Emissive Molecular Aggregates and Energy Migration in Luminescent Solar Concentrators

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CONSPECTUS

Luminescent solar concentrators (LSCs) are light harvesting devices that are ideally suited to light collection in the urban environment where direct sunlight is often not available. LSCs consist of highly luminescent compounds embedded or coated on a transparent substrate that absorb solar radiation over a large area. The resulting luminescence is waveguided to the thin edges of the substrate where the concentrated light can be used to improve the performance of photovoltaic devices. The concept of LSCs has been around for many years and yet the efficiencies of current devices are still below expectations for commercial viability. There are two primary challenges when designing new dyes for LSC applications. Reabsorption of dye emission by chromophores within the waveguide is a significant loss mechanism attenuating the light output of LSCs. Concentration quenching, particularly in organic dye systems, restricts the

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quantity of chromophores that can be incorporated in the waveguide thus limiting the light absorbed by the LSC.

Over the past few years, research in our group has targeted novel dye structures that address these primary challenges. There is a common perception that dye aggregates are to be avoided in LSCs. It became apparent in our studies that aggregates of chromophores exhibiting aggregation-induced emission (AIE) behavior are attractive candidates for LSC applications. Strategic use of AIE chromophores have led to the development of the first organic-based transparent solar concentrator that harvests UV light as well as the demonstration of reabsorption reduction by taking advantage of energy migration processes between chromophores. Further developments led us to the application of perylene diimides using an energy migration/energy transfer approach. To prevent concentration quenching, a molecularly insulated perylene diimide with bulky substituents attached to the imide positions was designed and synthesized. By combining the insulated perylene diimide with a commercial perylene dye as an energy donor-acceptor emitter pair, detrimental luminescence reabsorption was reduced while achieving a high concentration of the chromophores for light absorption. This account reviews and re-inspects some of our recent work and the improvements in the field of LSCs.

Introduction

A luminescent solar concentrator (LSC) is a non-imaging planar type of light concentrator, which consists of a monolithic waveguide (either glass or a polymer such as poly(methyl methacrylate), PMMA) that can harvest light and reduce the required area of expensive solar cells. An LSC relies on three important processes to concentrate light: absorption, luminescence, and trapping. Luminescent chromophores embedded in the waveguide absorb and emit light inside the waveguide. Most of the emitted light is trapped by total internal

reflection and concentrated to small area solar cells attached to the edges of an LSC (Figure 1). A key advantage of a LSC lies in its configuration wherein the concentrator and charge generation components are separated which allows for separate optimization of the light harvesting and energy conversion. Heating of solar cells is also mitigated since the absorption of the chromophores can be designed to collect only the visible to the near-infrared parts of the solar spectrum in contrast to geometric concentrators.[1]

The key to achieving concentration in a LSC is that the concentrator size must far exceed the solar cell size. For example, consider a LSC plate with an area facing the sunlight A_{face} that has a solar cell on the edge with an area A_{edge}: the geometric gain, G, of the LSC is then defined as the ratio A_{face}/A_{edge}. In the absence of any losses in the three main processes in a LSC, the light flux that impinges on the edge solar cells would be proportional to G and significantly higher compared to direct illumination. There are two common embodiments for LSCs shown in Figure 1a. Bulk-doped LSCs or homogenous LSCs are the earliest forms in the literature wherein the luminescent chromophores are homogenously dispersed in the polymer sheet. These devices are prepared by adding the luminescent chromophores during *in-situ* polymerization or hot extrusion – both being routinely used in the polymer industry. Thin-film LSCs are prepared by casting a thin polymer film containing luminescent chromophores on the surface of an index-matched waveguide (typically glass). However, it should be noted that a higher chromophore concentration is necessary (in order to absorb the same amount of light as a more dilute thick film) for thin-film LSCs, which will inevitably lead to concentration quenching. This leads to a compromise between light absorption and quantum yield.

The resurgence of LSC research has been initiated by interest in achieving net zero energy buildings using building-integrated photovoltaics (BIPV) where the LSC has a clear cut

advantage in aesthetic flexibility and potential for large-area photovoltaic devices over existing thin-film module strategies.[2] The highest reported efficiency for a LSC device is 7.1% reported by Slooff and co-workers in 2008 with 4 GaAs cells on the edges of a 5 cm × 5 cm LSC and a rear diffuse reflector.[3] They also showed that the short-circuit current is similar regardless of what solar cell is used on the edge of the LSC while the achievable performance mainly depends on the open-circuit voltage (V_{oc}) of each cell. Their results imply that comparison of LSCs can be difficult by just relying on power conversion efficiency (PCE) values for each LSC. The emergence of luminescent materials other than laser dyes, such as semiconductor nanocrystals,[4-6] inorganic phosphors,[7] and conjugated polymers,[8] has renewed the interest in LSCs.

a Operation schematic of a luminescent solar concentrator (LSC)
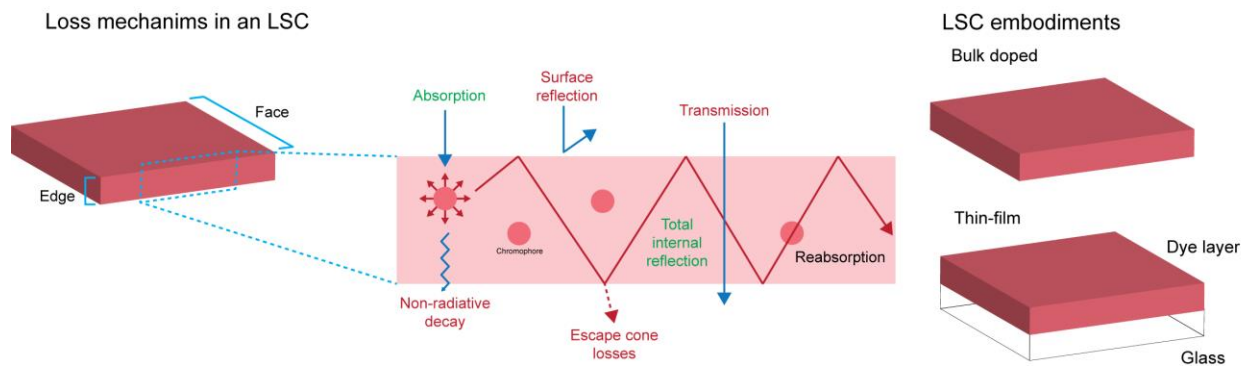
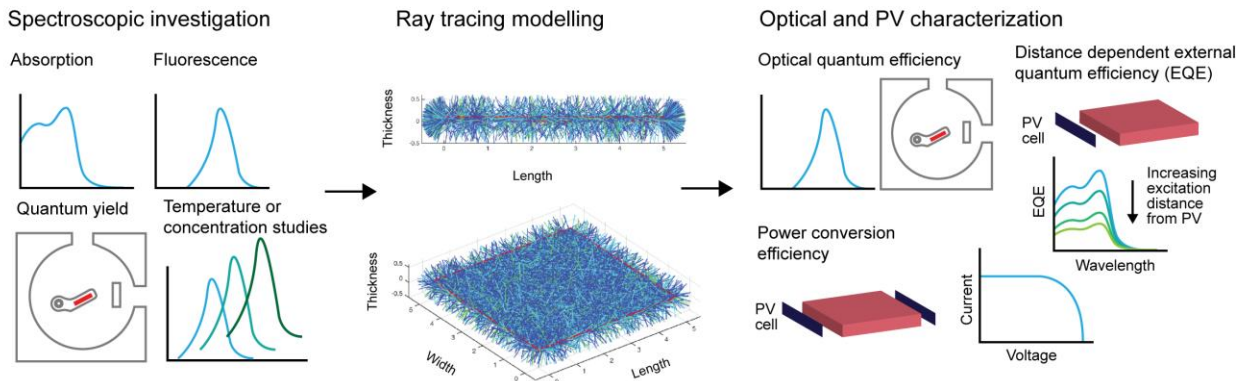**b** Characterization of chromophores for luminescent solar concentrators

Figure 1. Luminescent solar concentrators. (a) Schematic of the typical operation of an LSC. There are various mechanisms by which incident light can be lost: surface reflection, transmission, non-radiative decay, and escape cone losses (in red). Reabsorption is not the loss mechanism itself. Rather, it is the events that will occur after reabsorption – non-radiative decay or emission into an escape cone – that leads to reabsorption losses. Our LSC characterization workflow is depicted in (b). The photophysical properties of the organic chromophores are measured carefully both in solution and in the polymer matrix, which is typically poly(methyl methacrylate, PMMA). The measured photophysical quantities are used as inputs in ray tracing modelling as an intermediate screening procedure. The output of the model is then verified using various methods: optical quantum efficiency, power conversion efficiency of an LSC-PV assembly, and distance dependent external quantum efficiency measurements to investigate reabsorption.

Characterization of LSCs

While research into LSCs has spanned almost four decades, there has been no standardized measurement for device efficiencies. Figures-of-merit for LSCs and their respective definitions can vary between laboratories, in addition to different device configurations, and this complicates comparisons within the literature. In our work, we have used figures-of-merit that can be used to derive other LSC metrics regardless of definition, such as flux gain.

The optical quantum efficiency (OQE) is defined as the fraction of photons emitted on the edges relative to the incident photons.[9, 10] The OQE is given by

$$OQE = \Phi_F \eta_{trap} = \Phi_F \left(\frac{I_{total} - I_{face}}{I_{total}} \right)$$

where Φ_F is the emission quantum yield of the chromophore, η_{trap} is the trapping efficiency of the waveguide, I_{total} is the integrated emission intensity of the LSC in the integrating sphere, and I_{face} is the intensity of emission emanating from the top and bottom faces of the LSC. Edge and face emissions are differentiated by coating the edges with black acrylic paint that has a matte finish. The OQE of an LSC is related to the quantum yield of the chromophore of the LSC and trapping efficiency of the waveguide. An integrating sphere[9, 10] (Figure 1b) or a series of multiple detectors to simultaneously measure reflected, transmitted, and edge-emitted light[11] have been used to measure OQE of LSCs. The presence of an integrating sphere in many photophysics laboratories,[12] in addition to the relative operational simplicity and analysis procedures compared to the use of multiple detectors, are motivations for us to use the integrating sphere method to measure OQE.

Photovoltaic metrics are established figures-of-merit used both in the photovoltaic industry and academic laboratories. Power conversion efficiency (PCE) is defined as the ratio of the power output of the LSC (P_{out}) and the light power input from an AM 1.5G light source (P_{in})

$$PCE = \frac{P_{out}}{P_{in}} = \frac{V_{oc}J_{sc}FF}{P_{out}}$$

where V_{oc} is the open-circuit voltage, J_{sc} is the short-circuit current density, and FF is the fill factor. The PCE of a solar cell is calculated by measuring the current-voltage curve of the device (Figure 1b). The maximum possible voltage and current of a photovoltaic device are described by V_{oc} and J_{sc}, respectively.

Emissive aggregates

Organic dyes that have been used in LSCs suffer from severe concentration quenching, especially at the high concentrations necessary for efficient light harvesting. These organic dyes have small Stokes shifts and long absorption tails that overlap with the emission spectrum leading to reabsorption losses limiting efficiencies.[13] Chromophores that exhibit aggregation-induced emission (AIE) are observed to maintain high fluorescence quantum yields even at very high concentrations or as neat films.[14] This class of chromophores has been used as biological probes and in light-emitting devices, but was not examined for LSC applications until recently by our group.[15-17]

Tetraphenylethene (TPE) **1** is a prototypical AIE chromophore with a relatively high quantum yield even at very high concentrations, and a large Stokes shift in excess of 1 eV in PMMA.[16] Ray tracing simulations suggest that TPE in PMMA has very low reabsorption even at practical concentrator sizes (geometric ratio of surfaces to edges > 100). Several analogues of tetraphenylethene were synthesized to investigate if the AIE behavior observed in TPE is due to its molecular motif – rotatable phenyl rings with twisted core structures – and to extend the absorption of TPE towards the visible without conjugation of heterocyclic rings (Figure 1a). The photophysical characteristics for the TPE analogues were found to be similar to TPE. The TPE analogues were poorly emissive in solution but become highly emissive when in frozen 2-methyltetrahydrofuran glass or dispersed as 10% in PMMA films (Figure 1b). The quantum yields of the analogues are characteristically lower than TPE with **5** being closer to the quantum yield of TPE. The OQE of a simulated LSC using **5** as the chromophore in the waveguide decreases with increasing geometric ratio compared to the case when **1** is the chromophore in the LSC.[16] This apparent decrease was ascribed to the significant absorption tail of **5** that extends into the emission spectral region even though it has a large Stokes shift (defined as the difference

in energy of the absorption and emission maxima), which becomes pertinent at larger LSC sizes. The contribution of absorption tails have also been observed previously in other systems[18] suggesting the importance of accurate measurement of the absorption spectrum of chromophores in LSCs for ray tracing simulations.
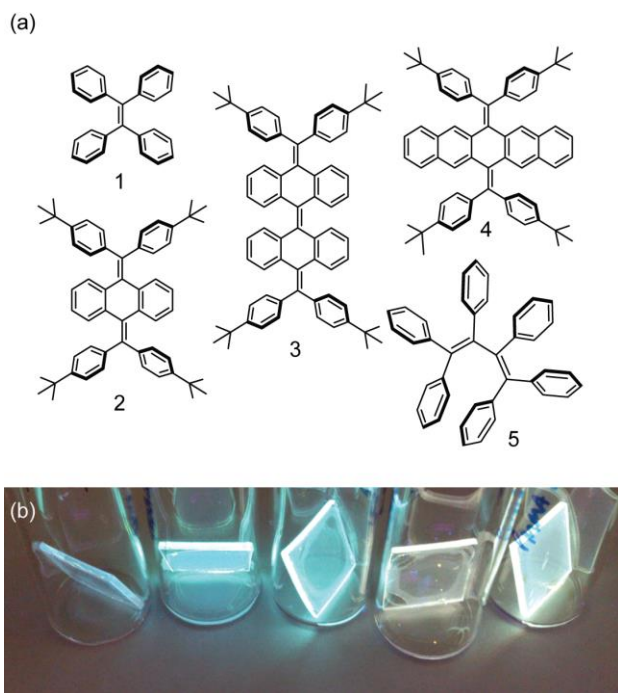

Figure 2. Tetraphenylethene and analogues. (a) Chemical structures of TPE **1** and analogues **2-5**. (b) Photograph of PMMA films containing TPE and analogues at 10% w/w in PMMA upon excitation with a UV light source.

The transparency of LSCs in the visible range is ideal for special applications such as visible-blind photodetectors or light-harvesting windows/device screens. A key requirement for visible light transparency is that the absorption range of the chromophores in the LSC must be in the UV (up to 400 nm),[19] starting in the near-infrared (starting from 750 nm),[20] or ideally a combination

of both. While TPE is an ideal chromophore to achieve a transparent LSC, the absorption range does not span the entire UV spectrum (only up to 350 nm). The analogues of TPE have lower quantum yields albeit having a broader absorption range. Another design approach to extend the absorption range in the UV while keeping the AIE behavior of TPE is to append larger aromatic hydrocarbons to the diphenylethene motif.[21] Pyrene is an ideal chromophore given its absorption in the UV and formation of excimer species that is expedient in achieving a large Stokes shift. However, pyrene at high concentrations can form non-emissive aggregates depending on the substituents.[22] Geminal pyrenes attached on the diphenylethene motif (Figure 3a) also show AIE behavior and are emissive even as aggregates[17] suggesting that the design strategy is effective in avoiding strongly quenching aggregates, i.e. strongly interacting H-aggregates.[23, 24] The photophysics of the regioisomers of the *gem*-pyrene ethenes **6** and **7** in solution and as aggregates are very distinct. Concentration dependent absorption and excitation spectra of **6** are suggestive of the formation of weakly interacting H-aggregates whereas **7** shows spectroscopic features that resemble both H- and J-aggregates. At very high concentrations in PMMA, the *gem*-pyrene ethenes show excimer-like emission spectra and Stokes shifts in excess of 1 eV. LSCs fabricated using **7** at a concentration of 50% w/w in PMMA showed comparable performance (average PCE of 0.32%; Figure 3b) with a state-of-the-art inorganic phosphor at a similar geometric ratio with the advantage of superior air stability.[19] **I**ncident **p**hoton-to-**c**urrent **e**fficiency spectra, IPCE (also known as **e**xternal **q**uantum **e**fficiency, EQE) of the LSC device (Figure 3c) did not have any features that were suggestive of scattering from large aggregates that could form at very high concentrations in PMMA. The *gem*-pyrene LSC device showed high transparency in the visible spectrum which is particularly attractive for light-harvesting window

applications (Figure 3d). This was the first report of an organic-based UV-harvesting transparent
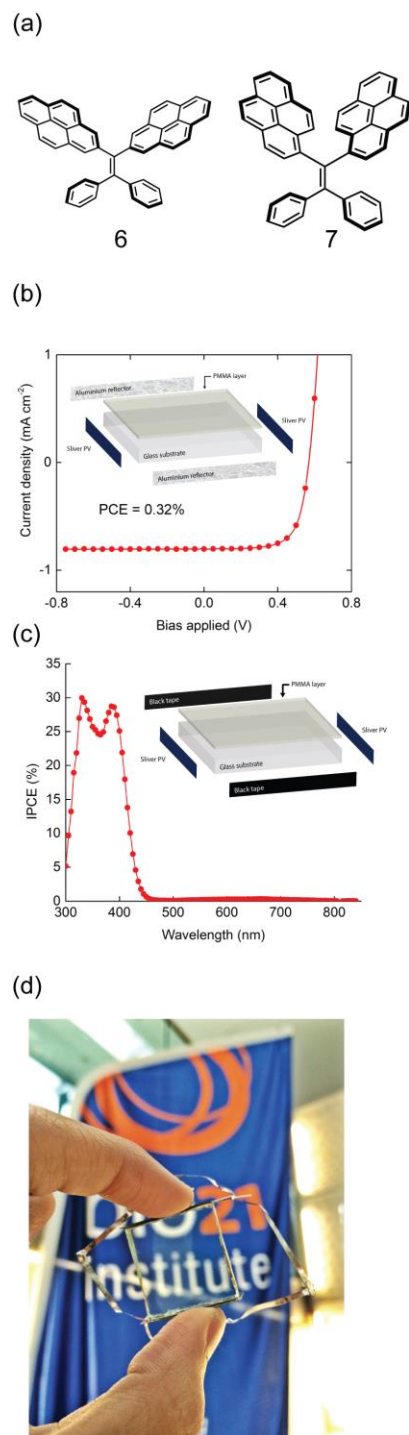
LSC that can operate in air.

Figure 3. Transparent LSCs enabled by *gem*-pyrene ethenes. (a) Chemical structure of *gem*-pyrene ethenes, (b) Current-voltage plot and (c) IPCE spectra of the LSC device, (d) Photograph of the *gem*-pyrene transparent LSC.

Excitation energy transfer and migration

Excitation energy migration and transfer is an attractive approach towards achieving an absorption range for an LSC that spans a large fraction of the solar spectrum (Figures 4a and b). Batchelder et al. pioneered the approach by using mixture of dyes in plastic hosts.[25] Later reports of the same approach improved the absorption range of LSCs but did not directly address the reabsorption problem.[26-28] Olson et al. proposed to use an energy transfer approach as a strategy to reduce reabsorption (Figure 4a).[29] Based on previous theoretical and experimental studies of energy migration (i.e. energy transfer between the same chromophores) and energy transfer,[30-32] it should be possible to achieve diffusive transport of energy among donors and then transfer the energy to a low concentration of highly emissive traps (acceptors) to reduce reabsorption. The concentrations necessary to achieve efficient energy migration approaching the diffusive limit could not be used in conventional dye systems as they are susceptible to concentration quenching[2] with the possibility of formation of excimers that compete in the energy transfer process.[33] Currie et al. applied the migration-trapping approach using rubrene and DCJTB (Figure 5a, compounds **8** and **9** respectively) in a tris(8-hydroxyquinolato)aluminium (Alq$_3$) host to reduce reabsorption.[9] The drawback of using rubrene with DCJTB in a migration-trapping approach is that rubrene still has significant absorption that overlaps with DCJTB emission (Figure 5b). It is unclear whether rubrene maintains its high quantum yield at 30% in Alq$_3$ since rubrene is known to suffer concentration quenching.[34] Maintaining a high fluorescence quantum yield even at very high concentrations is necessary for efficient energy migration.
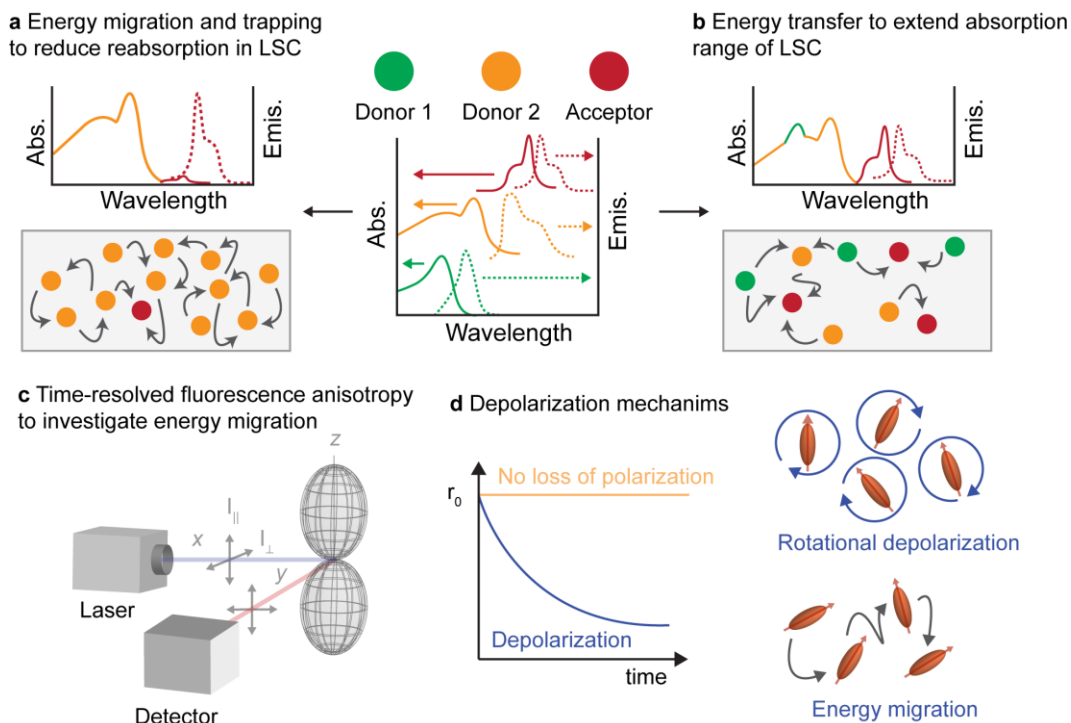
Figure 4. Illustration of energy transfer schemes used in LSCs. (a) The energy migration-trapping approach is a strategy to reduce reabsorption. A high concentration of donors harvest incident light and funnel the energy through energy migration, which eventually reaches a low concentration trap. (b) Energy transfer strategies have been used to extend the absorption range of the LSC or for color tuning.[27] (c) A schematic showing the time-resolved fluorescence anisotropy experiment set up. (d) In the absence of rotation within the lifetime of the chromophore, time-resolved fluorescence anisotropy is a useful technique to investigate energy transfer processes in condensed media. Theoretical models can then be used to describe the depolarization phenomena and infer energy transport characteristics.[31]

AIE chromophores are ideal materials for energy migration-trapping approaches in LSCs as they remain emissive at the high concentrations necessary for efficient energy migration. DPATPAN (Figure 5a, compound **10**) is a simple AIE chromophore that can be synthesized in

three reaction steps with commercially available materials.[35] It has an absorption that is well separated from the emission of DCJTB (Figure 5b) to avoid reabsorption and an emission that overlaps with the absorption of DCJTB for efficient energy transfer. The quantum yield of DPATPAN ($\Phi_F = 90\%$) was maintained even at concentrations exceeding 10% w/w (260 mM) in PMMA,[15] ideal for energy migration. To provide evidence of energy migration between DPATPAN dye molecules, time-resolved fluorescence anisotropy decay profiles of DPATPAN at different concentrations were measured. In this experiment, polarized light excites a subset of chromophores in the sample that have a component of their absorption transition dipole moment oriented in the direction of the electric field vector of the light - commonly referred to as photoselection (Figure 4c). Anisotropy (r) describes the extent of emission polarization with non-zero anisotropy values indicating polarized emission (Figure 4d). Depolarization of the emission occurs as energy migrates from one dye molecule to another, with different transition moment orientations, in the sample. Fluorescence anisotropy measurements provide an indication of the average angular displacement between absorption and emission transition moments. The extent of displacement or depolarization is dependent on the rotational diffusion of the isolated chromophores (in dilute solutions) in a specific solvent and temperature, or the efficiency of energy transfer at concentrations where the average distance among molecules is comparable to the Förster radius (Figure 4d). In the absence of a depolarization mechanism, the initial fluorescence anisotropy (r_0) remains constant over time.
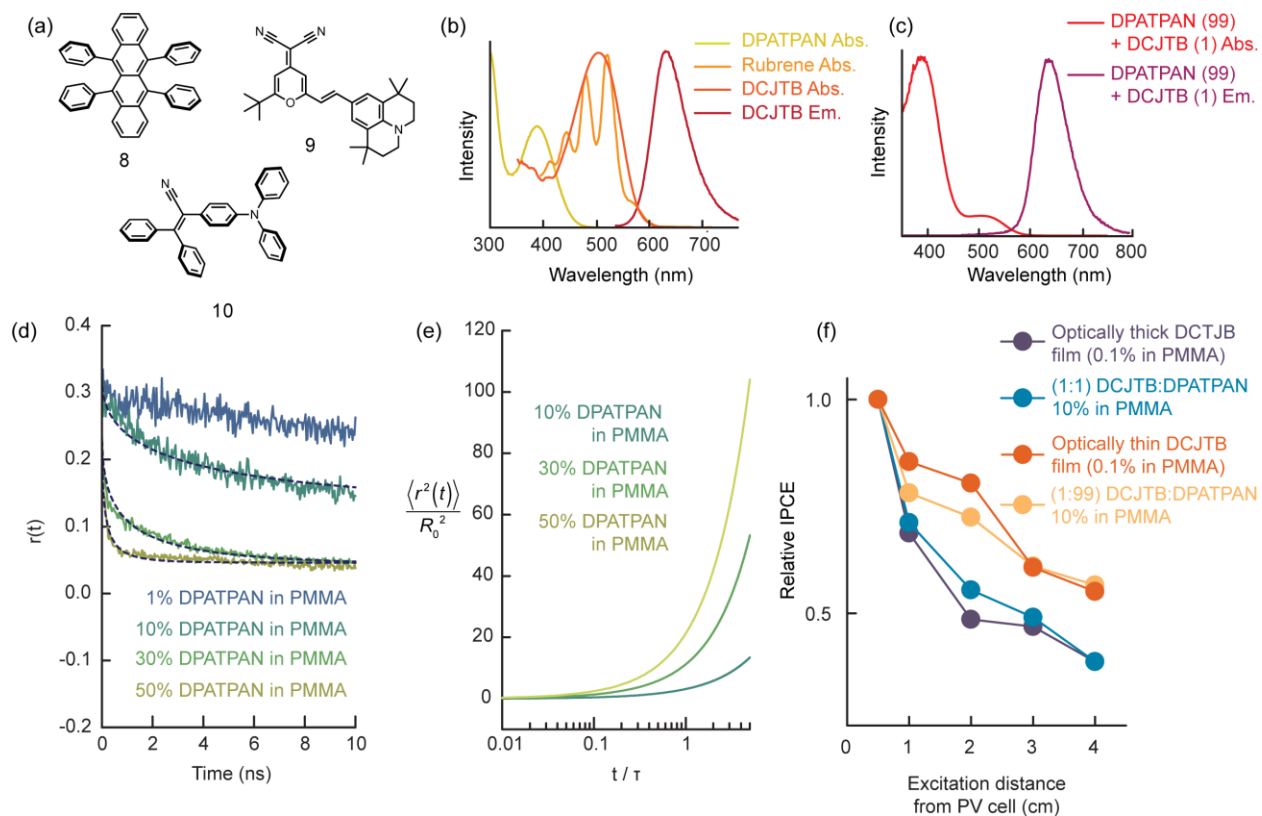
Figure 5. Energy migration in AIE chromophores. (a) Chemical structures and (b) absorption/emission spectra of rubrene **8**, DCJTB **9**, DPATPAN **10**. (c) Absorption/emission spectra of a DCJTB and DPATPAN-based LSC. (d) Time-resolved fluorescence anisotropy profiles for different concentrations of DPATPAN in PMMA. Dashed lines are global fits to the time-resolved fluorescence anisotropy traces[36] using Huber's theory.[37] (e) Mean squared displacement curves for different concentrations of DPATPAN in PMMA. The curves were calculated using GAF theory[30] using the derived fit parameters in Figure 5c. (f) Direct comparison of IPCE decay of DCJTB-only controls and DPATPAN-DCJTB devices.

The fluorescence anisotropy data for DPATPAN at various concentrations in PMMA showed an increasingly rapid decay of the anisotropy with concentration (Figure 5c). A global fit

of the anisotropy decays using Huber theory[37] provided strong evidence for energy migration at high concentrations of DPATPAN (Figure 5c).[36, 38] The transport properties of DPATPAN in PMMA, described by the mean square displacement $<r^2(t)>$ of energy migration (Figure 5d) calculated with GAF theory,[30] showed diffusive energy migration is achieved at close to one fluorescence lifetime for DPATPAN as the concentration approaches 50% w/w DPATPAN in PMMA. An LSC device comprising 1:99 mole ratio of DCJTB and DPATPAN dispersed as 10% in PMMA showed only DCTJB emission (Figure 5e) regardless of film thickness which suggests that Förster energy transfer, not trivial reabsorption, gives rise to only DCJTB emission. In distance dependent IPCE experiments, the performance of the DPATPAN-DCJTB LSC was superior to control films containing DCJTB only demonstrating that reabsorption can be reduced without sacrificing light absorption (Figure 5f).[15] The data also indicated that merely extending the absorption range of the LSC did not lead to reabsorption reduction.

Based on the time-resolved fluorescence anisotropy experiments, it was determined that the concentration necessary to achieve diffusive energy transport can be decreased if the overlap integral for the donor chromophore can be increased (low Stokes shift) while keeping the fluorescence quantum yield high. Perylene diimides are ideal candidates for energy migration due to their low Stokes shift and high quantum yield approaching unity in solution. However, perylene diimides are susceptible to concentration quenching[39] and can form aggregate traps[13] at concentrations necessary for efficient energy migration.[33, 38] Resistance to concentration quenching has been reported for bay-substituted perylene dimides[40] but this leads to a bathochromic absorption shift. Instead, we synthesized a molecularly insulated perylene diimide with bulky substituents attached to the imide positions (Figure 6a, compound **11**).[41] Substituents

at the imide did not perturb the electronic structure of the perylene core chromophore allowing the use of perylene **11** as the donor chromophore with Lumogen® F Red 305 (Figure 6a, compound **12** also known as LR305) as the acceptor. The photoluminescence quantum yield of **11**, with increasing concentration up to 58 mM in PMMA, was consistently high showing the effectiveness of our design (Figure 6c). The energy transport properties calculated from derived fit parameters revealed diffusive transport was reached in less than one lifetime at 58 mM (Figures 6e and 6d). This was in stark contrast to DPATPAN, in which diffusive transport within one fluorescence lifetime is obtained only at 50% w/w (~1300 mM). This difference in transport properties between DPATPAN and the insulated perylene diimide was a result of the higher spectral overlap integral of the perylene diimide compared to DPATPAN. The calculated diffusion length L_D for **11** was 23 ± 1.0 nm at 58 mM, which is longer than most reported perylene diimides in the literature confirming the efficacy of our insulation approach.[33] LSC devices fabricated using **11** (58 mM) and LR305 (15 mM) in PMMA gave a significantly higher short-current density when compared to LR305-only control devices (Figures 6f and 6g). In addition, the distance dependent IPCE data for the energy migration LSC showed reduced reabsorption when compared to the optically thick LR305 LSC (Figure 6h).
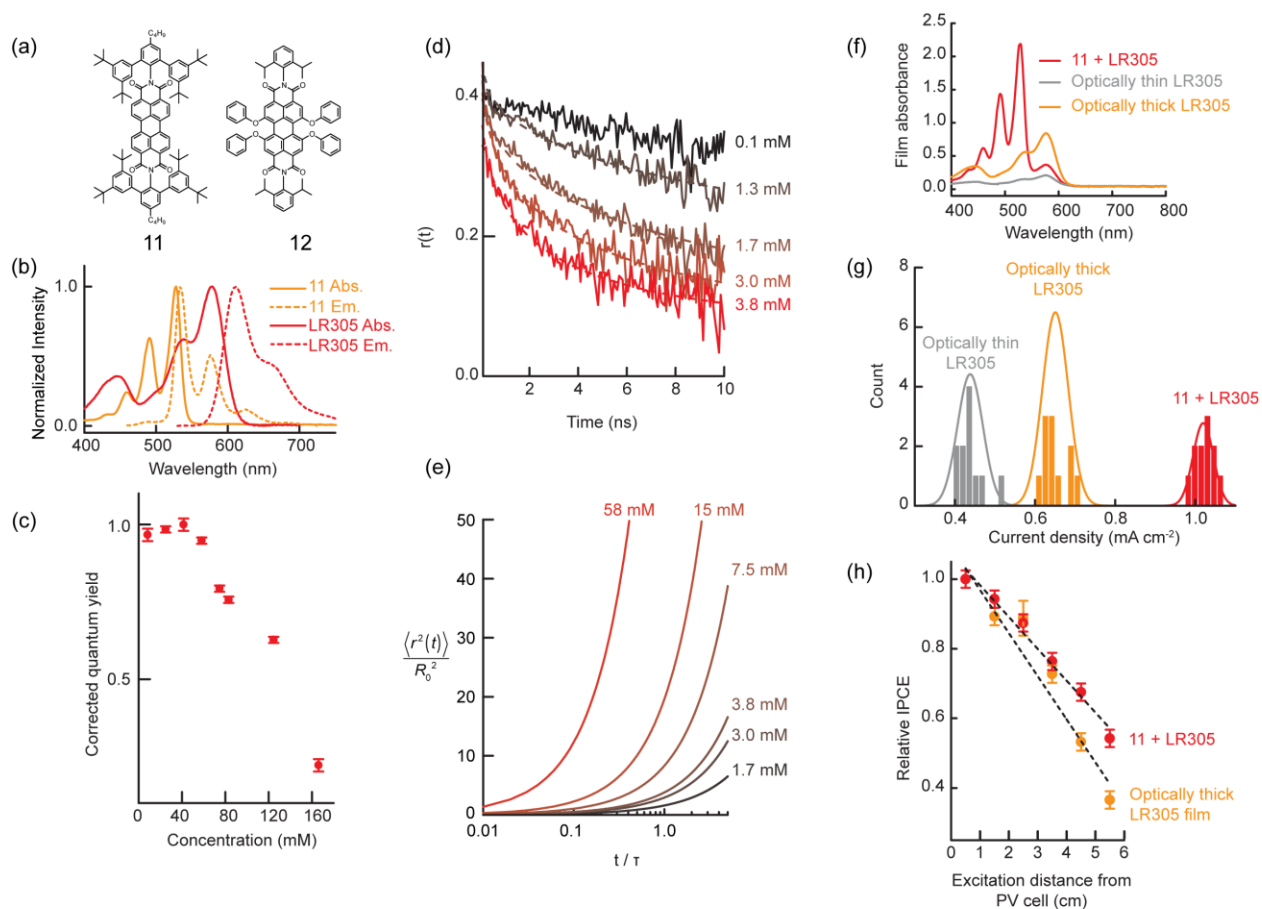
Figure 6. Energy migration with insulated perylene diimides. (a) Chemical structures and absorption/emission spectra (b) for the molecularly insulated perylene diimide **11** and LR305 **12**. (c) Concentration-dependent quantum yield of **11** in PMMA. (d) Time-resolved fluorescence anisotropy traces for different concentrations of **11** in PMMA and corresponding fit using Huber theory. (e) Transport properties calculated from derived fit parameters in (d). (f) Absorption spectra of the energy migration LSC (58 mM **11**, 15 mM LR305) and optically thin and thick LR305 only LSCs (both containing 1 mM LR305 to avoid concentration quenching) control devices for comparison. (g) Histogram of current density of the LSC devices (5 cm × 5 cm × 0.1 cm) showing the significant increase in current for the energy migration LSC (h) Comparison of

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IPCE decay as a function excitation distance between an optically thick LR305-only control device and energy migration LSC.

Concluding remarks and outlook

The selection criteria for chromophores in luminescent solar concentrators are well-defined. The material should have (i) high photoluminescence (quantum yield close to 100%); (ii) low reabsorption; (iii) tunable wavelength of emission; (iv) compatibility with the waveguide (typically a commodity polymer) and (v) high stability and lifetime under ambient terrestrial conditions. A class of chromophores with all of the above properties is yet to be found though recent work on nanocrystals suggests they are approaching this challenging target.[4] From the organic chromophores perspective, it has been a very interesting challenge to find dye structures that meet all of the desirable properties. We have shown that chromophores that show aggregation induced emission behavior are useful materials in thin film and energy migration applications that require high dye concentration without the negative impact of concentration quenching of fluorescence. Dye aggregation is traditionally considered a negative phenomenon in LSCs but we have demonstrated that emissive aggregates leading to excimer emission can be used to reduce the overlap between absorption and emission resulting in low reabsorption loss. Energy migration and transfer is also a viable strategy to reduce reabsorption. Efficient energy migration was achieved in a matrix containing a high concentration of a molecularly insulated perylene diimide and the absorbed energy was ultimately trapped and re-emitted by a highly fluorescent and stable commercial perylene diimide dye. The concentration ratio of energy transfer donor to acceptor in this system meant that the majority of light was harvested by the donor dye. Our time-resolved fluorescence anisotropy experiments provided evidence for energy

migration between donor dye molecules that is reminiscent of exciton diffusion processes in organic light emitting diodes and solar cells.[42, 43]

While we have made substantial progress in the development of organic chromophores for LSCs, there remain many avenues to pursue in new dye designs and device assembly. With optimized photophysical properties of the dye, light harvesting in LSCs might be further improved by dye alignment[44, 45] as well as examination of new materials to increase confinement of emission within the waveguide.[46] In looking forward to the applications of LSC devices, it will be extremely important to examine the stability and lifetime of not only the organic dyes but also the dye-polymer composite waveguides.[47] It is our view that further development of new emissive organic dyes can lead to commercially viable organic-based LSC devices.

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Notes

The authors declare no competing financial interest.

Biography

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Bolong Zhang was born in 1989 in Xiamen, China, studied at Fuzhou University (BSc, 2012) and the University of Melbourne (MSc, 2015). He is currently a PhD candidate at the University of Melbourne studying luminescent solar concentrator materials and device structure.

David J. Jones was born in 1960 in Launceston, Tasmania. He studied at the University of Tasmania, Hobart, Australia (PhD, 1995) and carried out postdocoral work at the University of Sheffield and Cardiff University before joining Prof Vernon Gibson at Imperial College London (UK) as team leader for the BP Catalyst Discovery Team. He returned to the University of Melbourne, Australia with Prof Andrew Holmes from Cambridge University in 2005 and has been the project coordinator for the Victorian Organic Solar Cell Consortium (VICOSC), before being engaged at the University of Melbourne as a Senior Research Associate in 2014.

Kenneth P. Ghiggino was born in 1951 in Sydney, Australia. He studied at the University of New South Wales, Sydney (PhD, 1976) and carried out postdoctoral research at the University of Southampton (1976-1978) before joining the University of Melbourne as lecturer in 1979. He has been the Masson Professor of Chemistry at the University of Melbourne since 1998. His research interests are primarily in the areas of photochemistry and spectroscopy including single molecule spectroscopy, ultrafast laser spectroscopy and luminescence spectroscopy.

Wallace W. H. Wong was born in 1978 in Hong Kong, studied at the University of Sydney (BSc/MSc, 2001) and the University of Oxford (DPhil, 2005) and carried out postdoctoral research at ETH Zürich and then at the University of Melbourne. He has been an Australian Renewable Energy Agency Research Fellow (2011-2014) and is currently an Australian Research Council Future Fellow at the University of Melbourne. He has been working in the area of organic electronic materials since 2006. His work encompasses semiconducting polymers, fullerene chemistry, luminescent dyes, continuous flow processing and supramolecular chemistry.

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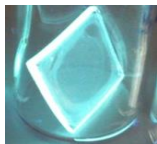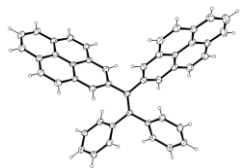
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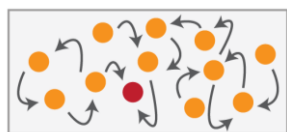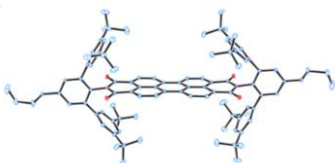
Energy Migration

Transparent LSC Device

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