparent luminescent solar concentrators for large-area solar windows enabled by massive Stokes-Shift nanocluster phosphors. *Adv. Energy Mater.*, 2013, **3**, 1143–1148.
62. Chowdhury, F. I., Dick, C., Meng, L., Mahpeykar, S. M., Ahvazi, B. and Wang, X., Cellulose nanocrystals as host matrix and waveguide materials for recyclable luminescent solar concentrators. *RSC Adv.*, 2017, **7**, 32436–32441.

Received 4 February 2017; revised accepted 4 December 2017

doi: 10.18520/cs/v114/i08/1656-1664