Presented at the 33rd European PV Solar Energy Conference and Exhibition, 25-29 September 2017, Amsterdam, The Netherlands

MORPHO BUTTERFLY INSPIRED COLOURED BIPV MODULES

Benedikt Bläsi, Thomas Kroyer, Oliver Höhn, Martin Wiese, Claudio Ferrara, Ulrich Eitner, Tilmann E. Kuhn
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstraße 2, 79110 Freiburg, Germany

ABSTRACT: In order to support acceptance and attractivity of building integrated PV (BIPV), there is a rapidly increasing demand for coloured PV modules. Especially, architects and building planners wish an individual colour choice, saturated colors, a homogeneous appearance for all angles of incidence and at the same time a high module efficiency. Furthermore, it is important that glare effects can be suppressed. State of the art concepts offer a restricted choice of colours, show a strong angular dependence, cause a high efficiency loss or do not allow for an efficient industrial production. We overcome these restrictions by using the Morpho butterfly effect, a bionic concept based on 3D photonic structures. Our novel technological realization of these structures is well suited for large scale production.

Keywords: Building Integrated PV (BIPV), Optical Properties, Module Manufacturing

1 INTRODUCTION

A detailed analysis of pathways for transforming the German Energy System by 2050 into a renewable energy system has shown that there a several alternatives of cost-effective energy systems and that these cost-effective energy systems include an installation of PV powerplants with 120 – 290 GW_p. This means that pv-modules with an area of 1200 – 2900 $km^2 \approx 15 – 36\ m^2$/capita would have to be installed. The study considers all sectors and energy carriers. The model-based study investigates scenarios of system development and related costs to transform Germany's energy system in line with climate protection targets. [1].

Another recent study has shown that the technically and economically feasible area on roofs and facades of buildings is much larger than the required PV area for a renewable energy system [2].

We assume that the findings for the German Energy system are applicable also to many other countries and that there is therefore a huge economic potential for BIPV-systems. This potential can only be harvested with technically and architecturally well designed BIPV building components. This does not only include an architecturally pleasing appearance but also high electricity yield in order to achieve the targeted CO_2-reduction in the building stock.

Principally there are two approaches to achieve a pleasant appearance:

(1) "visible PV": the arrangement of the PV-cells and the interconnections can be used a design pattern.

(2) "invisible PV": the modules can be completely black, white or coloured with invisible PV-cells and interconnectors.

In this paper, we focus on concepts with "invisible PV". More precisely, coloured modules with high saturation, angle independent colour appearance and a minimized colour induced efficiency loss are targeted.

Different technologies can be used in order to hide the cell array with coloured layers at the front cover of the module. The coloured layer can be either inhomogeneous or homogeneous. Frit printed dots are a typical example of an inhomogeneous layer. The colour impression is stronger when the density of the dots is increased, but the module efficiency decreases at the same time since the frit printed area is almost opaque. Homogeneous coloured layers should have a high transmittance in the wavelength range with non-negligible spectral responsivity of the pv-cells. Spectral selectivity of the colour layer generally leads to higher transmittance and higher colour saturation but it is difficult to achieve neutral colours like grey or white and the colour often depends on the viewing angle. State of the art concepts offer a restricted choice of colours or a low colour saturation, show a strong angular dependence, cause a high efficiency loss or do not allow for straightforward industrial production [3–9].

This paper presents a novel technological approach for coloured modules with high efficiency, strongly improved visual appearance and the possibility of industrialized mass production.

2 THE MORPHO BUTTERFLY EFFECT

2.1 Basic understanding of the Morpho effect

Microscopic analyses of scales on the wings of Morpho butterflies revealed a 3D structure consisting of vertical ridges with horizontal lamellae attached to them. The horizontal lamellae are stacked almost equidistantly, while the arrangement of the ridges shows no strict regularity, but a defined disorder.

The basic principle of the Morpho effect is that thin film interference effects and structure effects interact in one three-dimensional photonic structure [10]. Due to the complex interactions in this functional layer, the angle dependence that is typical for planar multilayer stacks can be compensated.

In Fig. 1, the main constituents of the Morpho effect as described in [11,12] are sketched: The spectral reflectance peak is caused by a Bragg stack interference effect. The finite width of the ridges (on the real butterfly appr. 500 nm) leads to diffraction and, hence, to angular spread. Finally, the disorder caused by the height variation reduces or even destroys the spatial correlation between the ridges. This leads to suppressed interference effects between the ridges.

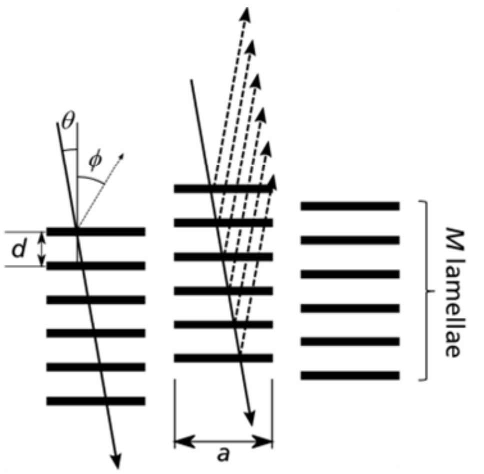

Figure 1: Main constituents of the Morpho effect: Interference from a finite Bragg stack (distance between lamellae d), diffraction from ridges of a given width a, and disorder caused by height variation. The angle of incidence is θ and the outgoing angle ϕ. (Sketches adapted from [11].)

2.2 From the 3D-Morpho to a corrugated thin film system

Structures as they can be found on the butterfly´s wing are extremely challenging to manufacture, especially if large area applications are aimed for. However, Chung et al [13] demonstrated that the Morpho effect can also be reproduced by a multilayer Bragg stack with alternating high and low refractive index (n_{high} and n_{low}) layers deposited on a substrate of defined roughness.

3 EXPERIMENTAL REALIZATION

The basic idea for the experimental realization has already been described in [14] and filed as a patent. However, in this earlier publication, only first qualitative results on glass samples could be shown, while in this paper PV module results are presented.

3.1 Module concept

For the integration in a PV module, the functional layer is applied to the rear surface of the module glass by a combination of structuring and sputter coating. In a standard laminated module it therefore is situated between glass and laminate (e.g. EVA). This means, that only the front glass has to be exchanged compared to standard module production. On the front side of the module glass, a texture may be applied in order to further enhance the colour tolerance and suppress glare effects (Fig. 2).

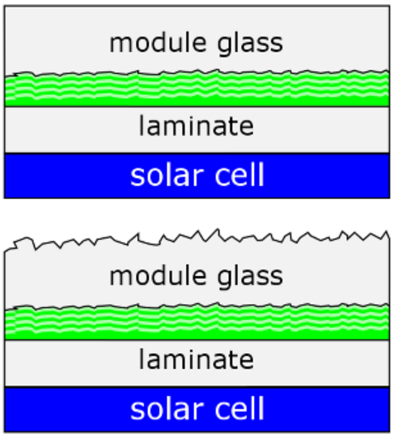

Figure 2: Sketch of the coloured module concept: the functional layer (green) is at the rear of the cover glass and in contact with the laminate. The front surface of the glass may be planar (top) or textured (bottom).

3.2 Morpho structures on Glass samples

To demonstrate the Morpho effect, glass samples were fabricated on small scale for the three colours red, green and blue. These glass samples were put on top of mini PV modules. The reflection at the intermediate interfaces (between glass sample and mini module) in the case of an air gap was eliminated by using a water film for approximate index matching. The photograph (Fig. 3) shows nicely the saturated colour. In the left part of the photograph, the module is not covered by the colour filter. So the dark grey solar cell is visible. In the central and right part, it can be seen that the bright colours only show up in the places where the cell is behind the filter. In the other areas with white background, high transmission is demonstrated. In a BIPV module, a homogeneous appearance with saturated colour will be achieved by using a black back sheet, black interconnectors and back junction cells (see below).

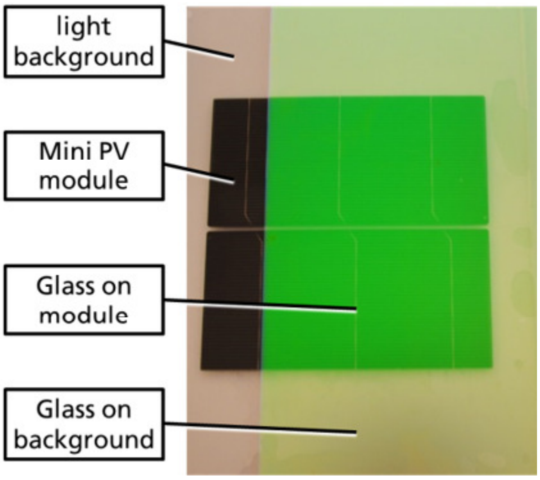

Figure 3: Photograph of a glass pane with colour layer applied to a mini module using a water film. In the left part of the photograph, the module is not covered by the colour filter. So the dark grey solar cell is visible. In the central and right part, it can be seen that the bright colours only show up in the places where the cell is behind the filter. In the other areas with light background, high transmission is demonstrated.

At these glass samples, angle dependent spectrometric reflectance measurements were performed. For the green coloured glasses, the spectra are shown in Fig. 4. One can clearly see the distinct and narrow reflectance peak at approximately 550 nm. Furthermore, the high angular stability of the peak position is evident.

It has to be noted that the spectra show additional reflection effects from rear interface (Morpho layer/air), which lead to a higher overall reflectance and a reduced saturation compared to the encapsulated module configuration.

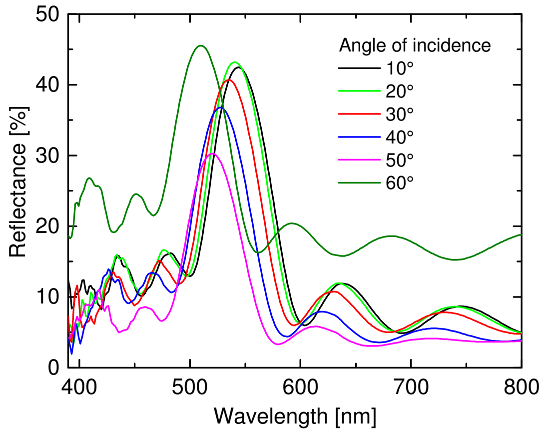

Figure 4: Angle dependent reflectance spectra, measured at the glass pane with green colour layer.

The measured reflectance spectra were used to deduce the colour appearance – via the representation of the spectra in RGB space (Fig. 5). Even though the RGB representation strongly depends on display and print properties, the high angular stability of the colours can be seen clearly.

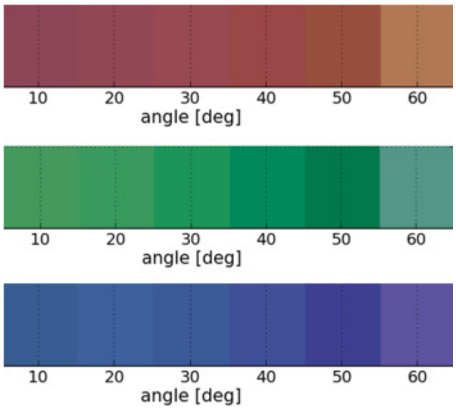

Figure 5: Representation of the measured reflectance spectra in RGB space.

In order to show the low angular dependence of the colours quantitatively, also the representation in the CIE chromacity diagram [15] is given (Fig. 6). Here x and y represent the normalized response of the blue and green receptors of the human eye. (The response of the red receptors is z = 1 – x – y.) The relatively large difference between the 50° and 60° values is caused by an enhanced overall reflectance at 60°, mainly caused by the rear interface. This effect can also be seen at the 60° spectrum in Fig. 4. In the laminated module, this effect will be suppressed.

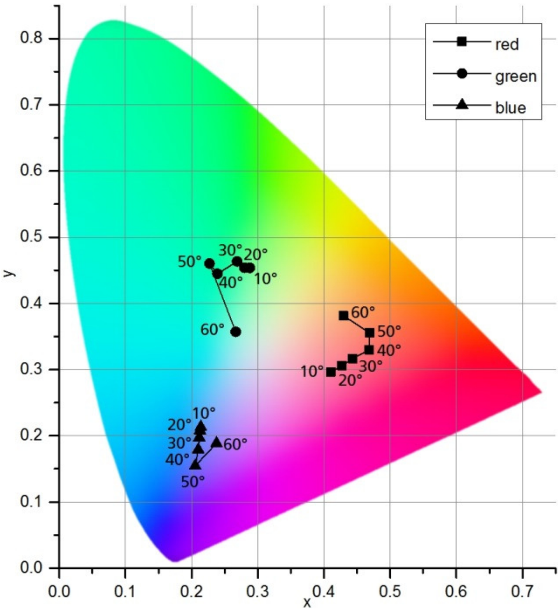

Figure 6: Representation of the measured reflectance spectra in the CIE chromacity diagram. The white point is at x = y = 0.33.

If one compares the reflectance spectrum with the external quantum efficiency (EQE) of a c-Si solar cell, it is evident that the reflectance is very low over the major part of the relevant spectral region. Hence, the module performance will not be strongly affected by the additional reflection losses. Since the Morpho layer/air interface leads to an enhanced reflection, the real module losses can be expected to be even lower. This is in line with the results shown in section 3.3.

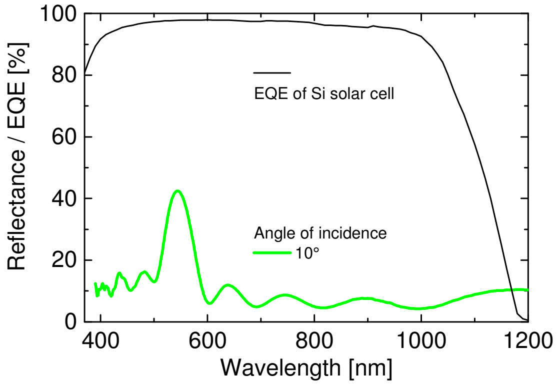

Figure 7: Comparison of measured reflectance spectrum (glass ample) and EQE of a c-Si solar cell.

3.3 Coloured modules

Demonstrator modules of the format 56 x 57 cm^2 (4 x 4 cells) were fabricated in the Module-TEC at Fraunhofer ISE. To show the effect of the functional layer, 8 modules with 3 different colours and 2 with uncoated glass were manufactured (Fig. 8). To reduce any disturbing internal reflection within the modules and maximize the effect of the filters the material selection was optimized. The used Sunpower Corp. back contact solar cells suit perfectly due to the missing metallization on the front side and thus appear homogeneously dark.

Figure 8: Photograph of the 56 x 57 cm^2 demonstrator modules with 4 different coating setups showing the colours red, green and blue; bottom right: uncoated glass.

To reduce the visibility of the electrical interconnection between the solar cells, we blackened the used connectors. For the rear side of the modules, a low reflective and deep dark backsheet foil was applied. (Fig. 9)

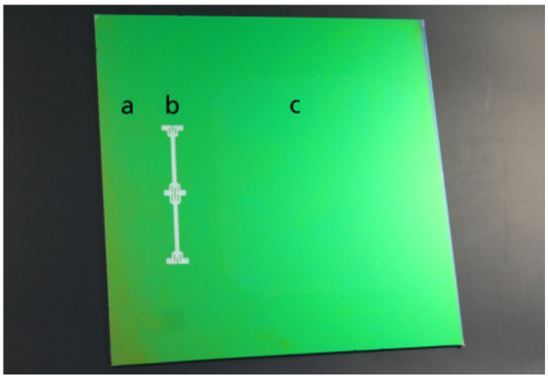

Figure 9: Photograph of a laminated test sample (20 x 20 cm^2) with green filter. Between cover glass and black backsheet, two interconnectors and one solar cell were laminated as demonstration.
Below a: blackened interconnector (invisible),
below b: standard interconnector,
below c: solar cell (invisible).
In a real module, only the narrow part of the interconnectors would be visible.

From a distance of only 1 m the modules appear highly homogenous and cells as well as connectors are invisible. Taking a closer look only the contours of the solar cell is visible due to the small mismatch in terms of colour and scattering between backsheet and solar cell. (Fig. 10)

Figure 10: Close up photograph of blue demonstrator. Electrical cell interconnection is matching to backsheet in terms of colour. Only contours of solar cells are slightly visible from a few distinct viewing angles.

The production of the modules themselves is equal to the manufacturing process of standard PV modules and thus should be transferable to any module production line as long as it is capable of interconnection of back contact solar cells. The module technology is also feasible with standard solar cells but with a slightly decreased overall homogeneity due to the high difference in terms of reflection between metallization and solar cell surface as well as the electric interconnectors.

For large area demonstration, the functional layer was applied to glass panes of the format 1.09 x 1.12 m^2 (7 x 7 cells). With these glass panes, PV module lamination was done at Ertex Solartechnik GmbH. As above, back contact solar cells from Sunpower Corp. and a black backsheet were used in order to achieve a homogeneous colour appearance with very high saturation (Fig. 11).

Power rating measurements at ISE CalLab PV Modules showed an extremely low colour induced efficiency loss. Compared to an uncoated cover glass, the relative loss of generated solar power for the coloured modules is appr. 7%. The power loss is in the same range for all three colours.

Figure 11: Photograph of the large area demonstration modules with the colours blue, green and red.

4 CONCLUSIONS

Using the Morpho effect, brightly coloured PV modules with high angular tolerance can be fabricated. We demonstrated the exemplary colours red, green and blue on large format BIPV modules.

With this technology, a large variety of colours can be achieved. A given colour appearance can be obtained by adapting the film and structure design of the photonic layer. Furthermore, mixed colours out of the RGB colour space can be composed out of functional layers for red, green and blue, respectively. With this approach a broad range of designs can be made accessible for architects. Since only the module glass is modified, standard solar cells can be used independent of the module design, making this approach also economically very promising. Similarly, the approach is applicable to solar thermal collectors.

5 ACKNOWLEDGEMENTS

Part of this work was funded by the German Federal Ministry of Economic Affairs and Energy under Contract Number 03ET1035A.

6 REFERENCES

[1] H.-M. Henning and A. Palzer, *What will the energy transformation cost? Pathways for transforming the German energy system by 2050*, 2015, www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/What-will-the-energy-transformation-cost.pdf.

[2] K. Fath, *Potenzial für Photovoltaik an Gebäuden in Deutschland. Entwicklung einer Methodik für großflächige solare Einstrahlungssimulationen und Hochrechnung mittels Data Mining*, Dissertation, KIT, 2017.

[3] A. Schüler, J. Boudaden, P. Oelhafen, E. de Chambrier, C. ROECKER, and J.-L. Scartezzini, "Thin film multilayer design types for colored glazed thermal solar collectors," Solar Energy Materials & Solar Cells **89**, 219–231 (2005).

[4] J. H. Selj, T. T. Mongstad, R. Søndenå, and E. S. Marstein, "Reduction of optical losses in colored solar cells with multilayer antireflection coatings," Solar Energy Materials & Solar Cells **95**, 2576–2582 (2011).

[5] F. Frontini, A. Scognamiglio, G. Graditi, C. Polo López, and M. Pellegrino, "From BIPV to Building Component," in *Proceedings of the 28th European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC)* (WIP, 2013).

[6] E. Klampaftis, D. Ross, and B. S. Richards, "Color, graphic design and high efficiency for photovoltaic modules," in *Proceedings of the 40th IEEE Photovoltaic Specialists Conference (PVSC)* (IEEE, 2014), pp. 25–29.

[7] V. Caer and A. Schuler, Laminated glazing with coloured reflection and high solar transmittance suitable for solar energy systems, US20150249424 A1 .

[8] C. Ballif, *Novel designs and materials for durable PV modules: applications on the ground, in cities and in the air* (2017).

[9] V. Neder, S. L. Luxembourg, and A. Polman, "Efficient colored silicon solar modules using integrated resonant dielectric nanoscatterers," Appl. Phys. Lett. **111**, 73902 (2017).

[10] S. Kinoshita, S. Yoshioka, and K. Kawagoe, "Mechanisms of structural colour in the Morpho butterfly: cooperation of regularity and irregularity in an iridescent scale," Proceedings of the Royal Society B: Biological Sciences **269**, 1417–1421 (2002).

[11] S. Kinoshita, Yoshioka S., Fujii Y., and Okamoto N., "Photophysics of Structural Color in the Morpho Butterflies," Forma **17**, 103–121 (2002).

[12] S. Kinoshita, S. Yoshioka, and J. Miyazaki, "Physics of structural colors," Rep. Prog. Phys. **71**, 76401 (2008).

[13] K. Chung, S. Yu, C.-J. Heo, J. W. Shim, S.-M. Yang, M. G. Han, H.-S. Lee, Y. Jin, S. Y. Lee, N. Park, and J. H. Shin, "Flexible, Angle-Independent, Structural Color Reflectors Inspired by Morpho Butterfly Wings," Adv. Mater. **24**, 2375–2379 (2012).

[14] B. Bläsi, T. Kroyer, O. Höhn, C. Ferrara, and T. E. Kuhn, "Coloured Module Glass for BIPV inspired by Morpho Butterfly," in *2016 OSA Light, Energy and the Environment Congress* (OSA, 2016), PW5A.2.

[15] E. C. Carter, Y. Ohno, M. R. Pointer, A. R. Robertson, R. Seve, J. D. Schanda, and K. Witt, *Colorimetry*, 3. ed. **15** (CIE, Central Bureau, 2004).