Research Article

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Nanocolloid simulators of luminescent solar concentrator photovoltaic windows

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Abstract: Transparent luminescent solar concentrator (LSC) windows with edge-attached photovoltaic (PV) cells have the potential for improving building efficiency without compromising aesthetics and comfort. Optimization of such windows requires an inexpensive simulator for experimenting with various designs. We report, for the first time to the best of our knowledge, the simulator of a transparent LSC window in the form of a plastic container filled with a colloid of photoluminescent nanoparticles (NPs) in an organic solvent (1-propanol). The exemplary NPs were produced by ball milling of the powder of rare earth (RE)-doped phosphor NaYF₄:Yb³⁺,Er³⁺ synthesized by the wet method. The NPs converted the ultraviolet (UV) solar spectrum into visible/near infrared (NIR) via spectral down-shifting and down-conversion (quantum cutting). With a photoluminescence quantum yield (PLQY) of the phosphor <0.4%, the LSC at a nanocolloid concentration of ~0.1 g solids per 100 mL liquids demonstrated a power conversion efficiency of 0.34% and a power concentration ratio of ~0.022 comparable to the LSCs with RE-doped NPs with 200 times greater PLQY. At the same time, the 3 cm thick LSC window simulator had ~90% transmittance to the sunlight. The content and concentration of the nanocolloid could be easily modified to optimize the LSC window performance without a costly window making process.

Keywords: rare-earth-doped compounds, spectral down-shifting, spectral down-conversion, quantum cutting, solar power, renewable energy, green power, energy-efficient buildings

1 Introduction

Luminescent solar concentrators (LSCs) operate by the principle of collecting solar radiation over a large area, converting it by luminescence, and directing the generated radiation into a relatively small output target particularly for producing photovoltaic (PV) electricity [1]. The idea of using windows as LSCs with edge-attached PV cells for harvesting solar power (Figure 1) and thus improving building efficiency without compromising aesthetics [2] has got traction and continues to be the focus of the research community [3–7]. The usefulness can be broadened beyond buildings to, for instance, cell phones and any other display devices that have a clear surface [8]. The extra weight of such LSC displays would not exceed a few grams. The application to the windows in the aerospace field can be also envisioned, but researchers would have to address issues like ruggedness and cost reduction. The LSC window must either have a thin (from several microns to a few millimeters) spectrum converting layer or embedded centers (atoms, molecules, or nanoparticles (NPs)) that capture solar UV photons with high energy hν₁ and re-emit visible or near-infrared (NIR) photons with less energy hν₂ < hν₁ that match the spectral responsivity of commercial silicon-based PV cells (Figure 1). The window will act as a lightguide directing visible/NIR photons to the edges with the PV cells attached. The PV cells will convert the energy of these
photons into a photoelectric current. The energy of the otherwise wasted UV component of solar radiation will be harvested and converted into electricity, thus improving the energy efficiency of the building. LSC windows must satisfy contradictory requirements, namely, be clear, colorless, and no-glow to provide maximum comfort to the inhabitants, and simultaneously, convert as much UV light into photoelectricity as possible [4]. The key issue of the LSC window development process is to find the proper spectral converting material that meets the requirements. In search of such materials, it will be helpful to use an inexpensive and simple simulation platform for rapid material testing without making actual windows. The purpose of the simulator is to reduce the parameters for the experimentalists so that fewer experiments are needed subsequently. This article describes such a simulator in the form of a transparent rectangular vessel filled with a liquid that carries the spectral converting centers of the material of interest. As an example, the nanoparticles (NPs) of a rare-earth (RE)-doped compound are considered. Such materials have been intensely studied as optical spectrum converters (both up and down) by the authors of this article in the past [9–27]. To the best of the authors’ knowledge, LSC simulators have been implemented computationally using the ray tracing method [28]. The existing experimental LSC prototypes to be mentioned below could not serve as cost-effective simulators due to their irreversible design and rigidity. In the next section, the materials and methods will be described. The sections on the obtained results, their discussion, and conclusions will follow.

2 Materials and methods

2.1 Solar spectrum converting nanocolloids

In this article, RE-doped fluoride NaYF$_4$:Yb$^{3+}$,Er$^{3+}$ [9–27] was chosen as an exemplary solar spectrum converting material to demonstrate the liquid LSC simulator. The selection of fluoride NaYF$_4$ as a host for RE ions is justified by its low phonon energy ($\sim$300 cm$^{-1}$) that makes multi-phonon-assisted nonradiative relaxation of excited ions negligible [29]. The energy level diagram of Er$^{3+}$ and Yb$^{3+}$ ions is presented in Figure 2. The erbium ion gets excited with a solar UV photon and emits down-shifted visible and NIR radiation in the bands at 520, 540, 650, 850, and 980 nm (marked with vertical arrows down). It can also perform energy exchange with the ytterbium ion through two quantum-cutting (down-conversion) mechanisms (marked by slanted dash-dotted arrows down) and cut the energy of the UV solar photon into the energies of two NIR photons emitted by two ytterbium ions.

The phosphor was synthesized using the wet method followed by baking the obtained micro-powder in ambient air and reducing it with ball-milling to obtain the nanopowder [9–27]. In a typical procedure, 2.1 g of NaF (0.05 mol) were dissolved in 60 ml of deionized water. Another solution was prepared by mixing $a \times$16 mL of 0.2 mol/L aqueous solution of YCl$_3$, $b \times$16 mL of 0.2 mol/L solution of YbCl$_3$, $c \times$16 mL ($c = 1 - (a + b)$) of 0.2 mol/L solution of ErCl$_3$, and 20 mL of 0.2 mol/L EDTA aqueous stock solution to form the metal–EDTA complex. All the chemicals were acquired from Sigma-Aldrich. The complex solution was injected into the...
NaF solution quickly, and the mixture was stirred vigorously for 1 h at room temperature. After stirring, the mixture was allowed to stay overnight for the precipitate to settle. The precipitate was collected and washed several times with distilled water and anhydrous ethanol. In the second stage of the process, the precipitate was dried in the open air for 48 h at 60°C to remove traces of water. The resulting powder had the doping rate according to the formula NaY₃F₈: Yb⁺³Er⁺³. Four samples of phosphor powders were made: NaY₀.₉₄F₆ : Yb⁺³Er⁺³ (sample A); NaY₀.₇₈F₆ : Yb⁺³Er⁺³₀₂ (sample B); NaY₀.₆₉F₆ : Yb⁺³Er⁺³₀₁ (sample C); and NaY₀.₆₃F₆ : Yb⁺³Er⁺³₀₃ (sample D). The freshly made crystalline powder had NaYF₄ host in a cubic phase. It was converted into a hexagonal β-phase more suitable for the spectrum conversion function using heat treatment in an open-air furnace in the temperature range of 400–600°C for 1 h. The temperature range and duration of heating were found to be optimal for the crystalline phase change [9–27]. After that, the phosphor powder was reduced to nanopowder by ball-milling in water using a PQ-N04 Planetary Ball Mill from Across International [9–27]. The next step was to extract the NPs from water and dry them before transferring them to an organic solvent. Two approaches were used. In the first method, the water colloid together with zirconia balls was extracted from zirconia cups of the ball mill and sonicated in an ultrasonic bath for 60 min. The water colloid was separated from the balls and allowed to settle for 24 h. The top, unsettled part of the colloid was again collected with a syringe and filtered through a 1μm PTFE filter. The filtered colloid was poured into a Petri dish and dried on a hot plate at ~80°C. After scraping, the dry powder consisted of flakes with 20 times smaller average size than in the case with no oleic acid added – of the order of 50μm (Figure 4).

Adding oleic acid to the water colloid of the ball-milled powder significantly reduced the size of the obtained flakes after drying and scraping. To find out if this affected the size of the resulting crystalline NPs aggregated in the flakes, X-ray diffraction (XRD) spectroscopy was conducted with a Bruker D2 Phaser X-ray diffractometer on three powder samples: the dry powder before ball milling; the ball-milled powder with big flakes (no oleic acid added), and the ball-milled powder with small flakes (oleic acid added). The results are presented in Figure 5. As one can see, the XRD spectra of both ball-milled powders, with oleic acid (spectrum 3) and without oleic acid (spectrum 4), had the same width of diffraction peaks, and the peaks were broader than those of the powder before ball milling (spectrum 2). In all three cases, the peaks and their positions corresponded to the hexagonal β-phase of NaYF₄ (plot 1 in Figure 5). Since the peak broadening is inversely proportional to the size of crystals in the powders [30], it could be assumed that the size of the monocrystalline NPs in both ball-milled powders (with small and big flakes) was approximately the same. Adding oleic acid just prevented assembling the NPs into

![Figure 3: The powder of phosphor sample D after ball milling, washing, drying the water colloid in a Petri dish in the open air and scraping from the bottom of the Petri dish. No oleic acid was added to the colloid before drying. (a) The photograph of the scales of the dry powder taken with iPhone 6 camera; dimensions: 17 mm × 17 mm. (b) The microscope photograph of the scales taken with magnification ×40; dimensions: X = 2,257 μm and Y = 1,674 μm. (c) The microscope photograph of the scales taken with magnification ×100; dimensions: X = 903 μm and Y = 670 μm.]
bigger flakes. This assumption was confirmed when both ball-milled powders were dispersed in 1-propanol. The size distribution of NPs was measured using the dynamic light scattering (DLS) method. The 10 mm fluorometric cuvettes filled with both nanocolloids in 1-propanol were put in a Zetasizer DLS instrument (Malvern Instruments). The measurement results in the form of size distributions (assuming the spherical shape of the NPs) are presented in Figure 6. The size of NPs made from the large-flake powder (described by distribution curve 1 in Figure 6) was determined as 172.6 ± 65.06 nm. The size of the NPs from the small-flake powder (described by distribution curve 2) was 228.0 ± 88.7 nm. Size distributions in both cases overlap, and the difference between average sizes of NPs is less than the spread of the distributions.

### 2.2 Optical properties of the spectral converting phosphor

Diffuse reflectance spectra of the synthesized phosphor micropowders with various concentrations of RE ions (Figure 7) were recorded with a Shimadzu UV-2600-ISR-2600 Plus UV-VIS-NIR spectrophotometer with an integrating sphere (measurable spectral range: 220–1,400 nm). The samples were prepared by compressing the micropowders...
excited by 372 nm UV laser spectral line of an Ar with a spectrometer AvaSpec F4:Yb3 \(^{2F7/2}\) into pellets with a 25-T manual hydraulic press. Following Aarts et al. [31], the absorption peaks in the diffuse reflectance spectra were related to the transitions from the ground states to various optically excited states of \(\text{Er}^{3+}\) and \(\text{Yb}^{3+}\) ions as presented in Figure 7. The strongest peak 6 corresponded to the optical absorbance of the \(\text{Yb}^{3+}\) ion due to the transition \(2\text{F}_{7/2} \rightarrow \text{F}_{5/2}\). The ion was responsible for the down-conversion NIR emission when relaxing back from excited to the ground state. The ratio of the strength of peak 6 to peak 3 (520 nm) of \(\text{Er}^{3+}\) was approximately 1:1, 10:1, and 30:1 in phosphor A (NaY\(_{0.99}\)F\(_{4}\):\(\text{Yb}^{3+}\), \(\text{Er}^{3+}\)), B (NaY\(_{0.78}\)F\(_{4}\):\(\text{Yb}^{3+}\), \(\text{Er}^{3+}\)), and C (NaY\(_{0.69}\)F\(_{4}\):\(\text{Yb}^{3+}\), \(\text{Er}^{3+}\)), respectively. This was roughly proportional to the ratio between the molar concentrations of \(\text{Yb}^{3+}\) to \(\text{Er}^{3+}\) in the samples. This correlated well with findings in ref. [31].

Photoluminescence spectroscopy of phosphor powders was conducted using excitation with a 372 nm UV diode laser LX2-375-70-CSB-PPA from Oxxius and 488 nm spectral line of an Ar-ion laser. The spectra were taken with a spectrometer AvaSpec-ULS4096CL-EVO with integrating sphere AvaSphere-30 from Avantes. Figure 8 presents the spectra of the powder of phosphor NaY\(_{0.83}\) F\(_{4}\):\(\text{Yb}^{3+}\), \(\text{Er}^{3+}\) (sample D), the most efficient among the synthesized ones in terms of photoluminescence. The spectra were adjusted to correspond to the same energy received from both excitation lasers. The peaks corresponded to the same absorption bands as in Figure 7. The new peak 5' corresponded to the band at 850 nm. This band does not exhibit prominent absorption in Figure 7.

Figure 7: Diffuse reflectance spectra of the powder samples of down-conversion LE phosphors. Curve A corresponds to NaY\(_{0.96}\)F\(_{4}\):\(\text{Yb}^{3+}\), \(\text{Er}^{3+}\); B – NaY\(_{0.78}\)F\(_{4}\):\(\text{Yb}^{3+}\), \(\text{Er}^{3+}\); C – NaY\(_{0.69}\)F\(_{4}\):\(\text{Yb}^{3+}\), \(\text{Er}^{3+}\). Absorption peak 1 corresponds to the transition in ion of \(\text{Er}^{3+}\):\(\text{I}_{15/2} \rightarrow \text{I}_{13/2}(380 \text{ nm})\); 2 – \(\text{Er}^{3+}:\text{I}_{11/2} \rightarrow \text{I}_{9/2}(338 \text{ nm})\); 3 – \(\text{Er}^{3+}:\text{I}_{11/2} \rightarrow \text{I}_{9/2}(520 \text{ nm})\); 4 – \(\text{Er}^{3+}:\text{I}_{11/2} \rightarrow \text{I}_{9/2}(540 \text{ nm})\); 5 – \(\text{Er}^{3+}:\text{I}_{11/2} \rightarrow \text{I}_{9/2}(650 \text{ nm})\); 6 – \(\text{Er}^{3+}:\text{I}_{11/2} \rightarrow \text{I}_{9/2}\) and \(\text{Yb}^{3+}:\text{F}_{2} \rightarrow \text{F}_{2}(980-1000 \text{ nm})\). All the spectra are normalized to peak 3: its depth is (–1) in arbitrary units.

Figure 8: Visible and NIR photoluminescence spectrum of the phosphor powder NaY\(_{0.83}\)F\(_{4}\):\(\text{Yb}^{3+}\),\(\text{Er}^{3+}\) excited by 372 nm UV laser (black curve) and by 488 nm line of an Ar-ion laser (blue). The peaks correspond to the absorption bands with the same numbers as in Figure 7. The new peak 5' corresponds to the band at 850 nm. This band does not exhibit prominent absorption in Figure 7.

Visible and NIR photoluminescence spectrum of the phosphor powder NaY\(_{0.83}\)F\(_{4}\):\(\text{Yb}^{3+}\),\(\text{Er}^{3+}\) excited by 372 nm UV laser (black curve) and by 488 nm line of an Ar-ion laser (blue). The peaks correspond to the absorption bands with the same numbers as in Figure 7. The new peak 5' corresponds to the band at 850 nm. This band does not exhibit prominent absorption in Figure 7.
fluorescent in the visible spectrum and thus uncomfortable for building residents. Therefore, it still makes sense to investigate RE-doped compounds with low PLQY in LSC simulators. The final judgment on the suitability of a particular material could be made based on the overall LSC performance.

2.3 LSC simulator

To simulate LSCs, a rectangular Plexiglass container was filled with the RE phosphor nanocolloid in 1-propanol as shown in Figure 9. This solvent has a low evaporation rate and low absorption in UV-VIS-NIR. The concentration of the nanocolloid was 0.193 g solids per 100 mL liquids. The container had dimensions 65 mm × 65 mm × 42 mm (2.9/16 × 2.9/16-1 × 15/16 inch). Four AOSHIKE polycrystalline silicon PV cells (5-voltage; current, 30-mA current; dimensions, 53 mm × 30 mm) were attached to the container sides. The PV cells were connected in parallel. The container was filled to the level of the PV cells. Figure 9b shows the near-UV (488 nm) laser beam passing through the nanocolloid in the container without the attached PV cells. In Figure 9c, the beam is visible through a red filter (laser protective goggles) thus proving that the nanocolloid converted the near-UV light into visible re-emitted by the phosphor NPs.

2.4 Experimental setup

Figure 10 shows the block diagram of the experimental setup to investigate the spectrum emitted by the nanocolloid in the LSC toward the edge-attached PV cells. Solar simulator LCS-100 model 94011A from MKS-Newport with Xe-lamp and Air Mass (AM) 1.5G filter was used as a light source. The shutter of the simulator was controlled with a shutter controller 71445 from MKS-Newport. The simulator produced an evenly illuminated square spot on LSC surface with dimensions ∼65 mm × 65 mm. A

| Band number | Wavelength (nm) | Phosphor NaY0.83F4:Yb3+,Er3+ in this article | PLQY (%) |
|-------------|-----------------|-----------------------------------------------|----------|
|             |                 | Excited with a 488 nm laser | Excited with a 372 nm laser | Thorlabs IR card VRC4 [34] | Gd2O3:Bi3+,Yb3+ [32] | CsPbBr3:Yb3+shell of SiO2 [35] | CsPb (Cl1−xBrx)3:Yb3+ [36] |
| 3           | 520             | 0.046                                    | 0.007 | 0.27                             | 0.028                        | 0.14                             | 8.7                              | 64                             | 190                             |
| 4           | 540             | 0.018                                    | 0.032 | 0.0375                           | 0.004                        | 0.015                            |                                  |                                 |                                 |
| 5           | 650             | 0.018                                    | 0.032 | 0.0375                           | 0.004                        | 0.015                            |                                  |                                 |                                 |
| 5’          | 850             | 0.018                                    | 0.032 | 0.0375                           | 0.004                        | 0.015                            |                                  |                                 |                                 |
| 6           | 980–1000        | 0.018                                    | 0.032 | 0.0375                           | 0.004                        | 0.015                            |                                  |                                 |                                 |

Table 1: PLQY of the synthesized phosphor in comparison with other materials

![Figure 9](image-url): (a) LSC simulator filled with the nanocolloid of phosphor NaY0.83F4:Yb3+,Er3+ in 1-propanol. (b) Side view of the 488 nm beam from an Ar-ion laser passing through the nanocolloid (from right to left) in the container of the LSC with the PV cells removed. (c) The same but taken through a red filter (laser protective goggles).

![Figure 10](image-url): Block diagram of the experimental setup to investigate the spectrum scattered by the LSC to the edge-attached PV cells.
A multimode optical fiber terminated with focusing optics was mounted near the edge of the LSC without PV cells attached. The other end of the fiber was connected to the spectrometer AvaSpec-ULS4096CL-EVO.

3 Results and discussion

3.1 Solar spectrum conversion in the LSC nanocolloid

Figure 12 presents the spectra of the light emanating from the edges of the LSC illuminated by the solar simulator and the light bulb. Spectra 1 are of the radiation directly from the light sources at grazing incidence with respect to the walls of the empty LSC container. Spectra 2 are of the radiation from the LSC filled with pure 1-propanol.
Spectra 3 were produced by the LSC filled with the photoluminescent nanocolloid. One can see that spectra 2 are lower than spectra 1. This was due to the total internal reflection of the light on the interface between the side walls of the filled LSC container and the air gap between the wall and the PV cell. The gap was not filled with an index matching substance to minimize the total internal reflection. But spectrum 3 is higher than spectra 1 and 2 approximately 18 and 43 times, respectively, in the case of the solar simulator (Figure 12a). In the case of the light bulb, spectrum 3 is higher than spectra 1 and 2 roughly 3 and 8 times, respectively (Figure 12b). The results indicate that the nanocolloid scattered a significant portion of the incident light toward the edges. This can be also seen in the photographs in Figure 9b and c. The scattering is strong for the light, which has a wavelength \( \lambda < \pi d \), where \( d \) is the average size of NPs, and beyond that limit rapidly falls to zero [38]. Since \( d = 228 \text{ nm} \) (Figure 6), the light was scattered when \( \lambda < 717 \text{ nm} \), on the left edge of the responsivity spectrum of the PV cell (spectrum 4 in Figure 12). To compare the shapes of the spectra in Figure 12 regardless of the intensity, they were normalized as shown in Figure 13. The spectrum of the radiation scattered by the nanocolloid towards the edges when the LSC was illuminated with the solar simulator (spectrum 3, Figure 13a) has less degradation of its long-wavelength part than in the case of the light bulb (spectrum 3, Figure 13b). The latter spectrum has its “red” portion diminished by half. This occurred because the light bulb spectrum was more concentrated in the region beyond 715 nm and thus less subject to the scattering towards the edges. The conversion of the UV solar spectrum into additional visible and NIR light by NPs could also contribute to spectrum 3 of the LSC illuminated with the solar simulator (Figure 13a). This light (of red color) can be seen in the photograph in Figure 9c.

### 3.2 I–V characteristics of LSC PV cells

The I–V characteristics of the PV cells attached to the LSC edges (will be called below as I–V characteristics of the LSC) were measured to evaluate the PV performance. The measurements were conducted using the LabVIEW software for I–V Test Station PVIV-1A from MKS-Newport [39, p. 14]. The error of the measurements was of the order of 0.1%. The results are presented in Figures 14, 15, and Table 2. The data on the generated PV power in Table 2 were computed as areas under the I–V curves [40] using the same LabVIEW program. Figure 14a shows the I–V characteristics of the LSC illuminated with the solar simulator. One can see that filling LSC with pure 1-propanol caused a significant drop of the photocurrent (curve 2) as compared to the empty LSC (curve 1). The PV power generated by the LSC decreased by 89.7% (Table 2, data row 2, column 3). This was due to the total internal reflection on the interface between the side walls of the filled LSC container and the air gap described in the previous subsection.

Filling LSC with the nanocolloid significantly increases the

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**Figure 13:** Normalized spectra of the photoluminescence at the edges of the LSC simulator. (a) LSC was illuminated with the solar simulator; (b) with the light bulb. Spectra 1 correspond to empty LSC (true spectra of the light sources), 2 – LSC filled with pure 1-propanol, 3 – LSC filled with the NaY_{0.85}F_{2}Yb_{0.12}Er_{0.03} nanocolloid in 1-propanol, 4 – normalized responsivity of the PV cells. In (a) the spectra were normalized to the intensity of the peak at 398.3 nm. In (b) the spectra were normalized to the intensity of the peak at 565.8 nm.
photocurrent (curve 3), and the PV power jumped up by 99.2% (Table 2, row 2, column 5) relative to the empty LSC. The results correlate with the relationship between the intensity of the spectra in Figure 12a. They can be explained by strong scattering of the “blue” portion (with $\lambda < 715$ nm) of the incident solar light toward the edges and by the conversion of solar UV to visible and NIR radiation that matched the spectral response (spectrum 4 in Figures 12 and 13) of the edge-attached PV cells (Figure 1). Figure 14b shows the $I$–$V$ characteristics of the LSC illuminated with the light bulb. Filling LSC with pure 1-propanol again caused the drop of the photocurrent (curve 2) as compared to empty LSC (curve 1) due to the total internal reflection. The PV power decreased by 85.1% (Table 2, data row 6, column 3). Filling LSC with the nanocolloid just slightly increased the photocurrent (curve 3) due to the scattering of some visible/NIR light toward the edges. But the power remained less than that of the empty LSC by 63.0% (Table 2, row 6, column 5). Despite spectrum 3 being generally higher than spectrum 1 in Figure 12b, its “red” portion (near the maximum of spectrum 4 of the PV cell responsivity) was relatively low (as Figure 13b also shows).

Figure 14: $I$–$V$ characteristics of the LSC simulator. (a) LSC was illuminated with the solar simulator at 1.0 Sun. $I$–$V$ characteristic 1 corresponds to the empty LSC; 2 – LSC filled with pure 1-propanol, 3 – LSC filled with the NaY$_{0.83}$F$_4$:Yb$_{0.14}$Er$_{0.03}$ nanocolloid in 1-propanol. (b) LSC was illuminated with the 40 W light bulb. $I$–$V$ characteristic 1 corresponds to empty LSC; 2 – LSC filled with pure 1-propanol, 3 – LSC filled with the nanocolloid.

Figure 15: $I$–$V$ characteristics of the PV set placed under the LSC and measuring the light passing through it. (a) LSC was illuminated with the solar simulator at 1.0 Sun. $I$–$V$ characteristic 1 corresponds to the empty LSC; 2 – LSC filled with pure 1-propanol, 3 – LSC filled with the NaY$_{0.83}$F$_4$:Yb$_{0.14}$Er$_{0.03}$ nanocolloid in 1-propanol. (b) LSC was illuminated with the 40 W light bulb. $I$–$V$ characteristic 1 corresponds to empty LSC; 2 – LSC filled with pure 1-propanol, 3 – LSC filled with the nanocolloid.
due to the scattering effects described in the previous subsection. There was also no UV radiation in the spectrum of the light bulb that the NPs might convert to extra visible/NIR. The nanocolloid-filled LSC illuminated with the light bulb thus produced less PV power than the empty LSC.

Figure 15a presents the $I$–$V$ characteristics of the PV set (six masked PV cells) placed under the LSC illuminated with the solar simulator. Filling LSC with pure 1-propanol caused the drop of the photocurrent (curve 2) as compared to the empty LSC (curve 1). The PV power dropped by 12.8% (Table 2, data row 4, column 3), and was probably due to the internal reflection of the light on the interface between the bottom of the LSC filled with propanol and the air gap between the LSC and the PV set under it. This power drop and, correspondingly, the loss of light was seven times less than in the LSC itself (89.7%, Table 2, row 2, column 3). Filling LSC with the nanocolloid slightly increased the photocurrent (curve 3) compared to the case of the LSC filled with pure 1-propanol (curve 2). But the photocurrent was still below the level corresponding to the empty LSC (curve 1). The power was still 10.6% less than in the case of empty LSC (Table 2, row 4, column 5). Apparently, the nanocolloid reduced the losses of the light passing through the LSC more likely due to scattering and conversion of the UV solar spectrum into additional visible and NIR radiation suitable for the PV. Figure 15b shows the $I$–$V$ characteristics of the PV set under the LSC illuminated with the light bulb. Filling LSC with pure 1-propanol again caused the drop of the photocurrent (curve 2) as compared to empty LSC (curve 1) due to the total internal reflection. The power decreased by 10.3% (Table 2, data row 8, column 3). Filling LSC with the nanocolloid reduced the photocurrent even more (curve 3), and the power was dropped by 12.8% as compared to empty LSC (Table 2, data row 8, column 5). This could be due to additional scattering of the light passing through the nanocolloid (with the spectrum modification described in the previous subsection) with no UV radiation converted to visible and NIR.

The last column of Table 2 summarizes the power measurement results. In the case of the solar simulator, the nanocolloid improved the PV power generated by the LSC by 1825.3% as compared to the LSC filled with pure 1-propanol. As measures of significant improvement 99.2 and 1825% are highlighted with bold in Table 2. At the same time, the nanocolloid brought the increase of the power measured by the bottom PV set by 3.2%. For the incandescent light bulb as an illuminator, the nanocolloid improved the power as compared to the LSC filled with pure propanol by 155.0%. But the bottom PV set showed a drop of power by 1.8%.

Based on the data in Table 2, the power conversion efficiency and related parameters of the LSC were estimated. The power conversion efficiency $\eta_{PCE}$ was defined as the ratio of the output power generated by the edge-attached PV cells of the LSC $P_{out}$ (14.44 mW, Table 2, data row 2, column 4) to the incident, input power $P_{in}$: $\eta_{PCE} = (P_{out}/P_{in}) \times 100\%$ [41]. For the solar simulator at 1.0 Sun (100 mW/cm$^2$ power density) and an illuminated spot size of 65 mm × 65 mm, the incident power was 100 mW/cm$^2 \times 6.5 \times 6.5 = 4225$ mW. The power conversion efficiency was thus

$$\eta_{PCE} = (14.44 \text{ mW}/4.225 \text{ mW}) \times 100\% = 0.34\%.$$  

The power concentration ratio $C$ (also called “flux gain” in ref. [42]) was defined as the ratio between the incoming and outgoing power density (radiance) [41]

$$C = G \frac{P_{out}}{(P_{in} \eta_{PV})} = G \frac{\eta_{PCE}}{\eta_{PV}},$$

where $G$ was the geometric gain of the LSC defined as the ratio of the LSC area and the area of the attached PV cells; $\eta_{PV}$ was the power conversion efficiency of the PV cells defined as the ratio between the electric power generated by the cell and the power of the incident light. The geometric gain $G$ of the LSC simulator was $G = \frac{42.25 \text{ cm}^2}{63.6 \text{ cm}^2} = 0.66$. The power conversion efficiency of the AOSHIKE silicon cells (for solar light) was measured to be -10%. Correspondingly, the power concentration ratio was estimated as $C = 0.022$. The power conversion efficiency of the presented LSC ($\eta_{PCE} = 0.34\%$) was 4.2 times less than that of the LSC reported in ref. [41] ($\eta_{PCE} = 1.44\%$), where the authors used microparticles (11 µm average size) of RE-doped phosphorescent compound CaAlSiN$_3$:Eu$^{3+}$ with two orders of magnitude higher PLQY (83%). The power concentration ratio ($C = 0.022$) was -56 times less than that of the LSC in ref. [41] ($C = 1.23$). It should be also considered that the concentration of the NPs in the presented LSC simulator (~0.1 g solids per 100 mL of the host) was six times less than the concentration of phosphor microparticles in ref. [41] (0.6 g per 100 mL of polymethyl(methacrylate) or PMMA host).

Because of the small size of the NPs (228 nm instead of 11 µm) and their low concentration, the 30 µm thick LSC simulator performed well as a transparent window transmitting -90% of sunlight (10.6% drop of passing light power – see Table 2, row 4, column 5) while 0.5 cm thick LSC in ref. [41] blocked almost all the incident sunlight (Figures 2 and 3 in ref. [41]).

The power conversion efficiency and power concentration ratio were also estimated in the case of the light bulb with no UV light in the spectrum. The total input
Power coming to the LSC from the light bulb was estimated as 
\[ P_{\text{in}}^{(\text{Light bulb})} = 29.36 \text{ mW}. \]

The output power from the LSC was \( P_{\text{out}}^{(\text{Light bulb})} = 0.255 \text{ mW} \) (Table 2, row 6, column 4).

The power conversion efficiency was estimated as 
\[ \eta_{\text{PCE}}^{(\text{Light bulb})} = \left( \frac{P_{\text{out}}^{(\text{Light bulb})}}{P_{\text{in}}^{(\text{Light bulb})}} \right) \times 100\% = 0.87\%. \]

The ratio \( C^{(\text{Light bulb})} \) was estimated as 
\[ C^{(\text{Light bulb})} = G \frac{\eta_{\text{PCE}}^{(\text{Light bulb})}}{\eta_{\text{PV}}} = 0.057. \]

Both performance parameters are 2.56 times greater than those of the nanocolloid LSC with the solar simulator. This was due to a better match between the light bulb emission spectrum and the responsivity spectrum of the PV cells (spectrum 4 in Figures 12 and 13).

### 4 Conclusion

The power of UV radiation is \(~8\) and \(~6\)% of the total power of sunlight outside the atmosphere and on the sea level, respectively [43]. The latter percentage is the upper limit for the power to be extracted from the sunlight by a transparent LSC window converting solar UV spectrum down to visible/NIR. The share of the output radiation power at the edges of the LSC simulator to the incident sunlight power can be estimated as 
\[ \left[ \frac{P_{\text{out}}}{P_{\text{in}}} \right] \times 100\% = \left( \frac{C}{G} \right) \times 100\% = \left( \frac{0.022}{0.66} \right) \times 100\% = 3.3\%. \]

This value is more than half of the maximum share that can be extracted from UV sunlight by converting it down to visible/NIR. Considering low PLQY of the photoluminescent phosphor, most of the visible/NIR light came to the edges due to selective (for wavelengths < 715 nm) scattering on the NPs, but not due to down-shifting or down-conversion (quantum cutting).

A clear plastic container filled with a nanocolloid converting solar UV spectrum into visible/NIR radiation can work as a flexible experimental simulator of transparent LSC windows. Various types of spectrum converting NPs and PV cells can be investigated with it in the lab environment. Two “clever” solutions were made during the feasibility study of the simulator. The first was the selection of 1-propanol as a solvent. It is polar and easily disperses NPs; it has a low evaporation rate and stays longer in the open container; it etches insignificantly the walls of the Plexiglass container; and it has weak optical absorption in the range from UV to NIR. The second clever solution was the selection of an incandescent light bulb with no significant UV spectrum as a reference light source for sunlight (simulated by a Xe-lamp with AM 1.5G filter). Using the light bulb led to a surprise

| Power improvement of LSC filled with nanocolloids relative to the LSC filled with pure 1-propanol | Power improvement relative to the empty LSC |
|---|---|
| % | % |
| Solar simulator, empty LSC | 7.25 | 99.2 |
| Solar simulator, filled LSC | 7.25 | 36.3 |
| Solar simulator, filled LSC under empty LSC | 0.36 | -10.6 |
| Solar simulator, filled LSC under filled LSC | 0.36 | -10.6 |
| Light bulb, empty LSC | 0.10 | -93.0 |
| Light bulb, filled LSC | 0.064 | -12.8 |
| Light bulb, filled LSC under empty LSC | 0.057 | -10.3 |
| Light bulb, filled LSC under filled LSC | 0.057 | -10.3 |
result that the proposed LSC simulator could be used to investigate visible sunlight reaching the edges due to scattering on the NPs separately from visible/NIR radiation re-emitted by NPs due to the sunlight spectrum down-shifting and down-conversion. At a nanocolloid concentration of ~0.1 g solids per 100 mL liquids, the 3 cm thick LSC simulator had a power conversion efficiency of 0.34% and a power conversion ratio of 0.022 while transmitting ~90% of sunlight. The results point to the feasibility of massive use of transparent LSC windows where the energy of the otherwise wasted (such as UV) light can be harvested while the visible light is comfortably transmitted and utilized by humans.

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