Structural color coatings for high performance BIPV

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Structural color coatings for high performance BIPV

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Abstract. Building integrated photovoltaics (BIPV) offer aesthetics and freedom of design for architects and home owners. This can accelerate implementation and free up new spaces for solar energy harvesting at building level, which is a necessary step towards a climate neutral built environment. Colored solar panels with high conversion efficiency and low cost price are an important development for large scale market penetration of BIPV. Here we report a solution processed structural color coating for solar panels and solar collectors. We show that virtually any color can be prepared, that the desired coating stack can be designed using optical calculations and that the exact color can be produced via a low cost solution process. Furthermore, we show that the light transmission for the colored glass plates is still very high, exceeding commonly used absorbing colors and enables very high solar cell efficiency. The colored PV panels have been tested in real environment and via accelerated lifetime testing for 3 years without any performance decline or degradation.

In the context of the Paris Agreement, and the European, national and regional objectives and associated legislation derived from it, the transition to a climate-neutral built environment is one of the main objectives [1]. In addition to reducing the total operating costs in buildings, on-site sustainable energy generation is key to realize net zero energy consumption. Here solar energy harvesting by photovoltaics is one of the most promising technologies to realize a self-sustainable built environment. Key aspects for architects, construction companies and home owners for widespread implementation of solar panels in buildings are freedom of design and aesthetics. Therefore building integrated photovoltaics (BIPV), where the solar panels are directly integrated in a building's façade, are an essential tool to offer architects a possibility to use essentially every part of the building surface to generate energy without impacting the aesthetics of the building [2]. A key aspect here is color. At the moment, most solar panels are usually dark blue or black in color. To offer differently colored solar panels is important for the acceptance and broad market introduction of BIPV, which is necessary to convince architects and consumers to integrate solar panels into building shells. There are several existing techniques on the market to realize colored BIPV products. One example is screen printing patterns of ceramic paints on a solar panels cover glass [3]. These materials derive their color from light absorption, which greatly reduces the electricity yield of the applied solar panels. Moreover, the applied colors are relatively dull. An option to reduce the impact of the front sheet coloration on the solar cell efficiency is by using an interference filter coating, which uses selective light reflection to create coloration [4]. The principle of selective reflection is based on nature. Beetles use this principle, for example, to achieve a metallic green color (Fig. 1). This leads to more sparkling (metallic) colors, and at the same time to much less loss of light entering the panel [5].

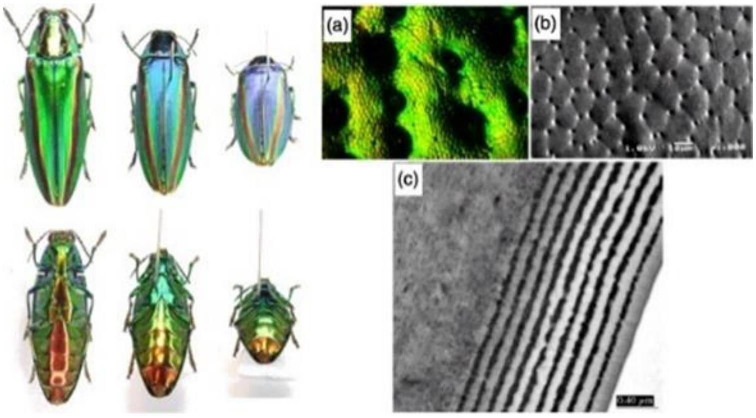

Figure 1 Structural color effect using an interference filter as a functional coating, based on green beetles in nature (reprinted with permission from [4]).

To achieve selective reflection, so-called interference filters will be used as a functional coating. Interference filters are multi-layer coatings, which alternately have a high and low refractive index, and are all between 30 and 200 nm thick. By properly setting layer thickness and refractive indices, all possible colors can be made with one and the same coating liquid, including architecturally relevant colors such as terracotta and light gray. The concept of using interference filter coatings for coloration of PV and solar collector panels has been reported by Schüler et al. [5-7] and is currently on the market sold by SwissINSO [8,9].

Another important aspect for colored PV is cost price and embodied energy. Currently multi-layer interference coatings for coloration of solar panels are produced by magnetron sputtering. This technique is commonly used in the glass industry, e.g. for production of energy-efficient window coatings. But the technique is cost and energy intensive, which increases the consumer costs of the colored PV and the embodied energy. Therefore a cheaper, less energy demanding production process is necessary to improve the energy balance and cost price of colored BIPV.

Sol-gel processing is a proven technology to produce highly damage resistant optical coatings for outdoor applications. DSM sells sol-gel derived coating processes for the production of anti-reflective coatings onto PV panels [10]. Schott and Prince Optics produce all kind of optical coating products for outdoor applications that are produced by sol-gel/dip-coating technique [11]. Estimated production costs for 50-100 nm single layer sol-gel coatings on a large scale are 3 €/m^2 depending on the material costs and the production volume. The two main benefits of sol-gel/dip-coat processing is that very homogeneous coating systems in the range of 20-200 nm can be obtained. It is a technique that is used to produce very precisely optical lenses. For colored coatings it is necessary that homogeneous layers can be produced. Also the refractive index can be easily adjusted by mixing of components in the coating solutions. The second benefit is that for prototypes the scale up to sizes up to 1.0 x 2.0 m^2 can be achieved relatively easy with low investment costs [12]. The sol-gel/dip-coating technique is a process that can be described in three main steps [12].

- Pre preparation. In the first step coatings solutions are prepared by mixing alkoxides with solvents and the substrates are cleaned.
- Coat process. In the second step a cleaned glass substrate is placed in a dip-coat machine and brought in the coating solution. The substrate is taken with an adjusted withdrawal speed from the coating solution.
- Cure process. After the coating step the coating is dried and cured.

For design purposes of the multi-layer interference stacks the thickness dependent optical constants and with them the transmission and reflection of multi-layer stacks can be calculated [6,13]. Via reverse engineering a required coating stack with material and layer thicknesses can be calculated to reach a desired color. For a proof of concept, we selected three commonly used colors, i.e. yellow green, tomato red and signal blue. We simulated 5 different coating stacks made of 3-5 alternating layers of SiO_2 and TiO_2, which resulted in reflection and transmission spectra shown in Figure 2. With these coating stacks the three selected colors could be achieved.

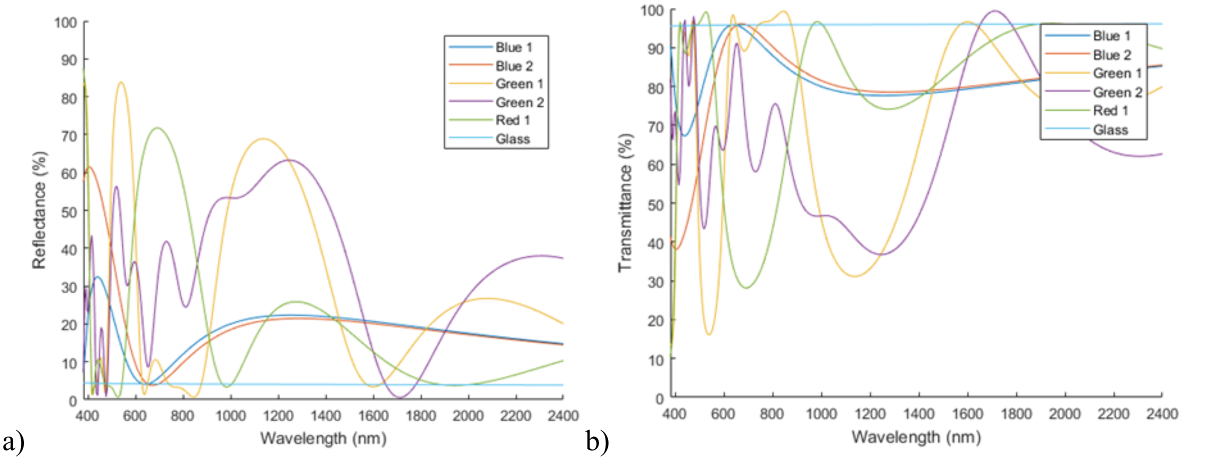

Figure 2. Simulated a) reflectance and b) transmission spectra for the 5 chosen coating stacks resulting in blue, green and red colored glass.

For experimental validation we selected two coating stacks representative for a blue and red color respectively. We used dip coating to prepare the alternating SiO_2 and TiO_2 coating stacks at the desired thicknesses resulting in the colored coatings predicted via simulations. Hereby we were able to coat 25 x 40 cm^2 glass plates with a red and a blue colored coating (Figure 3a,d). From Figure 3a and b it is clear that the blue sample is blue and the red sample is clearly red. The red sample is close to the terracotta color. In Figure 3b,e and Figure 3c,f the transmission and reflection data of the blue and red sample are given in the wavelength range 300-2400 nm. The reflection and transmission have been measured on five spots on the sample (for both samples), the curves are overlapping each other totally. This is an indication that the samples have very homogeneous optical properties.

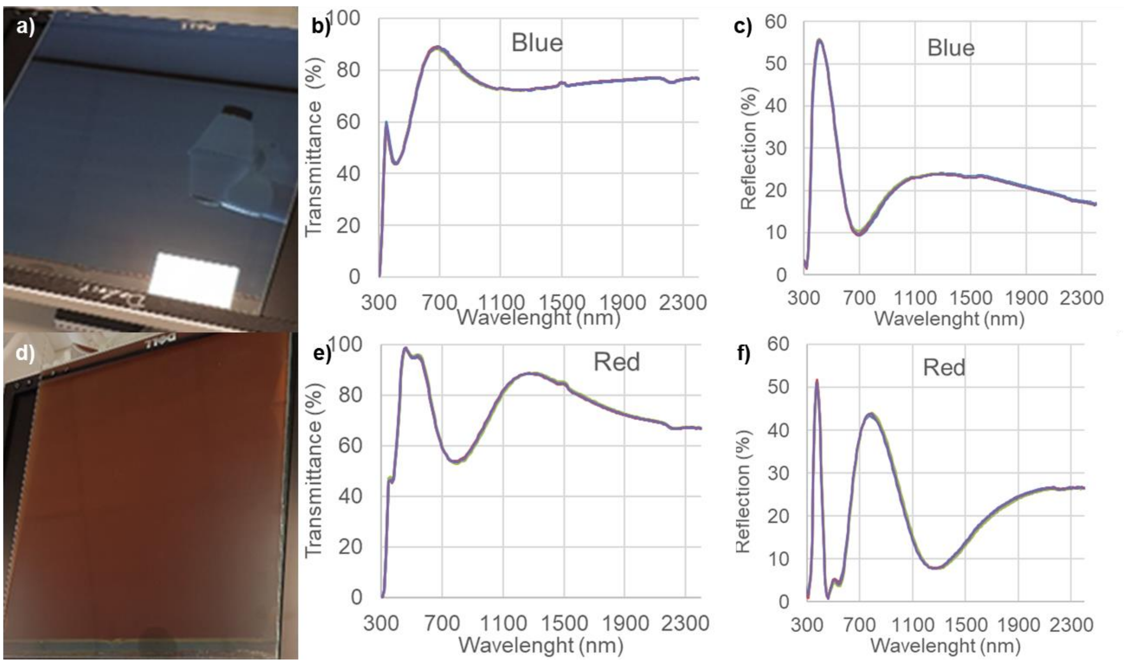

Figure 3. Appearance (a,d) and UV-vis-NIR transmission (b,e) and reflection (c,f) spectra of blue and red coated glass plates.

We compared the calculated optical properties with the measured optical properties of the manufactured sol-gel coatings. The reflection spectra of the blue and the red coating manufactured by sol-gel processing and by calculation were compared for the angles 0, 30 and 60°. Here a good comparison between both spectra could be shown. This means, that the optical calculation and manufacturing for the two prepared colors is quite in agreement. Furthermore we analyzed the color differences (*ΔE*) between the simulated and the prepared blue sol-gel and red sol-gel coatings. For all angles the color differences between the prepared and calculated spectra was lower than 6, which is an exactable result. Additionally we calculated the efficiency of total light transmission for the colored glass plates in comparison to clear glass. Here both colors only showed a reduced light transmission of approximately 20% over the whole spectrum. Since the external quantum efficiency of silicon PV is in a wavelength region between 300-1100 nm where high transmission values are achieved, the total efficiency loss by use of the colored glass plates as cover for solar panels is expected to be even lower.

For demonstration purposes the cover glasses have been applied to custom-made PV panels (Figure 4) and have been tested on the roof of a test building for a period of more than two years. Both coatings and colored panels were found to be stable in these tests, and no decrease in electricity production over time was observed. Furthermore we analyzed the coatings durability and colorfastness in accelerated lifetime tests. Here we could validate the performance and durability of the coating for a period equivalent to 3 years. Additionally we analyzed the pencil hardness of the coating which resulted in a hardness of >9 H for the red and blue coating.

Figure 4. Colored coatings on cover glass of PV panels, integrated and demonstrated on the roof of a test building by TNO and Zuyd.

In conclusion, we showed that glass plates can be colored by use of an interference filter. The required coating stack can be designed using optical calculations and produced on glass plates via solution processed dip coating. This enables the low cost production of colored cover glass for solar panels. The structural color coatings can be used on BIPV panels for roof tiles, building façades and other structural elements, as well as on solar collector panels. BIPV panels with the structural color coating show high cell efficiencies and power output. The power output is up to 20% higher than for panels colored with traditional pigments. Furthermore we have analyzed the performance, durability and colorfastness of the colored PV panels in real environment and in accelerated lifetime tests. Here no degradation or performance loss could be observed in a period of over 3 years. The outside test is still ongoing.

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