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Improving the Aesthetics of Photovoltaics Through Use of Coloured Encapsulants

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ABSTRACT: Photovoltaics (solar cells) are important in the creation of sustainable architecture, but are difficult to integrate into a wide variety of architectural styles, which is necessary if this technology is to be extensively used. Adding variety to the colour range in these installations will provide a way of making this solar energy technology more visually exciting, so methods need to be found to add colour at minimal extra cost, without loss of efficiency. Adding colour to photovoltaic encapsulant materials offers a solution. It is shown that fluorescent, organic Lumogen dyes (BASF) can be added to the photovoltaic encapsulant materials Sylgard 184 (Dow Corning) and EVA (Ethylene Vinyl Acetate). The dyes continue to fluoresce within these host materials. Encapsulating a photovoltaic cell with Sylgard containing Lumogen red 300 dye (BASF) demonstrates that light can be transported to a photovoltaic cell by the fluorescent dyes inside the encapsulant material that surrounds the cell. This slightly improves the electricity output from the photovoltaic cell, and is especially promising for use in light-transmissive photovoltaic arrays incorporating widely-spaced photovoltaic cells, such as architectural glass art that incorporates photovoltaics. Further work is needed to test and improve the performance of the dyes over time, to ensure that installations incorporating this technology can last for the minimum twenty years that is the current industry standard for photovoltaics.

Keywords: Photovoltaic; architectural glass; coloured encapsulants; fluorescence; building integration

PHOTOVOLTAICS (PV) IN THE BUILT ENVIRONMENT: THE CURRENT SITUATION

Solar energy is the best form of renewable energy for use in the built environment, because solar cells (known collectively as photovoltaics, or PV) can be integrated into architecture, and into cities. Many innovative designs have been developed, showing different methods of incorporating photovoltaics (PV) into building structures [1], but these are often limited by the appearance of the blue and black, square PV cells (figure 1).

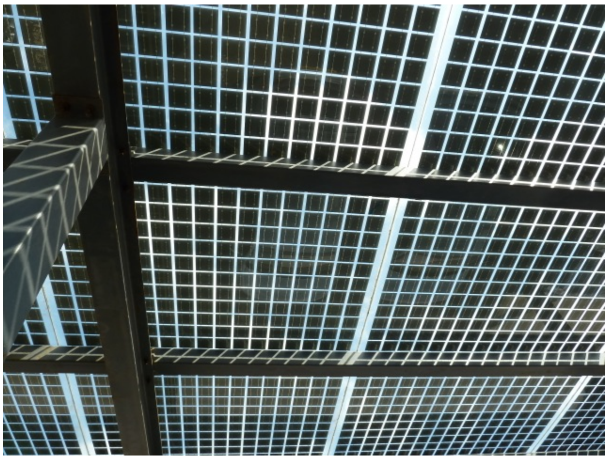

Figure 1: Square photovoltaic cells on a canopy at Narec, Blythe, Northumberland

Figure 2: Decorative window glass at Peters' Glass Studios, Paderborn, Germany, (left); and in Paderborn Cathedral (right) demonstrating variety in architectural glass designs.

PV can be applied over entire building envelopes, and is now established for application on roofs, with products such as PV roof tiles [2] now available to disguise the appearance of the PV. PV can also be incorporated into architectural glass; both by retrofitting, and in new-build. Glass façades provide one area where PV can be installed, but the tradition of decorative windows is so rich (figure 2), that building-integrated PV needs to be developed further for use in a wider range of architectural glass designs.

COLOUR AND PV

A greater variety of colour could assist in making PV a successful component of architectural glass; enabling it to be used with an ever-growing range of styles, applications and impacts. Figure 3, below, shows methods of colouring PV installations, grouped according to:

- **Colour variety** provided by the technology.
- **Low cost**: cheap varieties of PV are available, but have reduced efficiency; and short outdoor lifetimes in the case of organic and dye-sensitised PV.
- **Efficiency of the PV**: highly efficient devices, such as Gallium Arsenide PV, can provide larger amounts of electricity per unit area, but these types of PV are prohibitively expensive in architectural applications [3].

Crystalline silicon PV sits at the junction of good efficiency and low cost. It is up to 25% efficient (compared with maximum multi-junction cell efficiencies of 37.7%) [4]. It is the most widely used in architecture [5].

The colour of silicon PV can be changed by altering the thickness of the anti-reflection coating on the surface of the PV cells [6]; as shown in the 'wide colour variety' section of figure 3, but this modification causes reductions in the efficiency of the PV cells. The junction of 'good PV efficiency' and 'wide colour variety' shows that other methods of altering colour can only be applied to the areas surrounding the PV cells, such as the frame. Covering the PV cells, with coloured glass or films, would significantly reduce the amount of light reaching the cells, so much less electricity would be generated.

The centre of the diagram shows dyed, fluorescent PV encapsulant material. (Encapsulant materials such as Ethylene Vinyl Acetate (EVA) or silicones, such as Sylgard 184, provide protection for the brittle PV cells, as well as electrical insulation and prevention of moisture ingress.) Combining coloured encapsulants with PV cells gives a wide variety of colour, due to the availability of several dye colours; with minimal change in PV efficiency [7]; at minimal cost, as tiny amounts of dye are added to encapsulant materials that are an existing component of PV.

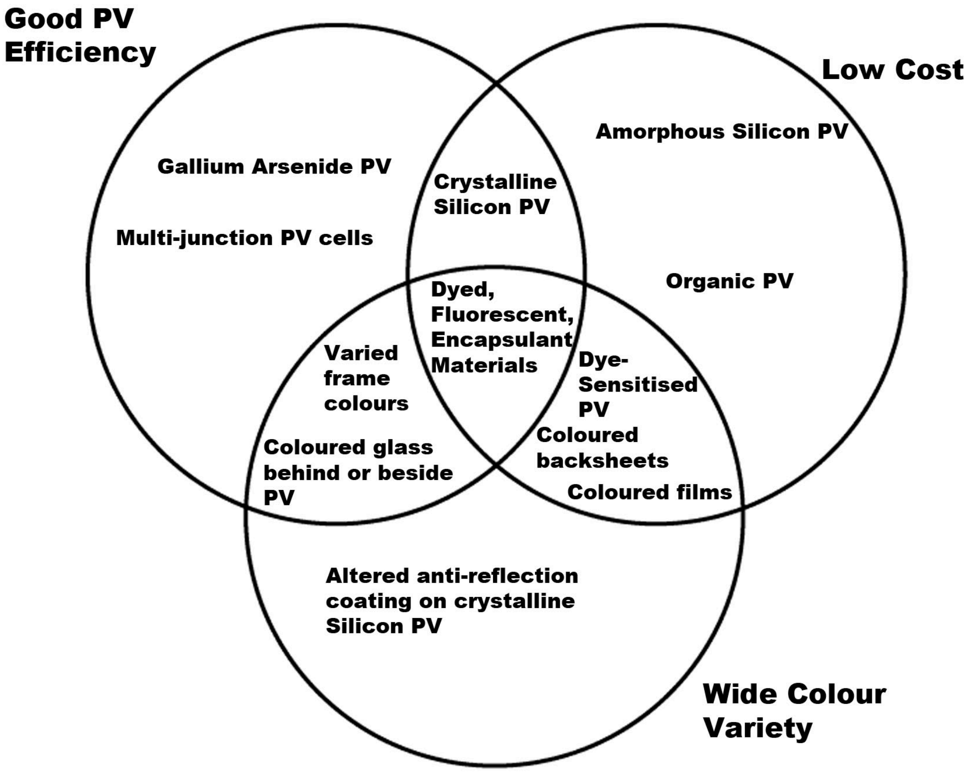

Figure 3: Methods of adding colour variety to PV, taking cost and device efficiency into account

The combination of crystalline-silicon PV cells and dyed encapsulant materials will operate best in light-transmissive PV designs: where the PV cells are well spaced, allowing some coloured light through; and where the dye can be used to direct light to the surface of PV cells in adjacent areas, as described in the next section.

HOW THE COLOURED, FLUORESCENT DYES TRANSPORT LIGHT TO PV CELLS

Adding fluorescent dyes to coloured PV encapsulants alters the appearance of PV cells, by spreading a layer of translucent, coloured material over them. Although some light is lost in passing through the coloured encapsulant layer, some light is also transported to the cell surface from surrounding regions, as shown in figure 4. Here, light shines on dyed encapsulant material, next to a PV cell. Dye molecules within the encapsulant material absorb the light, then re-emit it. The light can become trapped inside the material, bouncing from surface to surface in a process of total internal reflection, until it reaches the surface of the PV cell, where it can be converted into electricity.

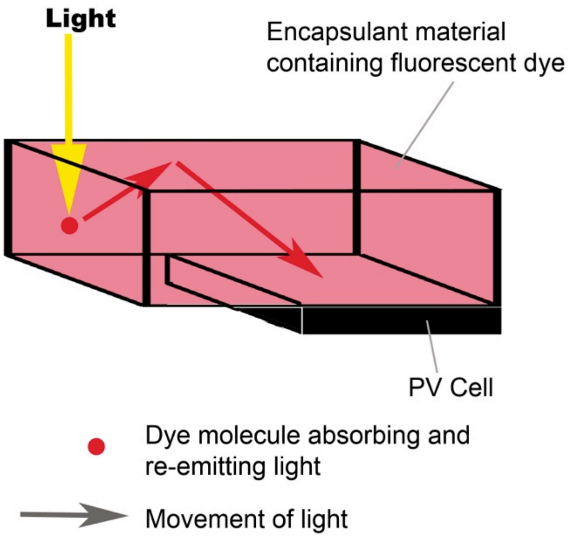

Figure 4: Schematic of light being absorbed by a fluorescent dye molecule, then re-emitted and reflected inside an encapsulant material, until it reaches the surface of a PV cell.

CHOICE OF FLUORESCENT DYES AND PV ENCAPSULANT MATERIALS

Two, different **PV encapsulants** were chosen for this research:

1. **Sylgard 184** (Dow Corning): a two-part silicone elastomer. Mixing the two components together in a 10:1 ratio gives a viscous liquid that cures to form a transparent, tacky solid.

2. The other encapsulant material is **EVA** (ethylene vinyl acetate: Vistasolar 486.00 from Solutia Solar): a flexible polymer sheet, which is placed over and under the PV cells, between sheets of glass (figure 5). The whole assembly is then laminated together, in a process involving heating, so that the EVA molecules cross-link to form a transparent glue. Application of pressure then forces air bubbles out.

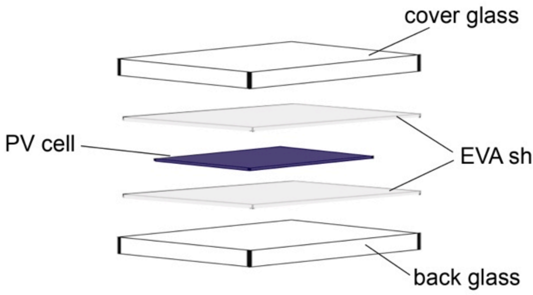

Figure 5: Exploded view showing layers of material for PV lamination with EVA (Ethylene Vinyl Acetate)

Coloured, fluorescent dyes were incorporated into both materials by dissolving the dyes in solvents. Fluorescent, Lumogen dyes (BASF) [8] were chosen, due to their stability and excellent ability to absorb, then re-emit, light [9]. For Sylgard 184, the dye-solvent mixture was stirred into the Sylgard; the solvent was evaporated off; then the Sylgard was cured in air. Dye was added to EVA sheets by soaking the sheets in a dye-solvent mixture, then putting the EVA sheets through a PV lamination cycle, involving heating and pressure, in order to cross-link the EVA molecules, making transparent sheets of EVA.

CHECKING THE PERFORMANCE OF THE COLOURED ENCAPSULANTS

Coloured encapsulant samples were tested to check that the fluorescent dyes were performing as expected once they were incorporated into the encapsulant materials. The tests were:

1. Transmission of light through the samples

Known wavelengths of light were passed through the samples to check how well light was transmitted (using a light-reflecting 'integrating sphere' in a spectrophotometer).

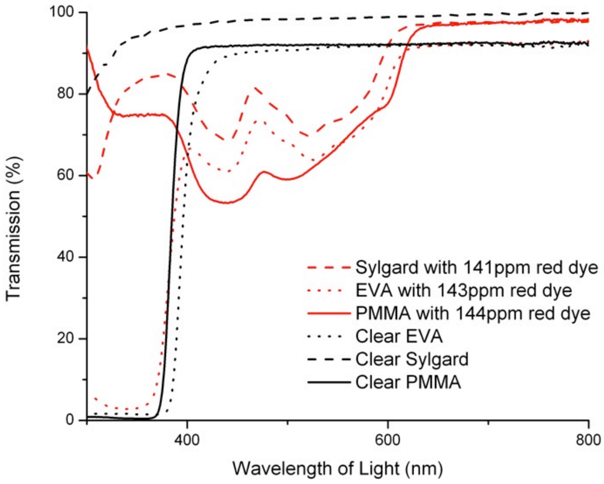

Figure 6: Transmission of light through clear PV encapsulant materials, compared with PV encapsulants containing Lumogen red 300 dye

Figure 6 (above) shows how the transmission of light varied for samples containing Lumogen red dye. PMMA (polymethyl methacrylate, or acrylic) is shown for comparison with the other materials, as it is well established as a host for Lumogen dyes [10]. Figure 6 contains three curves that show how light is transmitted through different materials containing Lumogen red 300 dye. All three curves have a similar pattern of troughs and peaks, showing that the Lumogen red dye is absorbing light in a similar way in each material. (The curve for PMMA has the deepest trough, due to the sample being the thicker than the EVA and Sylgard samples, so absorbing more light.) In comparison, the fainter lines show that clear EVA and Sylgard samples transmit more than 80% of light above 400nm wavelength.

2. **Fluorescence of the dye inside the samples**

Tests were performed to check that the dyes in the samples were fluorescing as expected. Lumogen red dye is very efficient at absorbing and re-emitting light when it is within a PMMA (poly-methyl methacrylate) host. For low dye concentrations, the efficiency (known as the photo-luminescent quantum yield) can be 100% [11]. The Sylgard 184 and EVA samples were tested in a spectrofluorometer. The results are shown in table 1, below. The right-hand column of the table shows that photoluminescent quantum yield values for the dye in Sylgard and EVA are less than the 100% value that is achievable for Lumogen red dye in PMMA, but that the dye is still fluorescing well within the two different encapsulant materials.

Host material	**Dye concentration** (ppm = parts per million)	**Photoluminescent quantum yield** (%)
Sylgard 184	187ppm	88 %
EVA	140ppm	77 %
PMMA	From low concentrations up to 1600ppm (with excellent dye assimilation into the PMMA)	98.5 - 100% [11]

Table 1: Comparison of the photoluminescent quantum yield of Lumogen red dye within each host material, to check that the dye is fluorescing as expected

3. **Power output of a PV cell with dyed encapsulant**

Monocrystalline PV cells measuring 52mm square (cut from larger PV cells) were tested in a solar simulator, to check the amount of power produced when 1000W/m^2 (1 sun) of light was incident on them. One cell was then encapsulated in Sylgard 184 containing 100ppm Lumogen red dye, then tested for power output underneath the same 1000W/m^2 light source. To encapsulate the cell, 17g of Sylgard 184 containing a 100ppm concentration of Lumogen red dye was poured onto a piece of float glass and allowed to set. The PV cell was then placed on top of the Sylgard 184 on the glass, where the tacky surface of the Sylgard held the cell in place. A further 17g of the same mixture of dye and Sylgard was then poured over the cell. The Sylgard spread out to form a circle on the glass, and fluorescence due to the dye could be seen at the edges of the glass (figure 7, below).

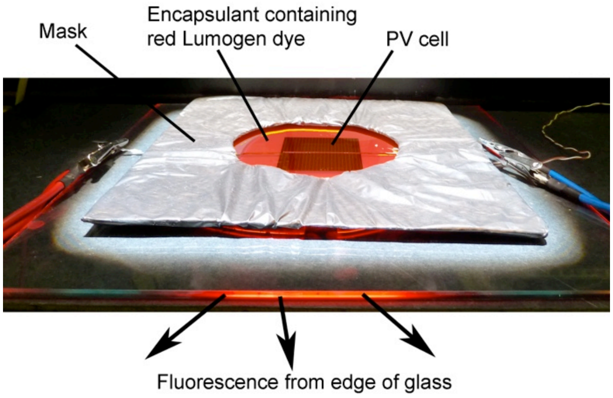

Figure 7: A PV cell encapsulated with Sylgard 184 containing red Lumogen dye. A mask exposes a precise area to the light from a solar simulator, whilst measurements of power output are made. Fluorescence can be seen at the edges of the glass.

A reference sample was made by encapsulating another PV cell in clear Sylgard. Each of these encapsulated cells was tested under a 1000W/m^2 light source. A mask with an 11cm diameter cut-out was placed over each test piece, so that the area exposed to light was the same for each cell (figure 7, above).

Power from cell without encapsulation (mW)	**Cell encap-sulation materials**	**Power from encapsulated cell (mW)**	**Increase in power** (%)
394.5	Clear Sylgard 184	402.3	2.0 %
404.1	Red 100ppm Lumogen dye in Sylgard 184	414.3	2.5 %

Table 2: Comparison of power produced by PV cells before and after encapsulation with Sylgard 184; with and without Lumogen red dye in the encapsulant

The maximum power produced by the cells is shown in table 2, above. Table 2 shows that there is a power increase when PV cells are encapsulated in Sylgard 184. When the encapsulated cells were exposed to light, the ratio of the area of the cell to the total area of the device that was exposed to light was 27:95. There was a significant area of encapsulant that was not directly over the PV cells. For the encapsulant containing Lumogen red dye, this meant that light shining on the encapsulant could be directed towards the surface of the PV cell, as shown in figure 4, above. The red dye directly above the PV cell blocked some of the incoming light, but the dye in the encapsulant beside the PV cell compensated for this by re-directing some light sideways, onto the PV cell surface. For this particular setup, a slight power increase was observed when using Lumogen dye in the PV encapsulant. The dye was acting to concentrate light onto the PV cell surface, at the same time as altering the appearance of the encapsulated PV cell.

THE PRACTICALITIES OF PUTTING COLOURED ENCAPSULANT MATERIALS INTO ARCHITECTURAL GLASS

Dyed encapsulant materials could be used on a large scale in architectural glass installations. Different artistic effects can be achieved with different types of encapsulant materials:

EVA sheet can be painted on with dyes in solvent, giving wide possibilities for different artistic effects.

Sylgard solutions spread to fill the area in which they are poured, but do not require a lamination process, so could be used in situations where lamination is not feasible.

For successful use of dyed encapsulant materials in architectural glass, **there needs to be very little change, in appearance and performance, as the dyed encapsulants age**. Ageing of the encapsulant materials depends partly on the type of solvent used to dissolve the dyes, before addition to the encapsulant material. A balance needs to be found between good solvents for the Lumogen dyes and lack of damage to the host material when the solvent is added to it. The stability of the dyes within the host material is also important. Heat-cured Sylgard 184 samples, containing Lumogen red dye, were seen to have a speckled surface appearance on the surface after 10 months of storage in the dark, but this did not occur with samples that had not been heat cured. Further investigations are required to find the best combination of solvent, host material and processing methods, to give minimal change in encapsulant appearance over time.

The stability of the Lumogen dyes themselves, over long periods, is still uncertain [12], and bleaching of the dyes will eventually occur, over time. Further testing will show whether these dyes can be used in installations that can be guaranteed to last for 20 years.

CONCLUSION AND FURTHER WORK

Fluorescent Lumogen dyes can be combined with the PV encapsulants EVA and Sylgard 184. This gives a method of adding colour variety to PV installations at minimal extra production cost, with minimal change in PV efficiency. The method is particularly promising for PV installations where light is to be transmitted through the gaps between the PV cells (light-transmissive PV applications). In these applications, the spaces between the PV cells become a source of coloured, transmitted light, whilst moving light energy to adjacent PV cells: creating both artistic and functional effects.

For this technology to be more widely adopted by architects, issues of cost, usability and environmental impacts will have to be researched further, before these materials can reach market testing stage. In particular, further work is required to establish the lifetime of the dyes within the encapsulant materials, to ensure a predictable lifetime for the PV installations, compatible with the lifetime of current crystalline-Silicon PV installations. This technology gives a way of generating enthusiasm about PV, by providing variety in appearance of PV installations, through addition of colour.

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