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Extraction of Trapped Light From Luminescent Solar Concentrators

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Introduction

In modern light sources such as Luminescent Solar Concentrators (LSC's) and Light Emitting Diodes (LED's), light is emitted within a light-guiding structure of high refractive index. Some of this light is trapped, and will not be able to escape. Similar problems are observed when collecting fluorescent radiation in waveguides [1] and scintillation detectors [2]. For lighting applications, this trapped light should be able to escape the light-guiding structure. In LED's this is commonly achieved with a special profile in the active zone. However, in LSC's the small light-emitting zone is remote from the large light collector so a different approach must be taken. This paper will focus on the extraction of emitted light from rectangular LSC's, and propose a way of extracting a large fraction of the trapped light.

Endlight vs. Trapped Light

Before going any further, it is important to make distinctions between the different categories of light within the light guide of a LSC system. Consider a LSC consisting of a rectangular block of transparent dielectric with perfectly parallel sides, containing a fluorescent dye. Light is emitted isotropically from the dye, so that a small fraction (referred to as 'endlight') will strike the end surface inside the critical angle cone and escape, as shown in Figure 1(a). By connecting a clear light guide to this edge, the endlight can be used as a light source. A larger fraction (referred to as 'side loss') will escape through critical angle loss cones at the top, bottom and sides of the block. Some of the side loss cones can be converted to endlight using suitable reflectors [3]. The remainder of the light is 'trapped light', and does not escape at any of the surfaces of the LSC. When a clear light guide is attached to the end of the LSC sheet, both the endlight and the trapped light will undergo total internal reflection and travel to the end of the light guide. 91% of the endlight will escape upon striking the end surface, and the remaining 9% is trapped by Fresnel reflectance. It has been shown elsewhere that the light reaching the end of the light guide is approximately half endlight and half trapped light [3, 4], therefore half of the available light remains trapped within the light guide (as illustrated in Figure 1(b)), unless the end surface of the LSC is given special treatment.

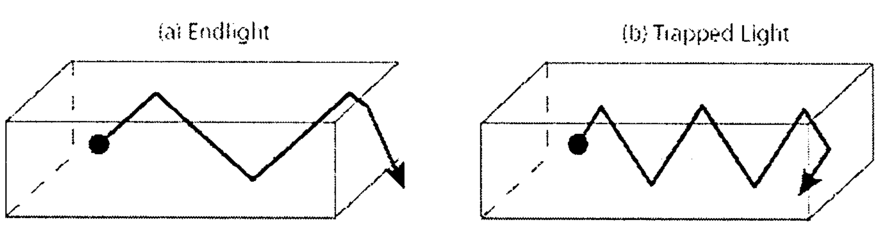

Figure 1: (a) Endlight can pass through an end surface, whereas (b) trapped light is totally internally reflected at all surfaces.

Extraction of Trapped Light

A large portion of the trapped light can be extracted by attaching a suitable luminaire [4]. Figure 2 shows a side view cross-section of the luminaire, where an optically continuous joint connects the light guide of thickness t to the luminaire of depth d and height h. The back surface of the luminaire is a diffuse white reflector. In some designs the side and end surfaces are also diffuse white reflectors.

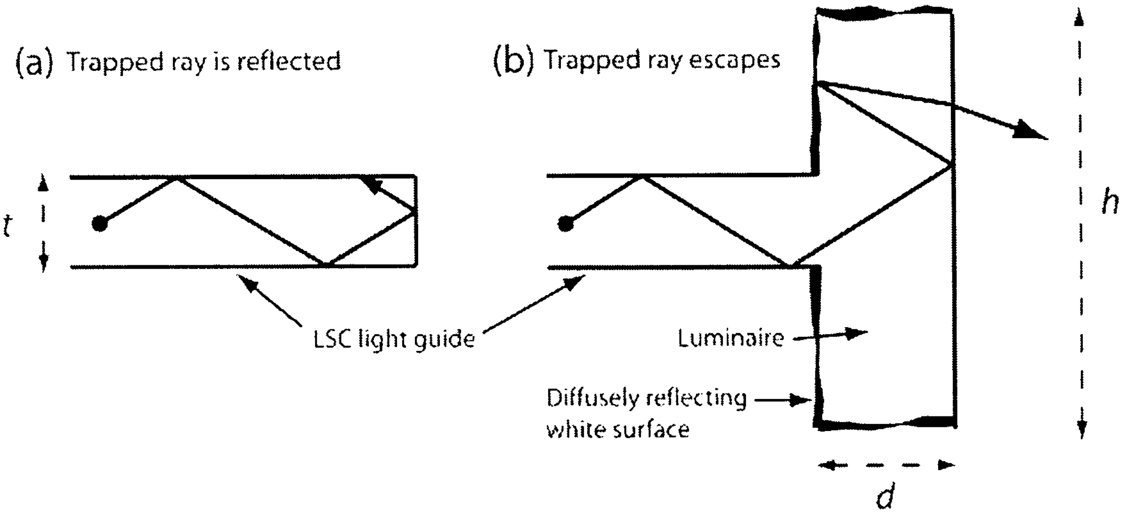

Figure 2: Extraction of trapped light from light guide of thickness t, by a luminaire of depth d and height h. (a) Without a luminaire, much of the light in the light guide is trapped. (b) Adding a luminaire enables the trapped light to escape.

The efficiency of a luminaire is indicated by its luminaire gain, G, which is the ratio of the luminous output with the luminaire (as in Figure 2(b)), compared to a flat end (as in Figure 2(a)). Let η_{end} and η_{trap} denote the extraction efficiencies of endlight and trapped light respectively. These are defined as the amounts of endlight and trapped light respectively escaping from the luminaire, as a fraction of the amounts entering from the light guide. The luminaire gain is,

$$G = \frac{\eta_{end} + \eta_{trap}\mathrm{F}_{\mathrm{at}}}{\eta_o}, \qquad (1)$$

where F_{at} is the ratio of trapped light to endlight at the end of the light guide. Computer models typically show F_{at} = 0.85, depending on the choice of dye and matrix. η_o is the endlight extraction efficiency of a light guide with a flat end (theoretically ~91%). An ideal luminaire would extract all of the trapped light, yielding a gain value of $G \approx 2.0$. However, due to a combination of absorption and light re-entering the light guide, the gain is practically limited to about 1.8.

Modelling Luminaire Gain

Theoretical values of η_{end} and η_{trap} for various luminaire designs were calculated by ray tracing, assuming isotropic emission from the dye particles within the LSC sheet. For simplicity, only the forward hemisphere is studied in these simulations – i.e. the hemisphere in the direction towards the light guide. Light emitted within the 'side loss' half-cones (solid angle $\Omega_{loss} = \pi(1-\mathrm{Cos}\chi)$, where χ = critical angle) exit the sheet, and the remainder (solid angle $\Omega_{TIR} = 2\pi - 6\pi(1\text{-}\mathrm{Cos}\chi)$) is totally internally reflected into the light guide, and then to the luminaire. All light entering the light guide is categorised according to its cone angle γ from the normal to the end surface, as either endlight ($\gamma < \chi$) or trapped light ($\gamma > \chi$). The paths of 1000 rays were traced and the endlight and trapped light were further divided into escaping rays and non-escaping rays. η_{end}, η_{trap} and G were calculated using these statistics, assuming values $\eta_o = 0.91$ and $F_{at} = 0.77$.

The results shown in Table 1 demonstrate that the geometry of a luminaire affects the extraction efficiency of trapped light. Increasing h leads to higher values of η_{trap} in all cases. When all edges are diffusely reflecting, 54-69% of the trapped light is extracted. If the edges of the luminaire are left clear, light can escape at any of the edges, boosting η_{trap} by 10% for both sizes. Hence these models predict that by careful luminaire design, up to 79% of the trapped light can be extracted, providing a gain in output of 73% compared to a flat end.

Table 1: Theoretical light extraction efficiencies and luminaire gain for various luminaires of total depth $d = 2t$, height $h = 5t$ & $8.3t$.

Luminaire Design	**Ratio of height to thickness, h/t**	η_{end} **(± 0.006)**	η_{trap} **(± 0.014)**	**Gain, G (±0.04)**
Diffuse reflector on all edges	5	0.96	0.54	1.51
	8.3	0.97	0.69	1.65
Diffuse reflector only on back surface	5	0.98	0.64	1.62
	8.3	0.97	0.79	1.73

Experimental Measurements

The above simulations were tested experimentally using the final two luminaires in Table 1. Each luminaire was optically joined to a separate LSC (containing the same dye) as shown in Figure 3 and the end of the LSC without the luminaire was polished flat. A fluorescent lamp was placed 30 cm from the end of the LSC, and the desired end was placed in an integrating sphere. Black tape was fixed across the width of the LSC sheet on the opposite side of the lamp to ensure that the ratio of trapped light to endlight is consistent no matter which end is in the integrating sphere. Luminaire gain G, was calculated by dividing the light output from the luminaire by that of the polished end of the LSC.

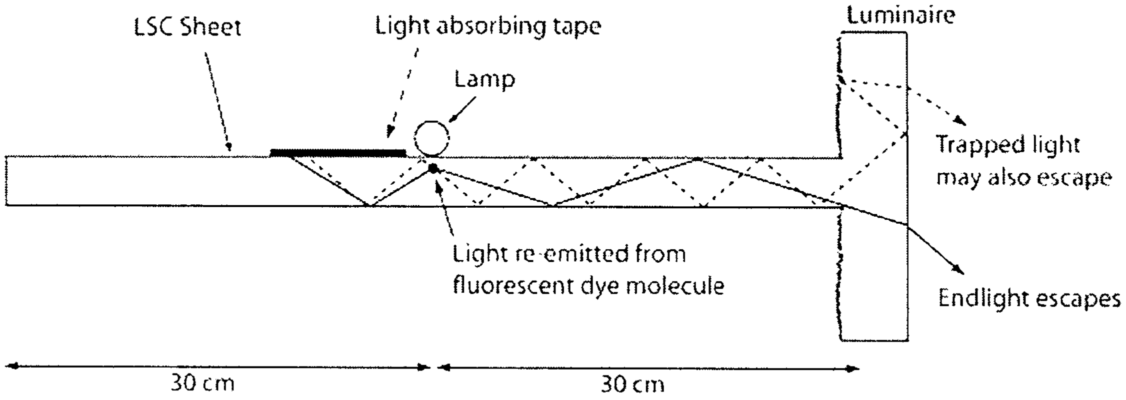

Figure 3: LSC sample design used to measure luminaire gain G. Light output is measured at each end separately with an integrating sphere. The black tape is placed on the right

hand side of the lamp to measure η_o, and on the left hand side to measure luminaire output.

The measured gain values are shown in Table 2, and they are well below the expected values. The poor performance observed here are believed to be due to tiny air-gaps in the joints that were visible upon close inspection. These small air gaps are significant enough to prevent most of the trapped light from entering the luminaire, and therefore the luminaire gain is significantly lower than expected. A luminaire gain of 1.59 was achieved for a luminaire with h/t = 25, by improving the joining technique to reduce the presence of visible air bubbles. Slightly smaller gain is expected for a height to thickness ratio of $h/t = 5$, but this does demonstrate that improving the optical quality of the joint improves the transmission of trapped light and enhances system efficiency.

Table 2: Measured luminaire gain for rectangular luminaires of depth $d = 2t$, with diffuse reflector only on the back surfaces.

Ratio of height to thickness h/t	Luminaire Gain, *G*	
	Measured	Model
5	1.29	1.62
8.3	1.30	1.73

Conclusion

When light is emitted within a structure of higher refractive index than its surroundings, the end surface must be given special treatment or else only half the light will escape. Ideally all the trapped light would be extracted, doubling the output. Ray tracing simulations have predicted that good luminaires can yield a relative gain of around 1.6 - 1.8. However, lower gain values around 1.3 have been realized experimentally, due to problems with the optical joint. More promising results of the order of 1.6 have been achieved with better joints.

References:

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