

Progress in Luminescent Solar Concentrator Research: Solar Energy for the Built Environment

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Abstract: This paper presents a concise review of recent research on the luminescent solar concentrator (LSC). The topics covered will include studies of novel luminophores and attempts to limit the losses in the devices, both surface and internal. These efforts include application of organic and inorganic-based selective mirrors which allow sunlight in but reflect emitted light, luminophores alignment to manipulate the emitted light path, and patterning of the dye layer. Finally, the paper will offer some possible ‘glimpses to the future’, and offer some additional research paths that could result in a device that could make solar energy a ubiquitous part of the built environment as sound barriers, bus stop roofs, awnings or siding tiles. Considering the reported efficiencies of the LSC are comparable to those reported for organic PVs, which are also being considered for use in the built environment, the results of the research on the LSC to date warrants more widespread attention.

Keywords: Solar energy, Luminescent solar concentrator, Building integrated photovoltaics, Review

1. Introduction

The European Committee wants all newly built buildings to be near-zero energy by 2020^[1]. This demands architects integrate energy saving and energy generation into their designs. To give architects more freedom, the devices saving and/or generating energy must be easily adaptable. A readily available energy source in a built environment is the sun, which is clean, safe, inexhaustible and reliable but generation of electricity with conventional photovoltaic (PV) cells has several disadvantages in this environment: the cells remain costly, modules are heavy, and limited in coloration (black and dark blue). Furthermore, PV cells respond optimally to direct sunlight, while in the built environment much of the sunlight is diffuse due to scattering and reflections by other objects, such as trees, buildings, and even clouds.

An alternative solar energy harvester was proposed in the 1970's, the luminescent solar concentrator (LSC)^[2]. In the LSC, sunlight penetrates the top surface of an inexpensive plastic or glass waveguide. This light is absorbed by luminescent molecules which are either embedded in the waveguide or applied in a separate layer on top or bottom of the waveguide. The luminescent molecules can be organic fluorescent dyes, or inorganic phosphors or quantum dots. The absorbed light is re-emitted at longer wavelengths, and a fraction of the re-emitted light is trapped in the waveguide by total internal reflection and becomes concentrated along the edges of the plate. Small PV cells attached to edges of the waveguide collect the emission light and convert it to electricity.

The LSC has potential advantages over silicon-based PV panels, especially in the built environment. For one, they can reduce the size of the PV cells more than 90% and the materials for making LSCs are inexpensive, reducing module prices. The plastic waveguide is lighter than the silicon PV panels, leading to a reduction in weight, which makes LSCs more viable for mounting to the sides of buildings. Sunlight can better penetrate the surface of the LSC waveguide from all angles, making them more appropriate for collecting non-direct sunlight. Lastly, LSCs have a great flexibility in design, which make them attractive for architects: they may be made thin and can be cut in any desired shape, cast in almost any color and may be transparent. Since LSCs can be thin, it becomes possible to make curved device. If the photon in/ photon out efficiency is high enough, the cost of electricity generated by the LSC could be competitive^[3]. These combined features make

LSCs interesting devices for increasing public acceptance of solar energy: while the efficiency of an LSC will be lower than an equivalent area of a silicon PV, the reduced cost and flexibility in design could make LSCs viable for the urban area. The LSC hasn't yet been commercialized owing to several drawbacks which limit their efficiency^[4]. Loss mechanisms for LSCs are shown in **Figure 1**.

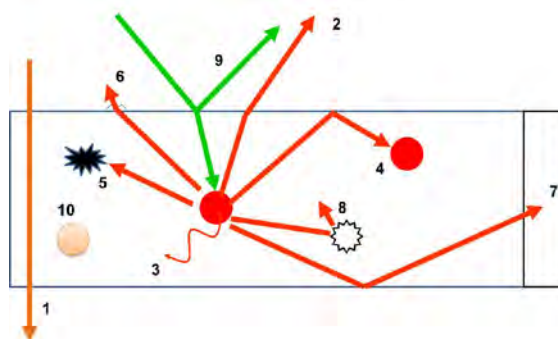


Figure 1. Loss mechanisms in LSCs: 1) Input light not absorbed by the dye molecules, 2) Light emitted outside capture cone, 3) Quantum efficiency of the dye molecules < 1, 4) Re-absorption of emitted light by another dye molecule, 5) Absorption of emitted light by the waveguide, 6) Surface scattering, 7) Solar cell losses, 8) Internal waveguide scattering, 9) Reflection from the top surface, 10) Limited dye stability.

The first loss is sunlight not absorbed by the dye molecules: this light is lost through the bottom surface. The second is light emitted by dye molecules under an angle which is refracted out of the waveguide instead of reflected internally- (> 40% of all absorbed energy may be lost through the top and bottom surfaces of the LSC^[5]). The third loss is absorbed photons not re-emitted by the dye molecules, but instead lost as heat and vibrations. Re-absorption of emitted photons by subsequent dye molecules via overlap of emission and absorption bands is a fourth loss. Waveguides can exhibit parasitic absorption, especially in the near infrared, and is the fifth loss cited. Sixth, imperfections of the waveguide surface can cause photons in the waveguide mode to leave the surface. Seventh, the PV cell at the waveguide edge has a non-uniform spectral response, with a fraction of incident photons being lost due to the finite conversion efficiency. Imperfections in the waveguide bulk lead to the eighth loss, scattered waveguided photons. In addition, a small part of the input light is reflected from the surface of the waveguide, shown as the ninth loss. Finally, there is loss caused by degradation of the dye molecules, primarily due to UV absorption.

2. Losses and Proposed Solutions

2.1. Surface Loss

Dye-emitted photons emitted inside the escape cone will be lost through the surfaces, and measurements suggest that 40-55% of all absorbed energy is lost in this way (this translates into a 50-70% loss of photons)^[5]: these results were confirmed by simulation^[6]. This surface loss is a key one for LSCs, and in the last couple of years multiple groups have done research on minimizing them by two processes: aligning the luminophores and applying selective mirrors.

Aligned luminophores: Organic luminophores are often dichroic in absorption and transmission^[7], opening new possibilities in controlling the spatial distribution of emitted light, provided that the physical ordering of the dyes is macroscopically controlled. The alignment of dichroic dyes in liquid crystalline (nematic) materials has been previously investigated^[8] and it was shown that the macroscopic alignment of the dyes in the liquid crystalline host resulted in anisotropy and dichroism in both absorption and emission. Aligning the dye luminophores perpendicular to the waveguide surface leads to an emission primarily in the direction of the waveguide, resulting in a sharp decrease of surface loss to less than 10%^[9], confirmed by simulations using collimated light^[6].

However, in this configuration the luminophores have low absorption, and concurrent low edge emission: trapping efficiency of emitted photons increases from ~65% to over 80% when vertically aligned luminophores in LSCs are excited by an isotropic light source^[10].

Luminophores can also be aligned planarly, or parallel to the waveguide surface. This configuration can direct light so that 60% more energy is emitted from two edges of the LSC compared to the other two edges^[11]: in this way the LSC can be used as a energy harvesting polarizer^[12] which could be used in displays, for example. Additionally, if light is emitted primarily towards just two edges, the number of PV cells on the LSC can be reduced to two or even one, further reducing LSC cost.

Selective mirrors: A second way to reduce surface loss is by applying wavelength-selective mirrors^[7, 21-31]. These mirrors are placed on top the LSC-waveguide with the goal that the reflectors not interfere with incoming sunlight that can be absorbed by the luminophores, but reflect only the luminophore-emitted light, which has a longer wavelength. Wavelength selective mirrors, made from chiral nematic (cholesteric) liquid crystals^[13] or inorganics^[13b,15], have both been applied to the LSC. Up to 30% of the light that had previously escaped the surface was turned into edge emission, translating into a 12% LSC output improvement using the organic reflectors^[14f]. Similar enhancements were determined using the inorganic reflectors^[4b]. Organic reflectors are cast from solution and spontaneously form the reflective layer: this is generally a much simpler and less expensive process than application of multilayer inorganic Bragg reflectors.

2.2. Re-absorption of emitted photons by other dye molecules

Most organic luminophores used in LSCs have small Stokes-shifts, leading to relatively large overlaps between the absorption and the emission spectrum^[15]. As a consequence, luminophores-emitted photons can be re-absorbed by another luminophore molecule during transportation through the waveguide. Re-absorptions are not losses by themselves, but the limited quantum efficiency of the luminophores and re-emission into the escape cone do result in losses^[16].

To reduce re-absorption events, researchers have experimented with luminophores with large Stokes-shift, like lanthanides^[17] and quantum dots^[18], but these classes of luminophore bring other challenges to the production of LSCs. Inorganics tend to suffer from low solubility in organic matrices, and often also suffer from a low absorption. To reduce the amount of reabsorptions Taleb et al.^[19] doped a dye with a polar and highly mobile material, like thionin. The dopant increased the separation of the absorption and fluorescence bands of the dye molecules, increasing the Stokes-shift and reducing (but not eliminating) the overlap in absorption and emission spectrum.

An option to reduce encounters of emitted light with the dyes is to only attach the dyes in a thin layer at the surface of the waveguide rather than filling the luminophore within the bulk of the waveguide. In this way, emission light may be transported predominantly in the clear host material, and only encounter the dye layer again every second internal reflection. These layers have been made of acrylates, via sol-gel techniques^[20], and polymerized liquid crystals^[11].

Using spatially-separated patterns of luminophores on top of a waveguide, the number of re-encounters emitted light could have with other dye molecules was reduced^[21]. The transport efficiency of the photons through the LSC increased with decreasing dye coverage. However, due to reduction in absorption, the total system output decreased. A lens system on top of the LSC is being developed that would increase absorption and thus the system output^[22].

2.3. *Dyes: Limited absorption, stability and fluorescence efficiency*

The spectral breadth of the dye absorption is an important factors determining the potential efficiency of the LSC waveguide. There are a number of luminescent materials being studied for possible inclusion in the LSC. The workhorse of the organic dyes are based on perylenes or perylene derivatives^[23]. The limitation of the organic dyes are often their lifetimes of operation in sunlight. Numerous studies are somewhat inconclusive as to the photostability of these materials: much depends on the processing conditions and polymeric environment of the fluorophore^[24]. Organo-metallic molecules with good photostability (such as porphyrins) have also been proposed^[25]. Inorganics such as lanthanides^[17] hold promise as long-lasting replacements for organics, possibly with extended Stokes shifts. However, they tend to suffer from decreased absorption, and solubility becomes a definite issue. There is a large research effort directed at using quantum dots in the LSC^[18], but they have not yet reached their promise as they continue to generally display small Stokes-shifts with limited photostability. A possible future research direction is into the use of surface plasmonics to enhance the emission of the dye materials, allowing the use of potentially lower quantum efficiency luminophores^[26].

To aid in luminophore absorption, it is standard practice to apply a rear layer to an LSC to act as a reflector. The reflecting back layer effectively doubles the path length of incident light through the dye layer for enhanced absorption. Some of the initial experiments used a silver mirror^[2b], but such a mirror is absorbing in the visible range. To avoid absorptive losses, most recent work has employed a white scatterer^[4, 27]. When separated from the waveguide by a small air gap, the rear scatterer can provide additional light for waveguides least 35 cm long^[28]. The scatterer also may direct that fraction of incident light that cannot be absorbed by the dye directly at the PV cell, allowing it to generate electricity. The separation of the scatterer from the waveguide by a low refractive index layer is important to maintain waveguided light in the trapping modes of the waveguide: every encounter with the attached scattering layer re-distributes the light, and a significant fraction of this re-directed light will be outside the waveguide modes of the system.

Another option is to allow the LSCs to be transparent. In this form, the device could be used as a window while generating electrical current. An alternative design uses, rather than a waveguide with embedded, inflexible dyes, two glass plates coated with a conductor, the space between being filled by a liquid crystal containing a dye molecule^[29]. The liquid crystal can be continually switched between orientations, from planar to homeotropic through application of a voltage across the plates. In the former state, the dye molecules follow the alignment of the LC host, and into a position of maximal absorption. The dye may then emit light which is partially trapped in the glass panes making up the 'window', and generate electrical current. By switching from planar to a tilt configuration, the output of the window necessarily drops due to reduced light absorption, but still produces a current, and the efficiency of edge output is actually increased. This design, while still needing considerable work to get transmissive properties correct with acceptable coloration, has advantages over other 'smart' windows. Photo- and thermochromics^[30] or standard blinds^[31] can, for example, be automatically switched between light and dark states, but generate no electricity. Thin-film PV modules can generate electricity^[32], but cannot have their transparency switched.

2.4. *Photovoltaic losses*

The standard silicon-based PV has a band gap corresponding to a photon of around 1100 nm (~1.1eV). Photons with energies above this threshold may still be processed by the solar cell, of course, but the excess energy of the photon is wasted, and converted most often into heat, and there is a reduction in the response of the cell for these shorter wavelengths. However, the LSC does not emit a spectrum remotely similar to the solar spectrum. Rather, it emits a narrow range of wavelengths, most-often centered at red and near-infrared wavelengths (630-720 nm at the

maximum). To better exploit the spectrum of the LSC, researchers have used type III-V PV cells based on GaAs and InGaP cells^[4a] and obtained record-setting efficiencies. If these cells could be produced economically, it could hold great promise for widespread adoption of the LSC in future. Another option could be the use of organic-based PV cells, which often have a ‘sweet spot’ in the spectral range where the LSC emits^[33].

2.5. Waveguide losses

Around 4% of incoming light is reflected from the waveguide surface (the refractive indexes of polymethylmethacrylate (PMMA) and polycarbonate (PC) being between about 1.49 and 1.59) and never enter the waveguide, and could thus be considered a loss. While anti-reflection coatings are very common in PV cells, they have not yet been applied to LSCs. As the LSC relies on total internal reflection from two smooth surfaces, textured systems as used in many antireflective coatings^[34] are not a viable option. Rather, coatings utilizing differences refractive indices can reduce these reflective losses and can be applied to polymeric materials^[35].

One challenge to produce luminophores with emissions approaching 800 nm for use in LSCs is that the waveguides, which are predominantly made of PMMA or PC, become parasitic, and absorb strongly at these wavelengths^[36]. Additionally, additives made for improvement of various characteristics of the host matrix (such as altering UV stability or hardness) can have large impact on the device’s capability of transporting light. For example, an additive that only shows a small absorption when measured through the width of the waveguide can have a severe impact on the edge output of the same object, for the pathlength is magnified many tenfold^[37]. As waveguides age, UV-generated damage creates light ‘traps’ within the polymer. Research into co-polymer systems has demonstrated enhanced photostability over the single component^[38]. Non-uniform edge emission from waveguides also causes additional losses, as illumination of the attached PV at anything less than uniformity results in decreased performance. Thus, the shape of the waveguide also influences the emitted light distribution^[39].

3. Future directions

There are a great number of improvements that can and need to be made on the LSC to make it a more viable option for use in the urban environment. One aspect we find particularly intriguing is to provide an opportunity for the use of organic-based photovoltaics (OPV). One of the greatest challenges for OPV has been the inability of utilizing the ultraviolet portion of the UV spectrum, as well as survive the high energies of the UV light which causes premature degradation of the OPVs through destruction of the dye materials. However, the LSC does not illuminate the attached solar cell with a solar spectrum, but a much more narrow-band of light, generally in the near infrared, the range of wavelengths where OPVs perform their best. Coupled with the lack of exposure to UV light, this could provide the OPV with the first real niche application where they could excel.

A second largely unexploited research area is in the field of plasmonics. Many research publications show when a fluorescent molecule is brought close to a small metallic nanoparticle there is an enhancement of the fluorescence^[40]. There has been application of surface plasmonics in PVs^[41], but to our knowledge, no extensive work in the field of LSCs.

It is the opinion of the authors that the rôle of the LSC in future urban renewable energy plan should be re-defined. Given the decrease in the costs associated with traditional silicon-based PV, it would seem folly to attempt to compete directly with the well-established, traditional PV panel on a rooftop. Rather, the LSC could best be used as a complement to silicon PV rather than a competitor, positioning itself in areas not normally accessible, such as areas with increased fractions of diffuse

light. The LSC is to be brought directly into public view, not ‘hidden away’ as most silicon PV panels. Applications could include sound barriers, telephone poles, and bus stop roofing.

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