Luminescent and Non-Luminescent Solar Concentrators: Challenges and Progress

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Abstract: Luminescent concentrators would allow for high concentration if losses by reabsorption and escape could be minimized. We present new phosphors and filters that facilitate this. Another type of lightguide-based concentrators, diffraction-based, is discussed as well.

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1. Introduction

In light-guide based solar-concentrator systems, sunlight is coupled into a plate and then guided towards small photovoltaic cells by total internal reflection (TIR). Such devices are attractive, since they are thin and inexpensive. There are several ways to couple sunlight into a light guide [1]: non-luminescent (scattering, refraction or diffraction [2]) and luminescent. Non-luminescent concentrators suffer from limitations given by conservation of étendue. In the case of diffuse light and/or non-tracking systems, the maximum attainable concentration equals \( n^2 \), where \( n \) is the refractive index of the light-guide material. In the case of direct sunlight, only limited part of the sky has to be covered and the attainable concentration can be higher. In Section 3, we will show how diffractive structures can be used in this respect.

Luminescent solar concentrators (LSCs) [3,4] do not suffer from this limitation. In an LSC, incident short-wavelength light is converted by a luminescent material into longer-wavelength light, which is guided towards the photovoltaic cells. If the energy difference between the incident short-wavelength and emitted long-wavelength light is \( \Delta E \approx E_{\text{in}} - E_{\text{out}} \), the maximum attainable concentration equals \( n^2 (E_{\text{out}}/E_{\text{in}})^2 \exp(\Delta E/kT) \), where \( T \) is the temperature of the concentrator [1].

The underlying reason for the limited attainable concentration in non-luminescent concentrators is that the light coupled into TIR will reencounter the scattering, refractive or diffractive structure and has a large chance to escape from the light guide. On the other hand, in the luminescent case, there is no fundamental reason why light in TIR cannot travel unaffectedly. Even the light that is not coupled into TIR can in principle be kept inside the light guide by the use of a wavelength-selective filter that reflects the luminescent light but not the incident light. In practice, however, there are many sources of loss in an LSC, like incomplete absorption, reabsorption of luminescent light, scattering and reflection of sunlight. In Section 2, new ways are presented to limit those losses.

2. Luminescent solar concentrator

2.1 Luminescent materials

Many luminescent materials that are being investigated for LSCs, like organic dyes and quantum dots, suffer from reabsorption. In this respect, rare-earth compounds are promising [5] since in general they have large shifts between absorption and emission spectra, whereas optical absorption between 4f levels is forbidden. We found that phosphors based on \( \text{Sm}^{2+} \) match closely the requirements [6]. In this ion, absorption from the 4f ground state to the 5d band is followed by radiationless decay to 4f levels that decay via line emission. In Fig. 1 the absorption and emission spectra of \( \text{Sm}^{2+} \) in a \( \text{SrB}_4\text{O}_7 \) matrix are shown, where \( \text{Eu}^{2+} \) is needed for appreciable absorption and emission. The absorption spectrum is broad, whereas the emission spectrum exists of a main peak at 686 nm and some smaller peaks. The absorption coefficient is approximately 300 cm\(^{-1}\) at 500 nm wavelength; it is approximately 0.1 cm\(^{-1}\) at 686 nm. The quantum efficiency is more than 90%. Although a main emission line at a somewhat longer wavelength would be preferred for an LSC, this is the best luminescent system we found.

For use in an LSC, such a phosphor has to be applied in or on top of a light guide, e.g. as particles dispersed in a binder, in such a way that luminescent light does not escape by scattering. One way to prevent this is having the phosphor as nanoparticles. However, it is not easy to produce such nanophosphors and in general their quantum efficiency is low. Another way of preventing scatter is by matching the refractive index of the binder to that of the phosphor (≈ 1.7). Binders that could be used are high-index polyimide or binders containing an appropriate fraction of \( \text{TiO}_2 \) nanoparticles. Unfortunately, it is not easy to make good layers of phosphor particles dispersed in such a binder because of incompatibility of ingredients, bad adherence, absorption of sunlight by the binder, or instability...
during exposure to light. Up to now, we were able to make thin layers (up to 20 µm) with reduced scatter. Thicker layers are needed, since the absorption length of our phosphor is around 30 µm.

![Absorption and emission spectrum of SrB₄O₇:5%Sm²⁺,5%Eu²⁺](image)

**Fig. 1.** Excitation (absorption) and emission spectrum of SrB₄O₇:5%Sm²⁺,5%Eu²⁺.

2.2 *Wavelength-selective filters*

Escape of luminescent light can be prevented by applying wavelength-selective filters. There exist a number of materials that may serve as filters [7]. An interesting class of filters are cholesteric liquid crystals, which act as Bragg reflectors for circularly polarized light [8]. It is possible to make broad-band filters by applying a pitch gradient in the cholesteric stack. Polarization-independent filters can be made either by combining two filters of opposite chirality or by combining two filters with the same chirality and a half-lambda wave plate. Recently [9] we realised such filters. The calculated angular and wavelength dependence of the reflectivity of such a filter is plotted in Fig. 2a. Note that the reflection band shifts to lower wavelength for larger angles of incidence. This implies that, for high incident angles, the incident sunlight will be reflected and hence be prevented from entering the light guide. This detrimental effect can be as large as the advantageous effect on the luminescent radiation [6].

![Reflectivity as a function of wavelength and angle of incidence](image)

**Fig. 2.** Calculated reflectivity as a function of wavelength and (internal) angle of incidence for (a) no dispersion and (b) special dispersion. The dispersion of the ordinary (solid line) and extraordinary (dashed) refractive index are shown in the insets.

In principle, it is possible to make a filter which does not have this angular dependence by a suitable dispersion of the constituent materials of the filter, as shown in Fig. 2b. We assume that the difference between the two refractive indices decreases with decreasing wavelength and vanishes at 550 nm. Indeed, the calculation shows no reflection below this wavelength. One may wonder whether it is possible to realize such a filter in practice. Most materials exhibit a dispersion that is larger when the refractive index is larger. However, liquid crystals can have the opposite behavior. Work is in progress to use this for realizing filters with little angular dependence.

3. *Diffractive concentrators*

A light guide with a transmission grating on top of it can diffract incident sunlight into TIR. Coupling light from incident angles around normal incidence into a light guide requires a grating period smaller than the wavelength. Recently [10], we showed how to optimize the diffraction efficiency for these small grating periods when the grating is produced as a surface-relief structure. We found the presence of regions in the space of incoming angles where
light is efficiently coupled into total internal reflection [11]. For an ordinary, symmetric grating, these regions occur for both the positive and negative first diffraction orders. For a slanted grating, the intensity of one of the orders is enhanced at the cost of the other. A typical result of a calculation (Rigorous Coupled-Wave Analysis) and a preliminary result of an experiment (for a sample made by interference holography) are shown in Fig. 3. Such a grating is able to couple light from a bright part of the sky into a light guide.

![Fig. 3. Angle dependence of total diffraction efficiency as a function of the angle of incidence in air for a slanted surface-relief grating ($\Lambda = 0.95\lambda$, $d = 1.33\lambda$, $\alpha = 22^\circ$). Left: Calculated. Right: measured ($\lambda = 650$ nm).](image)

4. Conclusion

In conclusion, luminescent solar concentrators have a great potential for harvesting sunlight, if losses can be overcome. We have shown some directions for that. Diffractive solar concentrators are promising as well, especially if much direct sunlight is available.

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6. References