RENEWABLE ENERGY

Better luminescent solar panels in prospect

Devices known as luminescent solar concentrators could find use as renewable-energy generators, but have so far been plagued by a major light-reabsorption effect. A new study offers a promising route to tackling this problem.

MICHAEL DEBIJE

"Any customer can have a car painted any colour that he wants so long as it is black." American industrialist Henry Ford was referring to his Model T cars, but this sentiment also applies to conventional solar (photovoltaic) panels, for which colour has proved an obstacle to their integration in cities and other populated areas where appearance is a factor to consider. Writing in *Nano Letters*, Bradshaw *et al.*[1] provide an enticing glimpse into the potential of a revolutionary renewable-energy generator — the luminescent solar concentrator (LSC) — for use in the built environment (Fig. 1).

The LSC was first suggested more than 35 years ago[2]. It is a simple device. It usually consists of a polymeric light guide that is either filled with luminescent molecules such as organic dyes and inorganic semiconducting nanocrystals (quantum dots) or topped by a thin layer containing these. Such luminophores absorb incident solar radiation and re-emit it at a longer wavelength; a fraction of the re-emitted radiation is trapped in the light guide by total internal reflection. In this way, the trapped light is directed towards the light guide's thin edges, where it exits the device (Fig. 2). The exiting light can be collected by attaching thin strips of photovoltaic cells that convert the light into electrical current[3].

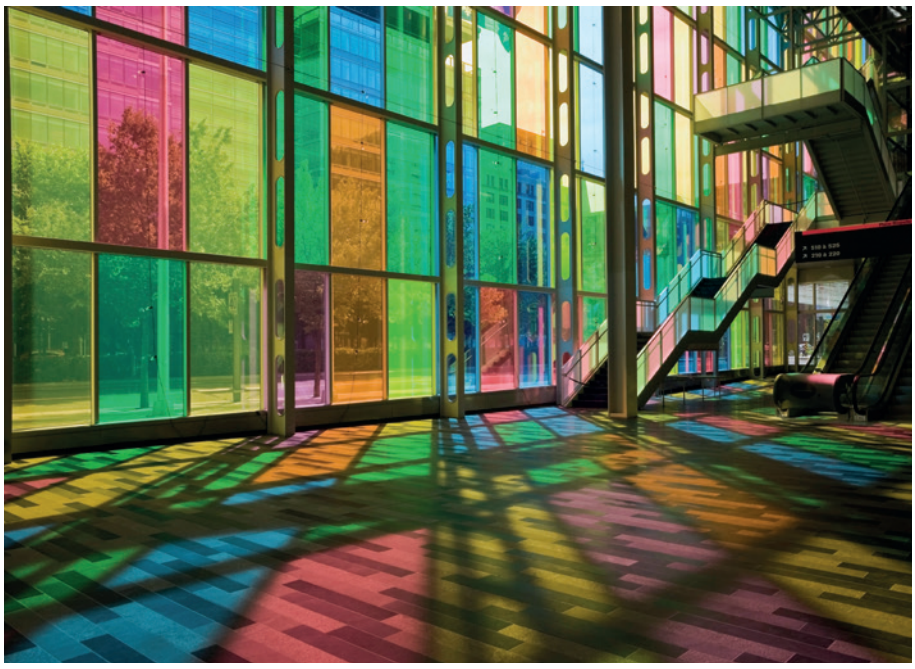
Owing to their bright colours, flexibility of both shape and form, and their lightweight nature, LSC panels could find applications in urban settings where the installation of conventional photovoltaic panels would be inappropriate — whether because of the presence of predominantly indirect sunlight or the risk of damage or for aesthetic reasons. An LSC panel will not generate the same electrical output as a conventional photovoltaic panel with the same surface area, but its potential as a structural building element (Fig. 1) and its adaptability to huge-area architectures make it an attractive option for turning common objects such as sound barriers, bicycle sheds, park benches and bus stops into electricity generators.

LSC panels have not yet come onto the market because of their modest light-to-electricity conversion efficiencies — a result of several light-loss mechanisms in the devices. These include restricted absorption ranges, losses from dye-emitted light directed outside the angles required for total internal reflection and absorption of light by the polymer that makes up the light guide. But the crucial loss mechanism that must be addressed is reabsorption of the dye-emitted light.

Most LSCs use organic fluorescent dyes as the absorbing and emitting species. There are many advantages to organic dyes: they are efficient light absorbers; they can have fluorescence yields approaching 100%; and they are generally soluble in the polymeric light-guide host. However, the Stokes shift of these dyes — that is, the separation of their absorption and emission peak wavelengths — is often small, yielding a significant overlap of the absorption and emission profiles. This causes reabsorption of dye-emitted light when it encounters subsequent dye molecules in the light guide. The reabsorption results in light loss from the device, either because the reabsorbing dye has a fluorescence yield of less than 100% or because the re-emitted light cannot be totally internally reflected and so is lost through the top or bottom surfaces of the light guide.

Inorganic quantum dots have long been studied as possible alternatives to organic dyes. For example, inorganic particles made up of a cadmium selenide (CdSe) core and a cadmium sulfide (CdS) outer shell have been developed for LSCs that have large Stokes shifts and so low reabsorption losses[4]. In their study, Bradshaw *et al.* describe a promising route to further minimizing losses by using zinc selenide/zinc sulfide (ZnSe/ZnS) core/shell nanocrystals 'doped' with ions of manganese (Mn^{2+}) and cadmium (Cd^{2+}) as the luminescent species. The researchers have produced $Zn_{0.87}Cd_{0.11}Mn_{0.02}Se/ZnS$ nanocrystals with fluorescence yields approaching 90%, and with minimal spectral overlap between emission and absorption.

The work demonstrates the importance of considering the 'tails' of luminophores' absorption spectra. These seem to be insignificant when measured through the thin width (about a centimetre) of the light guide, but become significant when measured through its length of many tens of centimetres: the tails can lead to a substantial reduction of the light that reaches the photovoltaic cell at the light guide's edge, restricting the overall efficiency of the device. Minimal absorption and emission spectral overlaps would reduce losses of light-guided emission to scattering and absorption by the polymer host itself, dramatically extending the possible operational size of the LSC. So, although LSCs based on



PERRY MASTROVITO/ALL CANADA PHOTOS/ALAMY

Figure 1 | A potential application of the luminescent solar concentrator. Coloured plastics and coloured glass panels such as those used in the striking facade of the Palais des Congrès in Montreal, Canada (pictured), could be turned into attractive electricity generators if modified to function as efficient luminescent solar concentrators.

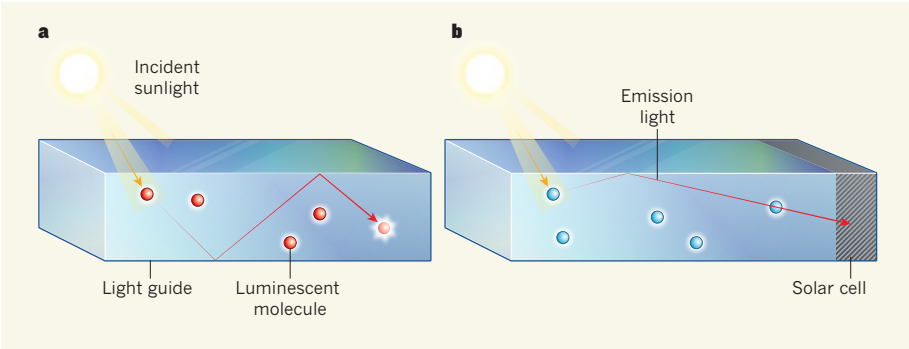


Figure 2 | The working principle of the luminescent solar concentrator. **a**, Incident sunlight (orange arrow) enters a polymer light guide and is absorbed by luminescent molecules. Light losses from reabsorption of emitted light (red arrow) are a consequence of using luminescent molecules that have overlapping absorption and emission spectra. **b**, Bradshaw *et al.*[1] describe luminescent nanocrystals (blue circles) that exhibit practically no overlap in their absorption and emission spectral profiles, and thus, no reabsorption. This results in more light being directed towards the light guide's small solar cell, which converts the exiting light into electrical current.

Cd^{2+}/Mn^{2+}-doped ZnSe/ZnS nanocrystals absorb less of the incident solar spectrum than CdSe/CdS nanocrystals, they could outperform the latter in long light guides.

The fluorescence yield has often been considered the defining factor for LSC dye selection. However, Bradshaw *et al.* introduce and analyse CdSe nanocrystals doped with copper ions ($Cd_{0.999}Cu_{0.001}Se$) which, despite having a fluorescence yield of less than 40%, exhibit broad absorption of incident light and large Stokes shifts that exceed the current leading luminophores in LSCs. Their result suggests that broad-spectrum incident-light absorption and large Stokes shifts are more important than fluorescence yields for obtaining high-output emission in metre-scale LSCs.

If these nanocrystal materials, measured by Bradshaw *et al.* in solution, can be produced in bulk quantities and incorporated uniformly into solid polymeric light guides, and have long-term stability in sunlight, a major step forward in LSC performance may soon be realized. And once polymer sheets are available that contain such luminophores with good absorption in the peak of the solar spectrum, it will be possible to tackle the second major loss mechanism of LSCs, which is emission through the top and bottom surfaces of the light guide. This can be overcome by applying selective reflectors to the LSC surface[5]. Successful outcomes on all these fronts could increase the efficiencies of LSCs to levels that would enable their use in large-area urban settings. ■

Michael Debije *is in the Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, 5600 MB Eindhoven, the Netherlands.*
e-mail: m.g.debije@tue.nl

1. Bradshaw, L. R., Knowles, K. E., McDowall, S. & Gamelin, D. R. *Nano Lett.* **15,** 1315–1323 (2015).
2. Weber, W. H. & Lambe, J. *Appl. Optics* **15,** 2299–2300 (1976).
3. Debije, M. G. & Verbunt, P. P. C. *Adv. Energy Mater.* **2,** 12–35 (2012).
4. Meinardi, F. *et al. Nature Photon.* **8,** 392–399 (2014).
5. Debije, M. G. *et al. Appl. Optics* **49,** 745–751 (2010).

NEUROSCIENCE

Spotlight on deep-brain stimulation

Taking inspiration from a modern technological advance, a classic technique — low-frequency electrical stimulation of a deep-brain region — has been refined to combat cocaine addiction in experiments in mice.

ALIM LOUIS BENABID

Electrical stimulation of deep-brain regions is used to treat a range of human disorders, from Parkinson's disease to obsessive-compulsive disorder. But despite the fact that this technology is almost 30 years old, the mechanism by which it works is still unknown, making improvements difficult. By contrast, optogenetics, in which light-responsive proteins are engineered to regulate gene expression in target cells, is a more recent, well-understood technology, but cannot currently be used in humans. In a paper published in *Science*, Creed *et al.*[1] take inspiration from optogenetics to forge a fresh approach to treating cocaine addiction in mice, using a refined version of deep-brain stimulation (DBS). The results of the study suggest that the cellular mechanisms by which DBS modulates neural networks could be better understood, and that knowledge from optogenetics might inspire ways of improving DBS.

DBS induces different effects depending on the frequency of the stimulation. Low-frequency stimulation (LFS) typically causes neuronal excitation, through well-understood mechanisms that follow the classical principles of neurophysiology. But high-frequency stimulation (HFS), which is a powerful and flexible surgical tool, does not seem to follow these standard rules. HFS mimics the effects of lesioning techniques, in which cells are destroyed or removed from the brain, indicating that HFS is not excitatory. Indeed, HFS seems to inhibit neuronal impulses overall, but, paradoxically, the termini (axons and fibres) of some neurons seem to be excited by HFS (ref. 2). There is no clear explanation for this contradictory effect, although observations in both experimental and human situations suggest that there are several underlying mechanisms at work[3,4].

In addition to its poorly understood mechanism, DBS lacks spatial specificity, regardless of the frequency. DBS-induced electrical pulses provoke changes in electrical fields that spread unevenly in all directions, depending on spatial differences in tissue conductivity. Furthermore, differences in the neuronal make-up of a tissue can affect excitability, and so DBS can modulate different functions in tissues that have different neuronal compositions[5]. In short, it is hard to predict exactly what effects DBS will have.

By contrast, the beauty of optogenetics lies in the ability to precisely plan an experimental set-up. The type of light-sensitive protein used to engineer the cells tells us which neurons will be stimulated — and in response to which specific wavelength of light[6]. Furthermore, we can exercise a high level of spatial and functional control by restricting the diffusion of the light to small subsets of cells. We understand what we are doing, and where.

Using optogenetics to inspire DBS strategies might provide a way of gleaning a better understanding of the mechanisms underlying DBS[7]. For instance, applying the knowledge gained from optogenetics to identify drugs that could be combined with DBS to modulate neuronal activity might produce effects that are different from those obtained using DBS alone. This approach would, in effect,