

Using liquid crystals to improve the performance of luminescent solar concentrators

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ABSTRACT

The luminescent solar concentrator (LSC) has been proposed as a cost-effective solution to bring electricity generation from sunlight into the built environment. The basic LSC design consists of a plastic plate containing or topped by a thin layer of fluorescent dyes. The dyes absorb sunlight and re-emit it at a longer wavelength. A fraction of this light is trapped by total internal reflection and becomes concentrated along the edges of the waveguide, where one can place small photovoltaic cells to convert the emitted light into electrical current. With its flexibility in color, shape, and size, it would appear ideally suited for exploitation by the architect for use in façades and other structures in the urban surroundings. However, limitations in performance have hindered widespread adoption of the devices. In this work I present modifications to the standard LSC using liquid crystals to assist in collecting, directing, and controlling both the incoming and emitted light in the device, as well as describing additional features to allow on-demand adjustment of transparency.

Keywords: luminescent solar concentrator, liquid crystal, solar cell

1 INTRODUCTION

The luminescent solar concentrator (LSC) was first suggested in the late 1970's [1,2] as an alternative to the photovoltaic solar panel. The LSC is a very simple device at its heart. It consists of a plastic or glass panel which acts as a waveguide, and mixed inside the panel, or topping the waveguide as a thin film, are luminescent molecules, most often organic fluorescent dyes, inorganic phosphors or quantum dots. These luminophores absorb the incident sunlight and re-emit the light at longer wavelengths. A fraction of this emitted light becomes trapped in the high refractive index waveguide and travels via total internal reflection towards the edge(s) of the waveguide. To these edges small, efficient photovoltaic (PV) cells may be attached to convert the concentrated light into electrical current. The LSC has the advantages over standard PV panels in that their coloration, variability in shape, and their lighter weight could make them ideal for use in the urban environment. In addition, the LSC is able to use both direct and indirect sunlight efficiently, which allows for more widespread placement without the need to tilt the panels.

However, a number of aspects of the LSC need to be improved upon before they are able to enter the

marketplace. In particular, the efficiencies of the LSC are still rather modest [3,4]. The limitations of the LSC stem from the lossiness of the waveguides. In particular, two loss mechanisms are addressed in this paper, and they are illustrated in Figure 1 below.

The first loss is caused by the overlap between the absorption and emission spectra of the luminophores used. Light emitted by one luminophore can be re-absorbed by a second luminophore. Given that the luminophores are often less than 100% in their quantum yield of emission, this translates into loss of photons.

Additionally, there is a significant fraction of light that is emitted at angles outside the effective 'capture cone' of the waveguide, and thus escapes the top or bottom surfaces of the device. We have measured up to 50% of the absorbed energy (and 60% of the absorbed photons) are lost through the top and bottom surfaces of the waveguide [5].

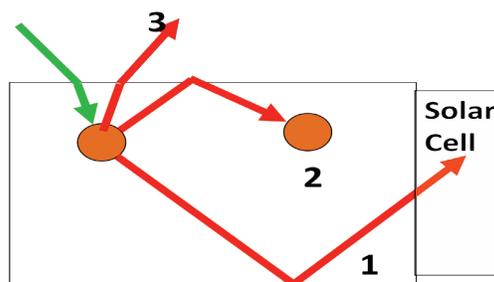


Figure 1: Schematic of the functionality and loss mechanisms of a luminescent solar concentrator. Incoming light (green) is absorbed by a luminophore. A portion of the emitted light (1) is trapped by total internal reflection and exits the edge, where it is converted into electricity by an attached photovoltaic cell. Some of the emitted light is reabsorbed by a subsequent dye molecule (2) and will either be lost due to limited quantum yield of emission, or emitted in the wrong direction. Finally, a significant fraction (3) will be emitted at an angle outside the 'capture cone' of the waveguide, and be lost.

Our laboratory has addressed these loss mechanisms using a rather unconventional material: the liquid crystal (LC). The possibility of exploiting the solvent deposition and self-assembling nature of these molecules makes them very inviting for use in large-scale, rapid production applications. We have applied the liquid crystals towards addressing the loss mechanisms in the LSC described above in a static sense by using them to align the dye molecules

and take advantage of the dichroic nature of the dyes to direct light emission in a less random way, and in the form of a chiral nematic (cholesteric), have applied them as a selectively-reflecting layer to reduce surface losses. But the liquid crystal has application beyond the static case: we shall also describe their use in an addressible format to produce a ‘smart’ window that can generate electrical power as well as variably control light ingress in a space.

2 DIRECTING EMISSION

Liquid crystals may be induced to align in various ways by judicious application of alignment layers on the surface of the waveguide. One option is to align the liquid crystals homeotropically (that is, with the long axis of the molecule perpendicular to the waveguide surface). When one adds a fluorescent dye to the LC, in many cases the dye guest will align with the LC host.

The dye DFSB-K160 (Risk Reactor) was added to a host LC and deposited as a thin film on a PMMA waveguide. The top surface losses as a function of light absorbed were determined for the dyes, and the results may be seen in Figure 2. The homeotropically aligned system dramatically reduced the surface losses to less than 5%. However, the total edge output was considerably lower than in the isotropic case for two reasons. The first, in the homeotropic state, the absorption dipole of the dye is in the worst position for absorption. Secondly, the light emitted by the dye becomes trapped in the higher refractive index liquid crystal layer ($n_{avg} \sim 1.6$) rather than entering the PMMA waveguide ($n \sim 1.49$), and in the LC layer the reabsorption is very high.

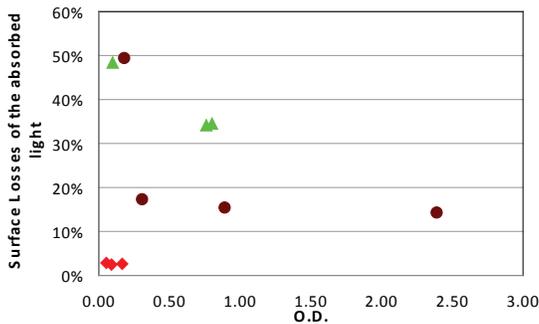


Figure 1. Measured surface loss from thin layer- PMMA samples with three different alignments of K160: isotropic (brown circles), planar (green triangles) and homeotropic (red diamonds)

An alternative alignment is to place the LCs in a planar alignment so they lie flat on the surface of the waveguide. This should improve absorption, and due to the dichroic nature of the dye emission, should enhance edge output for two edges compared to the other two. The degree of alignment of the dye in the planar LC was determined by

$$R_a = (A_{par} - A_{per}) / (A_{par} + 2A_{per}) \quad (1)$$

where R_a is the dichroism parameter in absorption, and A_{par} and A_{per} are the absorption of light polarized parallel and perpendicular to the alignment direction, respectively.

Emission from the edges of the waveguides were determined for the edges parallel and perpendicular to the alignment direction of the dyes, as illustrated in Figure 3, and a ratio between the two orthogonal sides were determined and given in Table 1 [6].

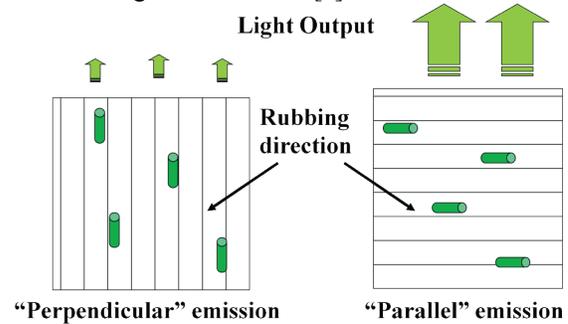


Figure 3. Definition of E_{per} and E_{par} . The green cylinders represent individual dichroic dye molecules.

As may be seen, an increase in the dichroism in absorption resulted in an increase in the emission of the parallel edge as a function of the emission from the perpendicular edge. If one was to project emission to a $R_a \sim 0.7$, which is approximately the alignment of the LC host themselves, one could expect almost twice as much light from the parallel edge as the perpendicular. This could be very beneficial in reducing the number of PV cells that need to be added to the edges of the LSC from 4 to 2 (or even less). However, as seen in Figure 2, the surface losses do not decrease in this orientation, and, in fact, may increase.

Table 1. The ratio of parallel to perpendicular edge emission as a function of dichroism in absorption for three fluorescent dyes.

Dye	R_a	E_{par}/E_{per}
Rhodamine B	0-0.03	1-1.05
DCM	0.25-0.5	1.1-1.3
DFSB-K160	0.4-0.6	1.2-1.6

This naturally suggests that the optimal dye alignment could very well be an intermediate between the homeotropic and planar forms, namely, a tilt alignment. In this configuration, the light will be emitted into the waveguiding more more directly, while at the same time maintaining a high degree of absorption for the dyes. Production of tilt aligned dye molecules is underway in our laboratory.

3 SELECTIVE REFLECTOR

To reduce the surface losses in the LSC one could use of selective reflector which passes incident light that is absorbed by the dye molecules, but reflective to light emitted by the dyes. By adding a chiral molecule as a dopant to a LC host, it is possible to form an alignment of planar LC where each subsequent molecular plane has a small 'twist' when compared to the underlying layer. This twist is perpetuated through the depth of the film. These films then may act as a Bragg reflector. The reflection wavelengths are dependent on the 'pitch' of the helix (the distance for a complete 360° rotation of the LC molecular director), while the width of the reflection band is a function of the difference between the ordinary and extraordinary refractive indices of the host LC (normally about 75 nm) (see Figure 4) [7]. The chiral nematic (cholesteric) thus created will be reflective for circularly-polarized light of a handedness matching the helicity of the cholesteric: that is, a right-handed cholesteric will reflect right-circularly polarized light. The reflection wavelength may be easily tuned by changing the concentration of the chiral dopant. These organic layers may be deposited from solution and will self-assemble, which gives them distinct production advantages over inorganic Bragg reflectors, which must be constructed layer-by-layer in a very exacting way [8]

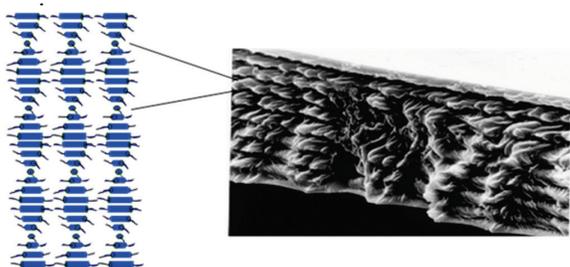


Figure 4. Schematic depiction of a chiral nematic (cholesteric) liquid crystal (left) and an SEM image of a cross-section of a cholesteric showing the 1D bandgap periodicity (right).

We have previously demonstrated that by applying cholesterics to the top of a waveguide containing the common LSC dye Lumogen Red305 (BASF), we are able to convert ~30% of light otherwise lost through the surface into useable edge output [9]. This work demonstrated that the effectiveness of the cholesteric was extremely dependent on the position of the reflection band, as the reflectors are angularly dependent.

Computational methods have been developed to make predictions of performance of the cholesterics when applied to fluorescent waveguides [10]. In the process of this work it was apparent that the effectiveness of the LSC should improve upon the broadening of the reflection band, as there was a significant fraction of the emission spectrum

that lay outside the reflection of the narrow-band cholesterics.

Simulations of the broadband cholesterics were made using the same architecture as the narrow band reflectors made experimentally: that is, with two right-handed reflectors located on either side of a halfwave plate. The halfwave plate converts the left-circularly polarized light that passes through the first right-handed reflector into right-circular light which would be reflected by the second layer, thus creating a total reflector. For the broadbands, we simply layered each side of the halfwave plate with two narrow band reflectors with reflection centers shifted by 75 nm. A calculation of the reflection efficiency of such a construct as a function of incoming light angle and wavelength may be seen in Figure 5.

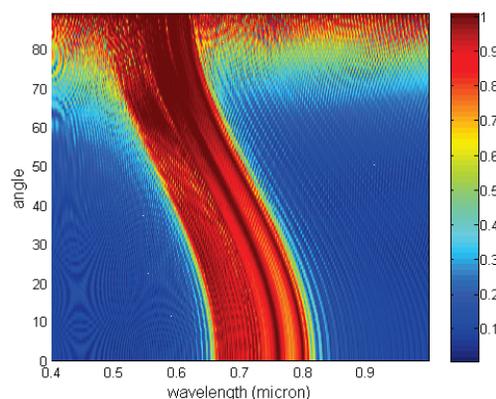


Figure 5. Simulated efficiency of reflection for two pairs of right-handed cholesterics on either side of a halfwave plate as a function of incident light angle and wavelength.

Given the spectra and spacial profile of the emission light, we calculated the effect of broadening the reflection band from 75 nm to 150 nm for incident light normal to the surface of the waveguide as a function of the central reflection wavelength for the Red 305 dye which has an emission peak at 630 nm. The results of this calculation are found in Figure 6, demonstrating the advantage of producing the wideband variety of cholesterics.

4 DYNAMIC SYSTEMS

To this point, we have described the use of LCs as aligners and reflectors in the form of thin, solid films, caused by the uv-light induced crosslinking of reactive LC monomers. There could be much to gain by maintaining the liquid crystalline nature of the system as well, namely as switchable 'smart' windows [11].

By using an LC host layer doped by a quantity of fluorescent dyes sandwiched between two glass plates coated with indium tin oxide layers, one is able to 'switch' the orientation of the LCs, and hence the dyes, by application of a small electric field across the gap. In the 'rest' state, in other words, at zero applied field the LCs are

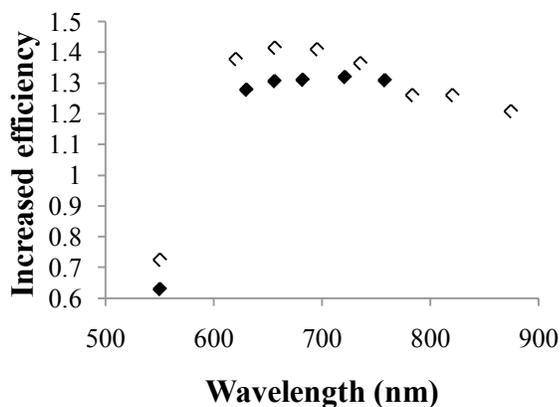


Figure 6. Calculated enhancement factor of emission for a Red 305 waveguide topped by a 75 nm narrow band (black) or 150 nm broadband (white) cholesteric reflector as a function of central wavelength of reflection for the cholesteric upon exposure to light normal to the waveguide surface.

in the planar state, which conveniently corresponds to the maximum absorption position of the associated dye molecules. The emitted light from the dyes is trapped by total internal reflection within the glass plates, and becomes concentrated along the edges of the waveguides where we can attach PV cells for conversion to electricity. By applying a field across the cells, any orientation of the LCs up to homeotropic can be attained, allowing increased transparency of the window. In this latter case, the absorption of the dye molecules is lower due to their high tilt with respect to the E-field of the incident light, but at the same time the efficiency in light transport in the window is enhanced (see Figure 7)

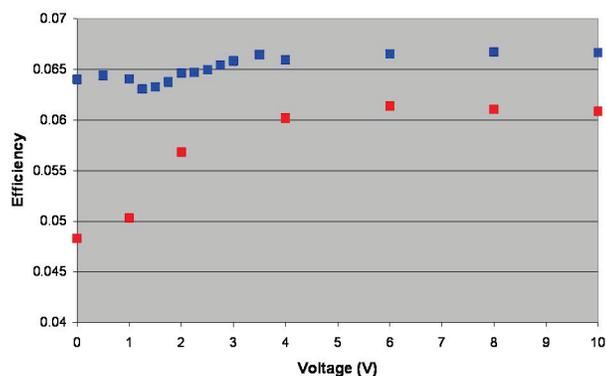


Figure 7. Efficiency of emission of 5 x 5 cm² ITO cells doped with 0.5% K160 from edges parallel (blue) and perpendicular (red) to the alignment direction of the liquid crystals (where efficiency is integrated edge emission / calculated total energy absorbed) as a function of applied voltage.

This configuration has some distinct advantages over, for example, both photo-, electro-, or thermochromic systems [12] which are able to adjust transparency automatically with changing sun conditions, but without any electrical generation, and transparent, thin-film silicon, CIGS, or organic solar PV which can generate electrical current but cannot alter their transparency.

In these 'smart' windows, the 'off' state consumes least energy, and presumably is used in the high solar flux period between late morning and early afternoon, which produces the most edge emission. In the shorter periods of the day when transparency is more desirable, the window consumes power but generates current more efficiently. Work continues to make the windows more visually appealing for working and living spaces, as well as to increase the on/off contrast.

5 CONCLUSION

For many years the loss mechanisms of the LSC were accepted as a matter of course. By application of technologies developed in the study of LCD screens we can gain a manner of control over the direction of photon flow, prevent the leakage of light from the system, and allow user-driven switching of the system to enhance comfort levels. We believe these are important advances to making the LSC a viable complement to the traditional solar PV panel, in that the LSC can find widespread use in areas not normally accessible to panels due to cost or aesthetic limitations. Our vision is to make the LSC ubiquitous with the urban setting.

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