The MorphoColor™ Concept for Colored Photovoltaic Modules and Solar Thermal Collectors

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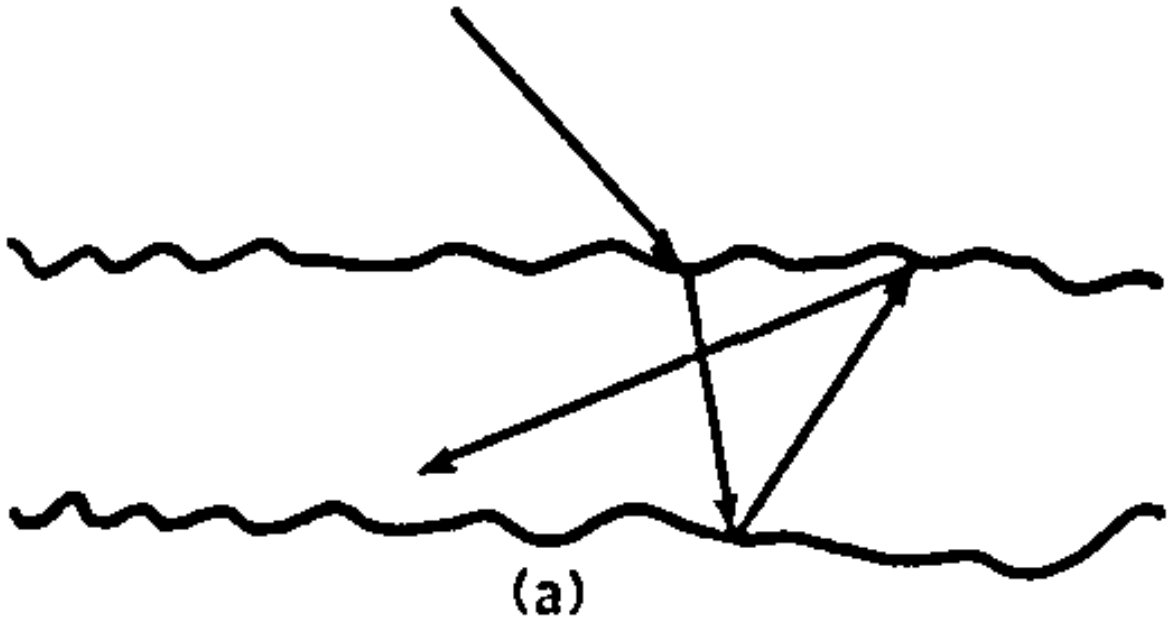
Fraunhofer Institute for Solar Energy Systems ISE

Symposium 40 Years of Light Management

OSA Advanced Photonics Congress 2021

29th July 2021

Introduction
40 Years of Light Management …

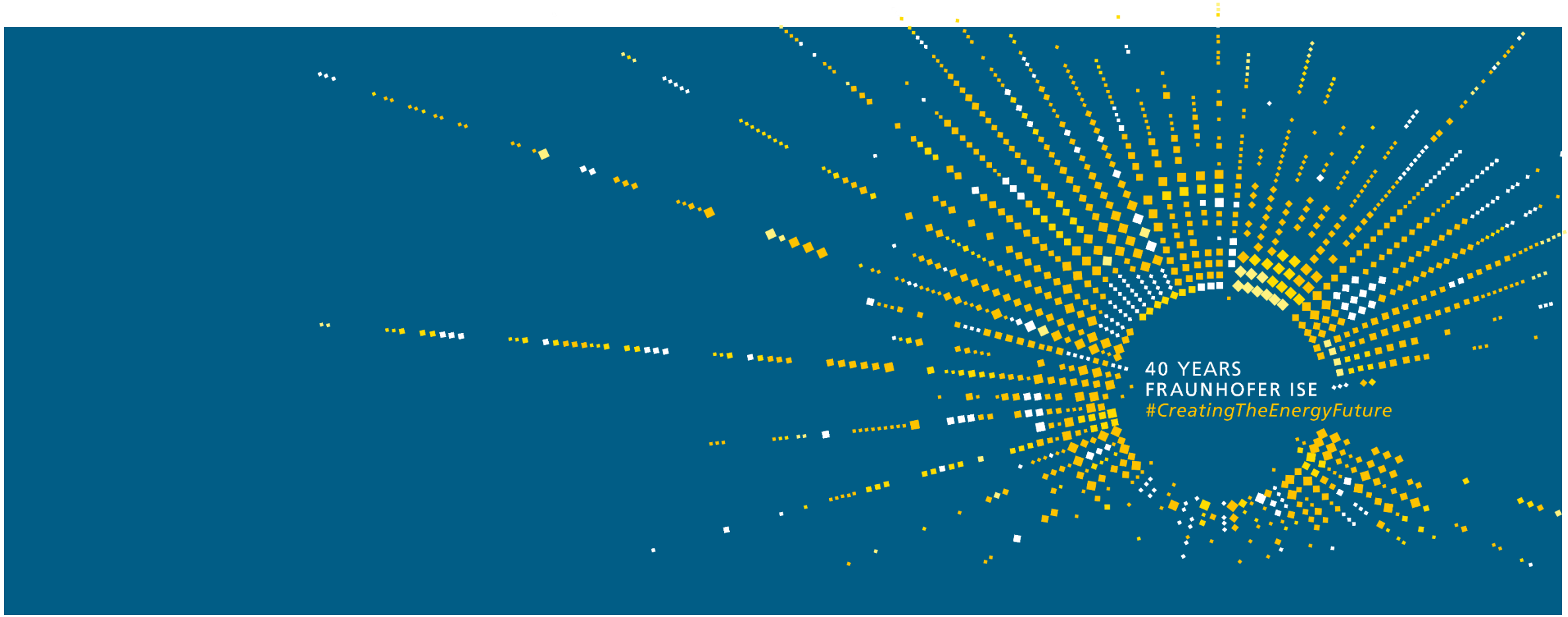


Yablonovitch, E. (1982): Statistical ray optics.
J. Opt. Soc. Am. 72 (7), S. 899–907. DOI: 10.1364/josa.72.000899.

Introduction

40 Years of Light Management …

… and 40 Years of Fraunhofer Institute for Solar Energy Systems ISE



Introduction

40 Years of Light Management …
… and 40 Years of Fraunhofer Institute for Solar Energy Systems ISE

Adolf Goetzberger:
Optical confinement in thin Si-solar cells by diffuse back reflectors.
In: Proceedings of the 15th IEEE Photovoltaic Specialists Conference, S. 867–870 (1981).

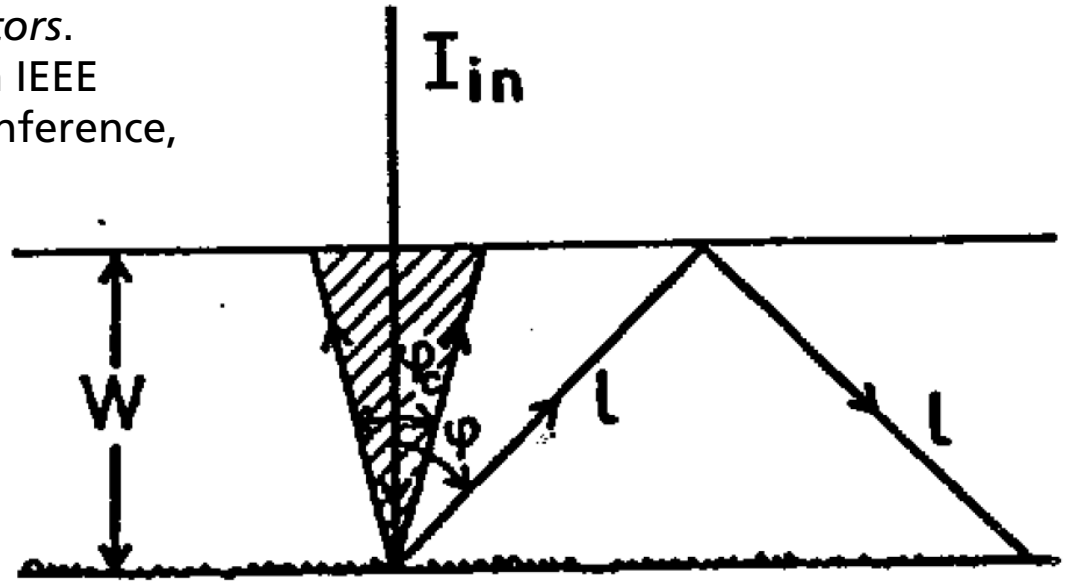
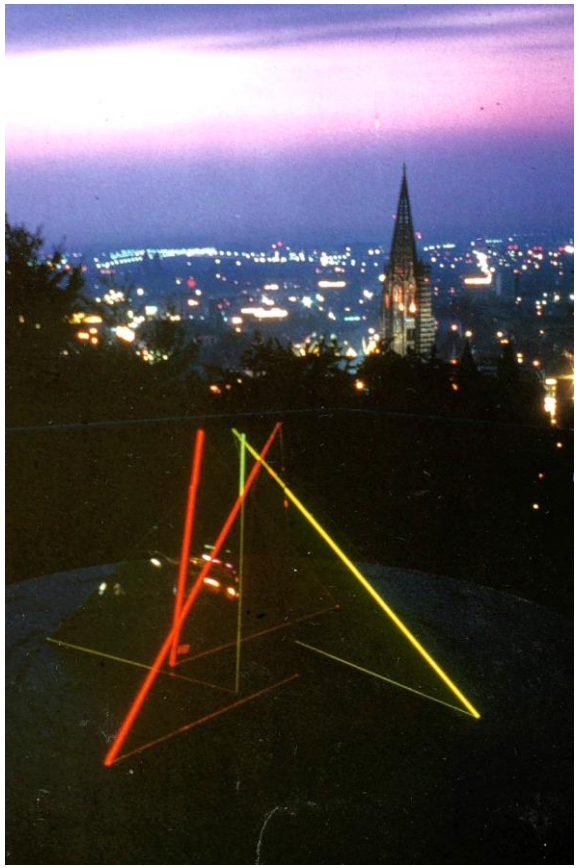
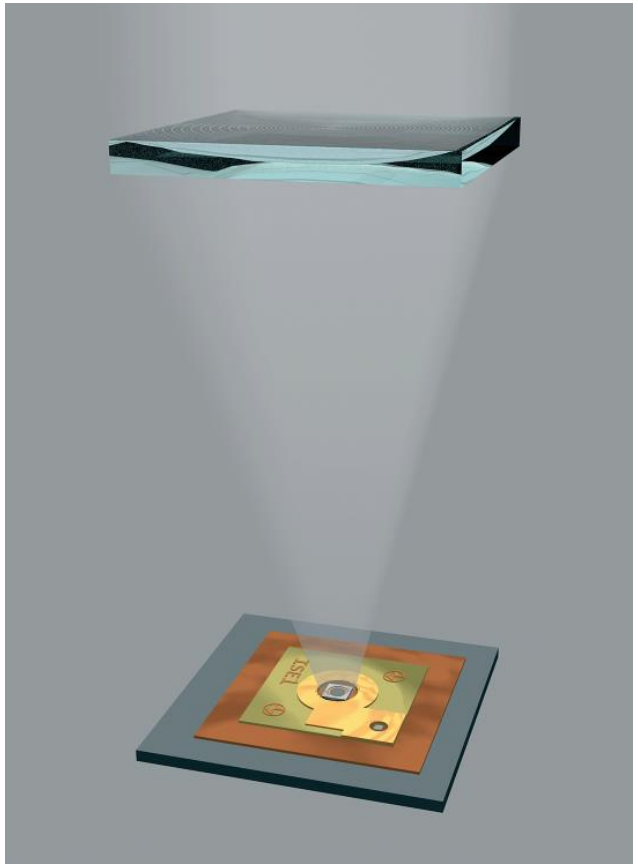


Fig. 2: Diffuse back reflector leads to loss cone determined by critical angle for total internal reflection φ_c.

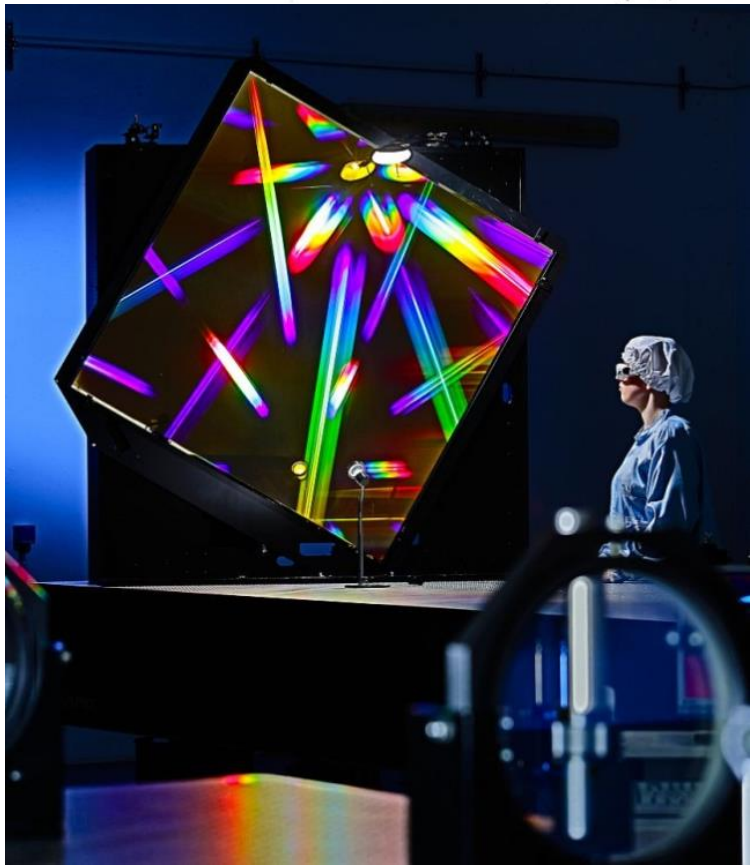
Introduction
Light Management at Fraunhofer ISE



Fluorescent concentrator



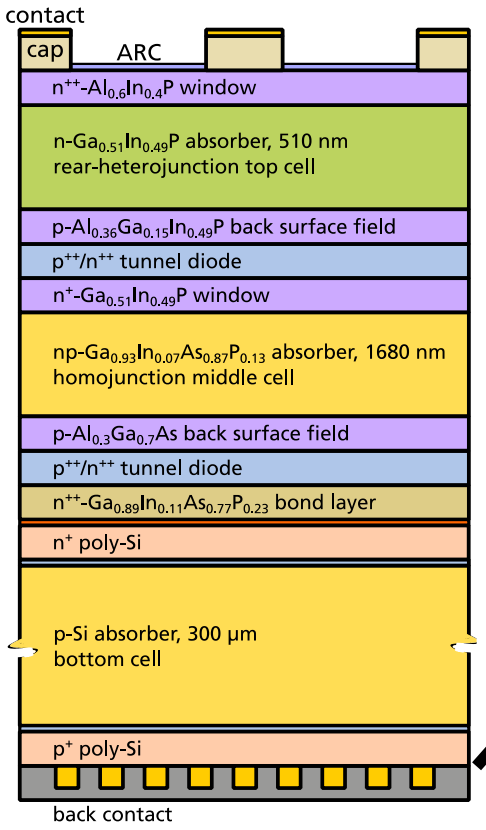
Concentrating photovoltaics

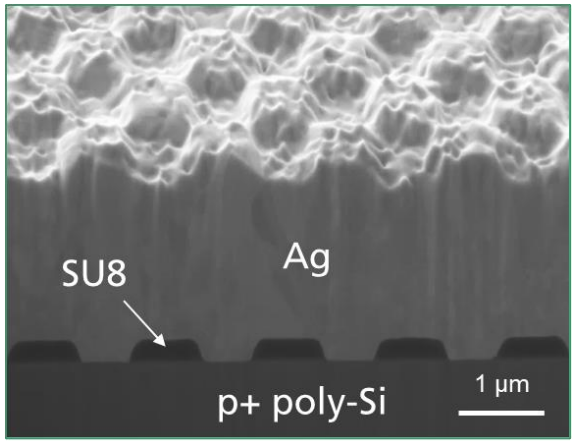


Large area micro-/nanostructures

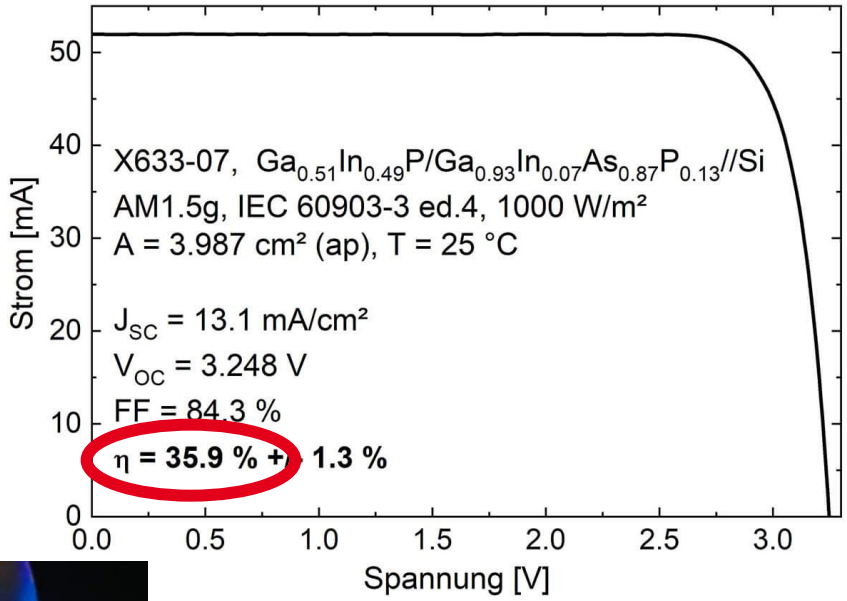
Introduction
Light Management at Fraunhofer ISE

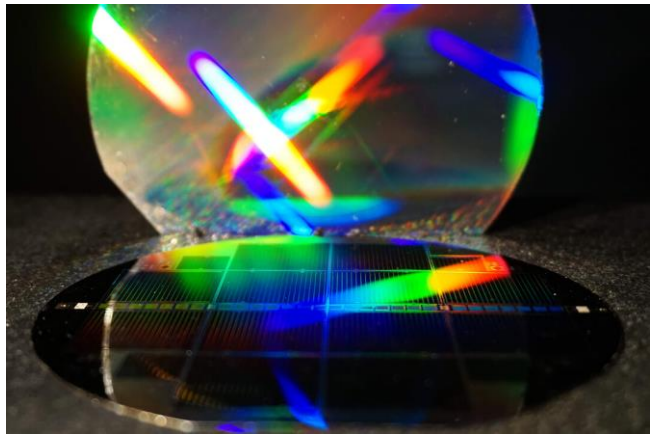
III-V//Si triple junction solar cell with rear side grating





R. Cariou et al,
Nat. Energy 17,
S. 183 (2018).





Fraunhofer ISE press release: "Tandem Photovoltaics Enables New Heights in Solar Cell Efficiencies – 35.9 % for III-V//Silicon Solar Cell", April 23, 2021

Motivation

High Efficiencies Essential for Solar Energy Systems

Motivation

High Efficiencies Essential for Solar Energy Systems … but also Acceptance!

- Building Integrated PV (BIPV) has a huge potential (roofs and façades)
- E.g. Germany: PV potential in buildings twice of what´s needed for energy transition
- Integration of PV more likely if
  - people like it
  - heritage protection can be fulfilled

➔ Aesthetics is a key for acceptance

- *But*: Aesthetics should not impair efficiency

Photo: Joachim Gattenlöhner

Motivation

Vehicle Integrated Photovoltaics (VIPV): Fueling Future Cars

- High performance shown already decades ago:
  - Mercedes Solar Silver Arrow (Tour de Sol, 1985, Switzerland)
- > 10 000 km/year solar powered possible*
- Again: To enable large scale deployment, good integration is the key

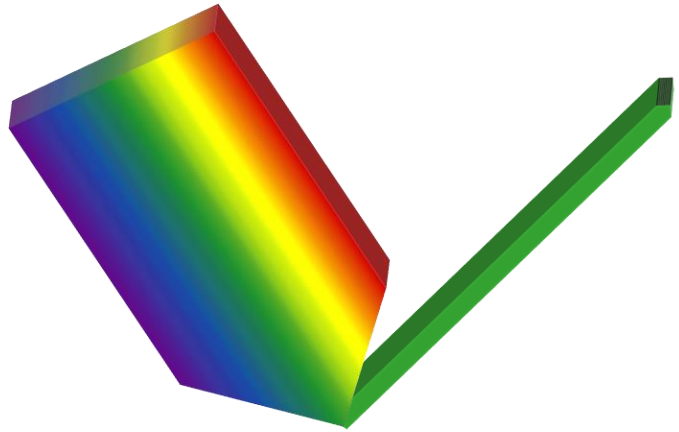
© AEG Telefunken, Wedel

*M. Heinrich et al, „Potential and Challenges of Vehicle Integrated Photovoltaics for Passenger Cars“, EU-PVSEC 2020, 6DO.11.1

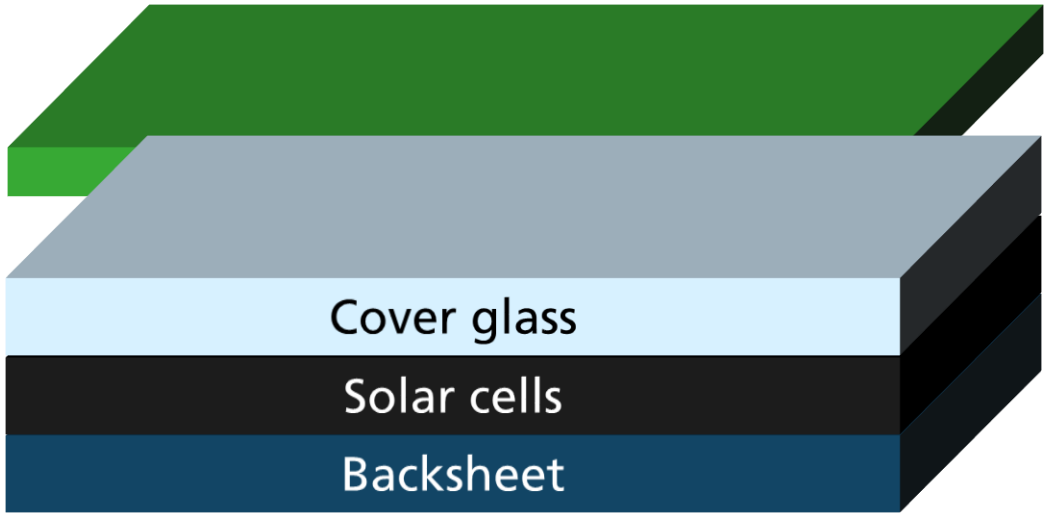
Motivation

What is needed for good integration with high efficiency?

- Colored modules and collectors with
  - Bright, but also muted color choice
  - Angular stability of the color effect
  - High efficiency



- More technically
  - No absorption
  - Spectrally narrow reflectance
  - ➔ Minimized loss
  - ➔ High color saturation



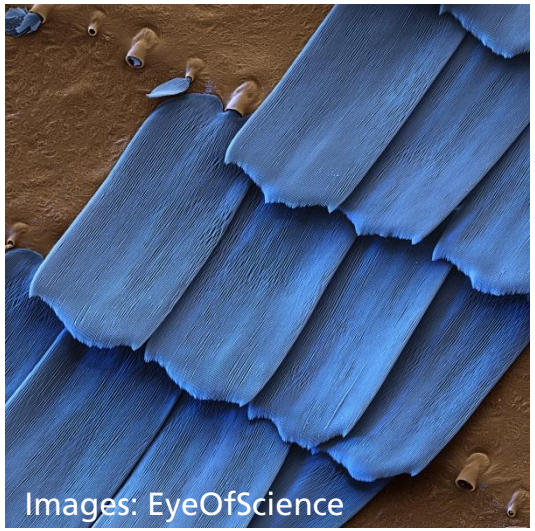
- Color layer integrated in module

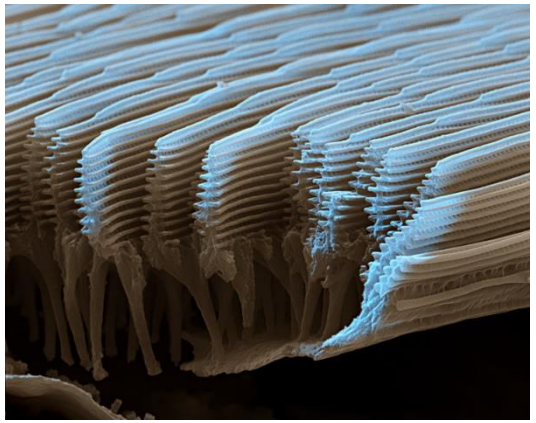
Motivation
Inspiration from Nature

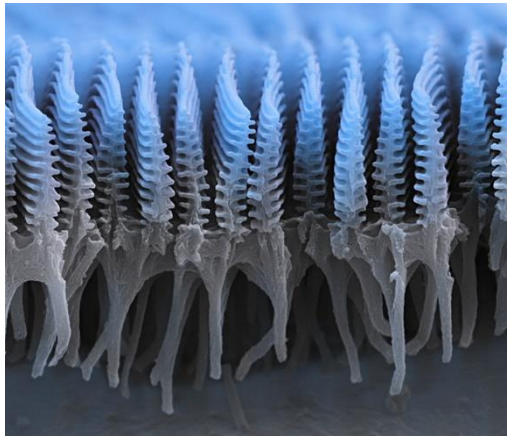
- The Morpho butterfly features
  - Bright blue color
  - High angular tolerance
  - BUT: no transmission!

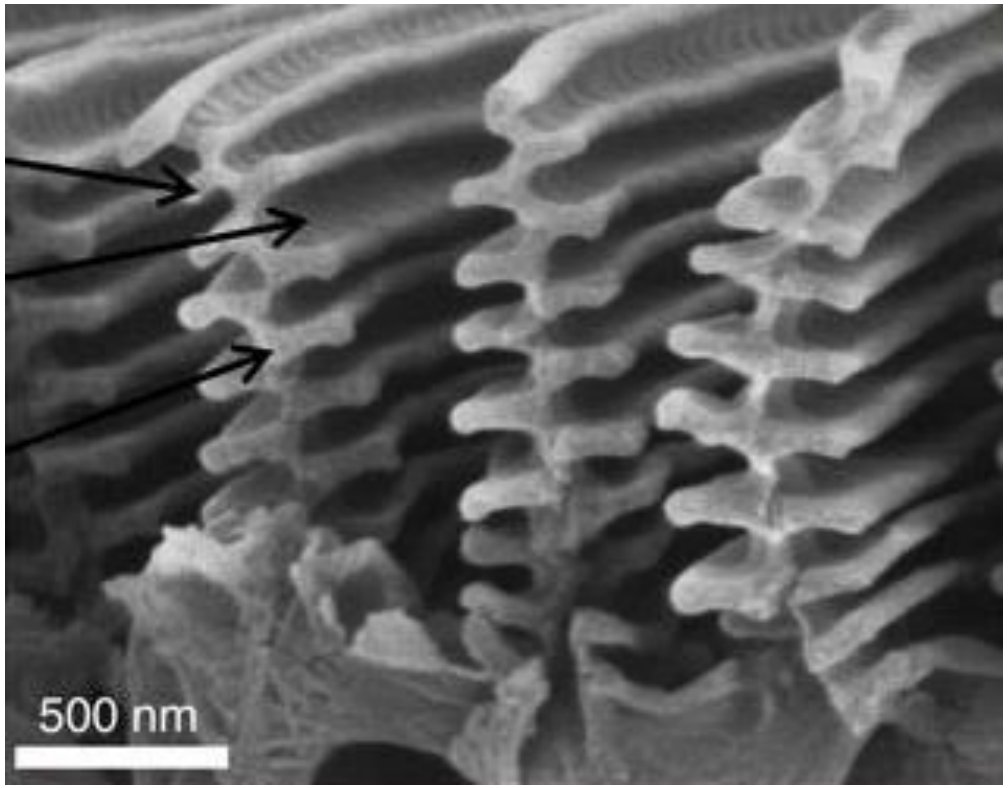
➔ **Take up the inspiration and adapt it!**

Where do the colors come from?
The Morpho Butterfly







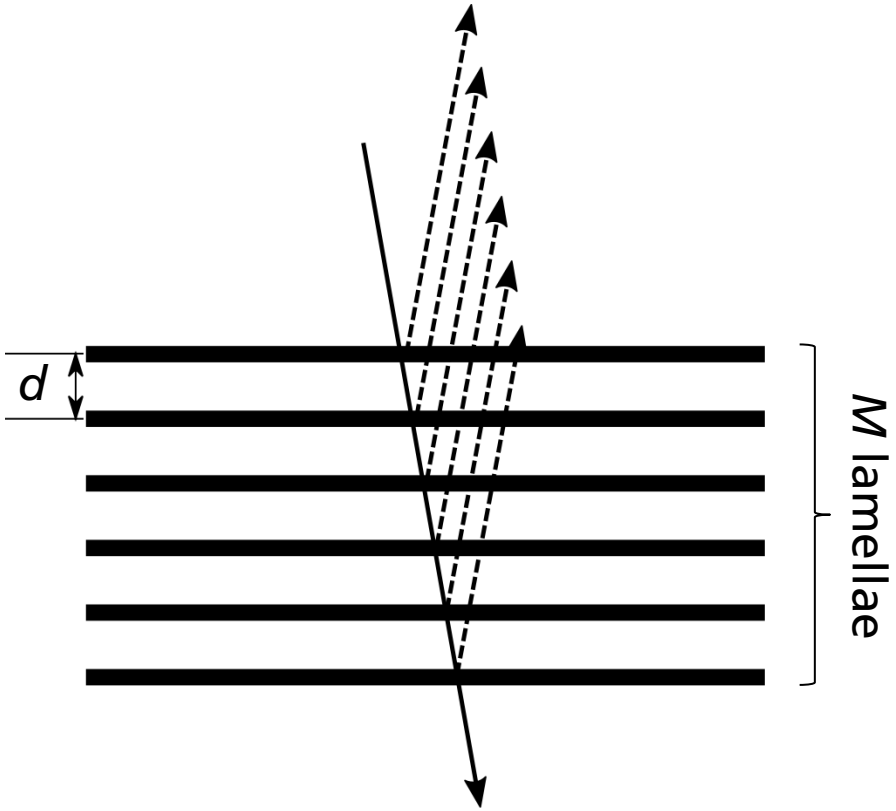


R. A. Potyrailo, et al,
Nature communications **6**, 7959 (2015).

Where do the colors come from?
A Simple Model to Explain the Morpho Effect

Basic idea

- Color from Bragg stack consisting of *M* thin lamellae



Where do the colors come from?
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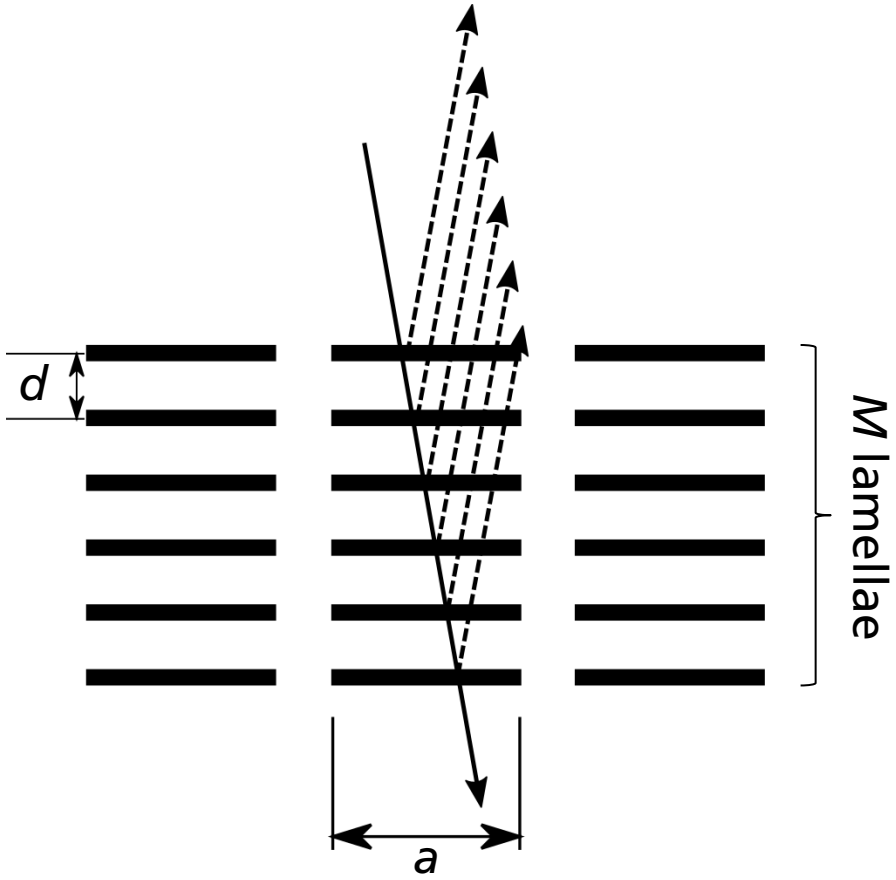
Basic idea

- Color from Bragg stack consisting of *M* thin lamellae
- Lateral assembly of ridges of width *a*



Sketch adapted from:

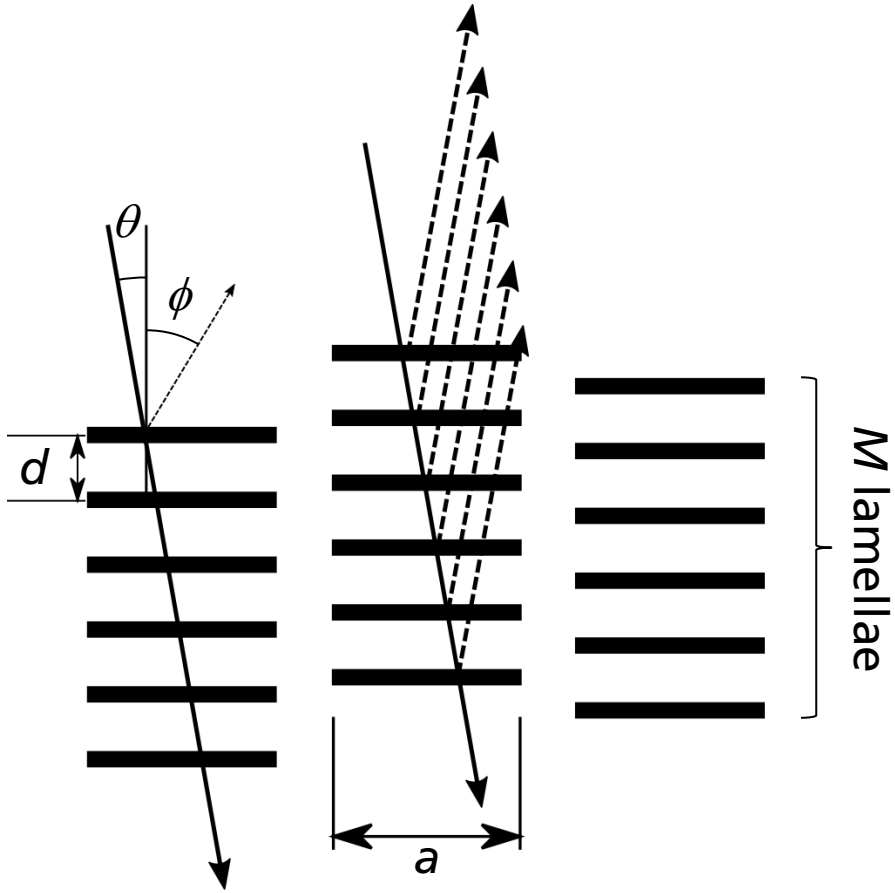
S. Kinoshita, et al,
Forma **17**, 103–121 (2002).

Where do the colors come from?
A Simple Model to Explain the Morpho Effect

Basic idea

- Color from Bragg stack consisting of *M* thin lamellae
- Lateral assembly of ridges of width *a*
- Disorder

➔ Angular spread from diffraction at ridges and disorder



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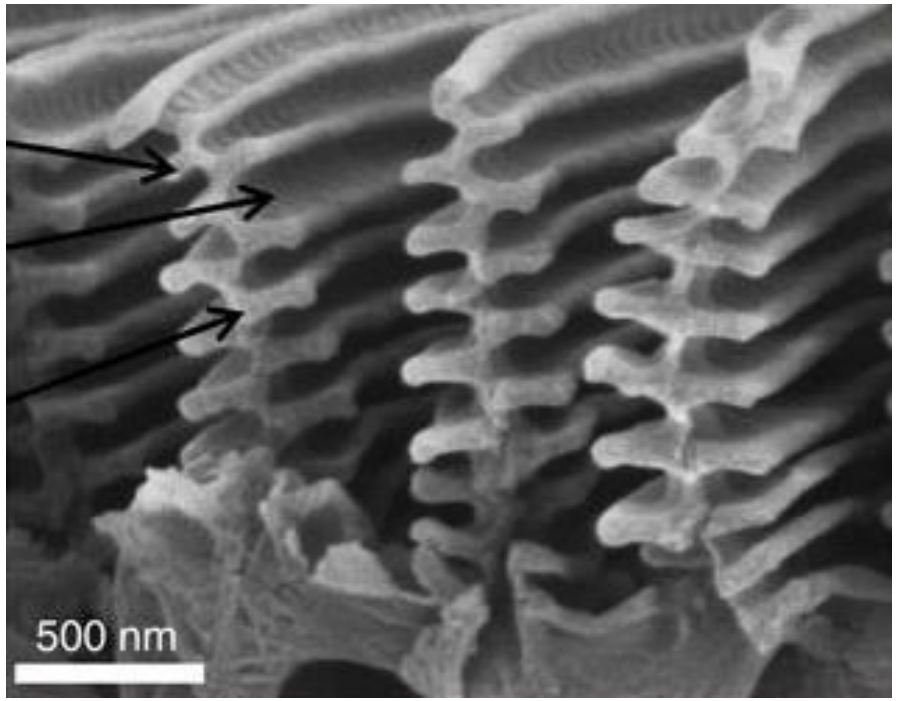

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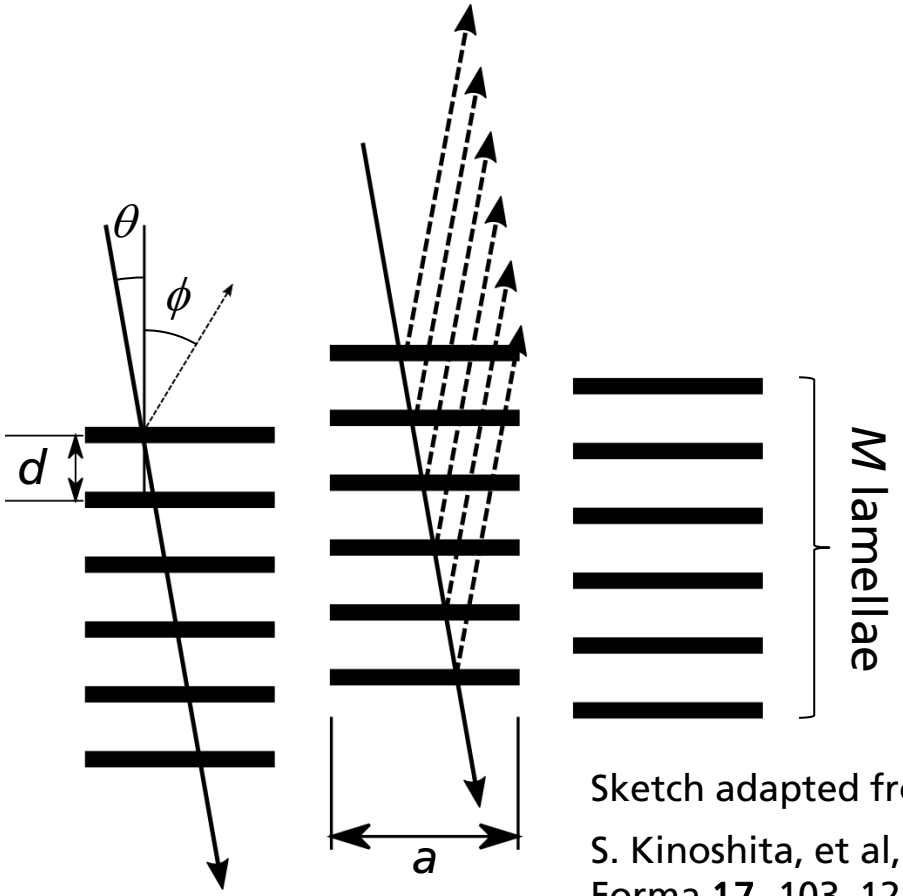

Sketch adapted from:

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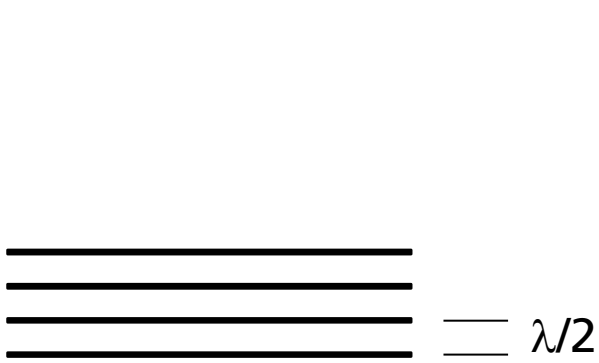
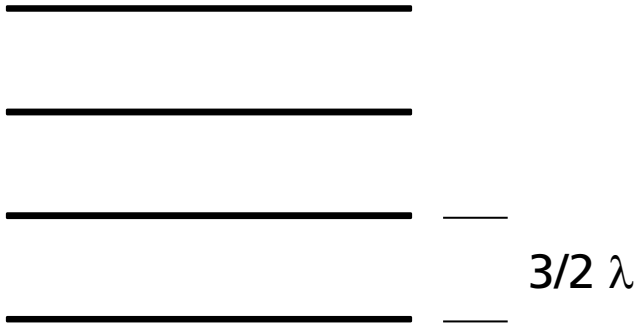
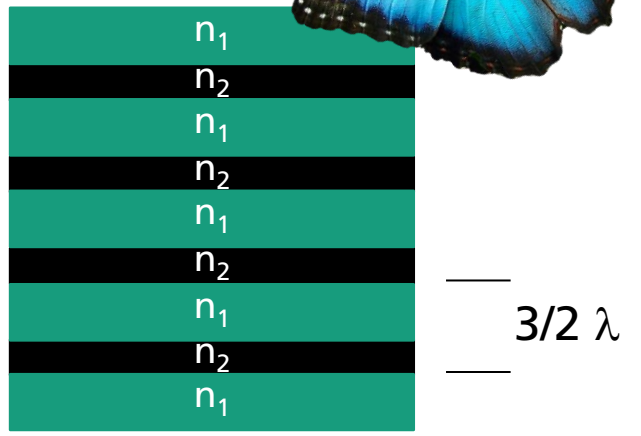
Forma **17**, 103–121 (2002).

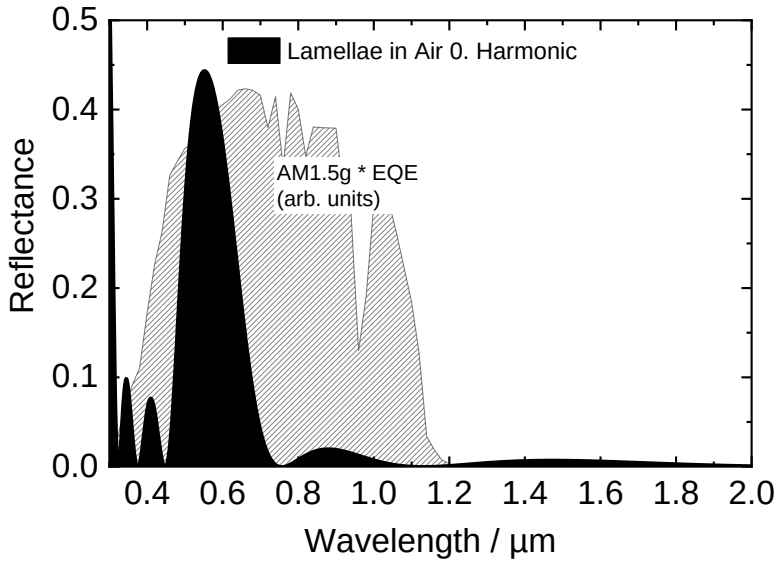
The MorphoColor™ Concept

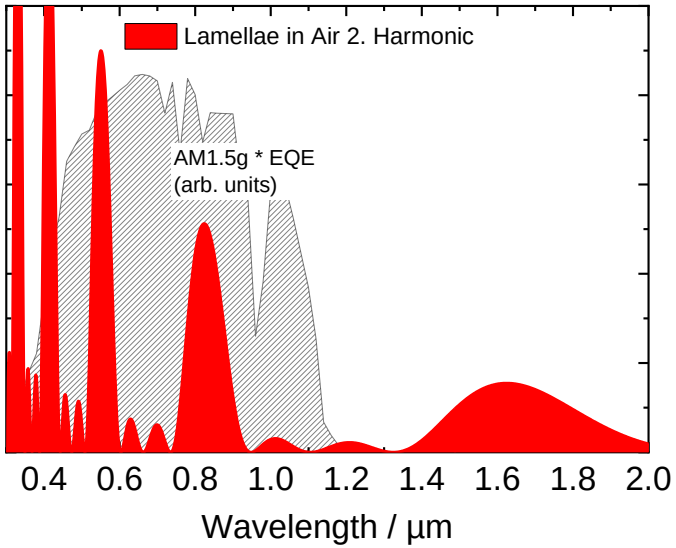
How do we get a narrow reflectance peak?

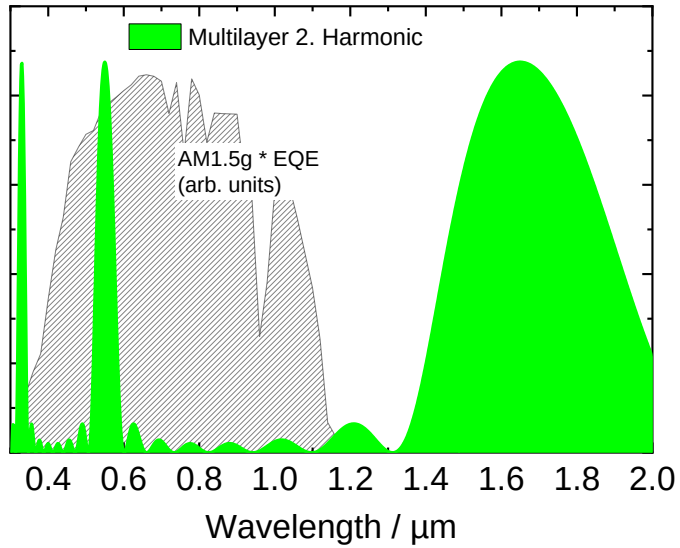










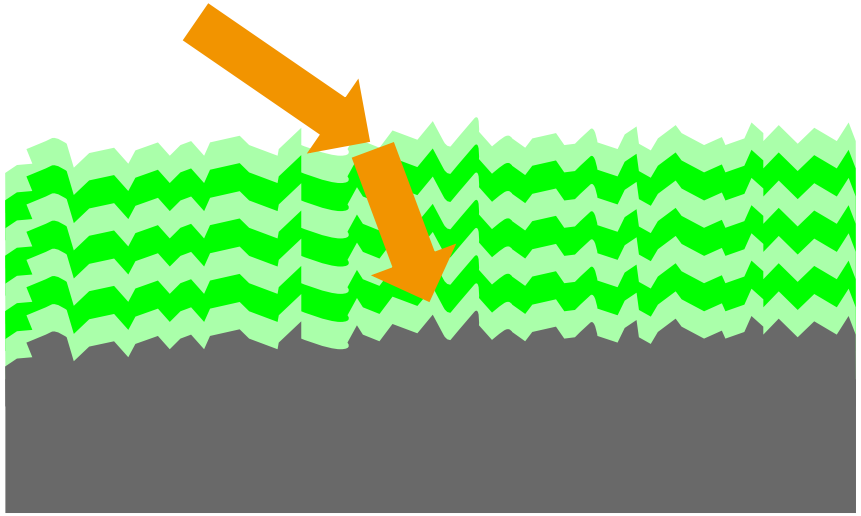


Bläsi, Kroyer, Kuhn, Höhn, „The MorphoColor Concept for Colored Photovoltaic Modules“, IEEE JPV, DOI 10.1109/JPHOTOV.2021.3090158

The MorphoColor™ Concept
Realization as Multi-Layer System

Chung et al: 0 harmonic Bragg stack
as thin films on rough surface

- higher refractive index in Bragg stack
- Refraction: smaller propagation angle within the stack
- Better color stability than in nature



K. Chung et al, "Flexible, Angle-Independent, Structural Color Reflectors Inspired by Morpho Butterfly Wings," Adv. Mater. **24**, 2375–2379 (2012).

The MorphoColor™ Concept

Effect of the narrow reflectance peak: mini Module

Rear side: transparent/black back sheet

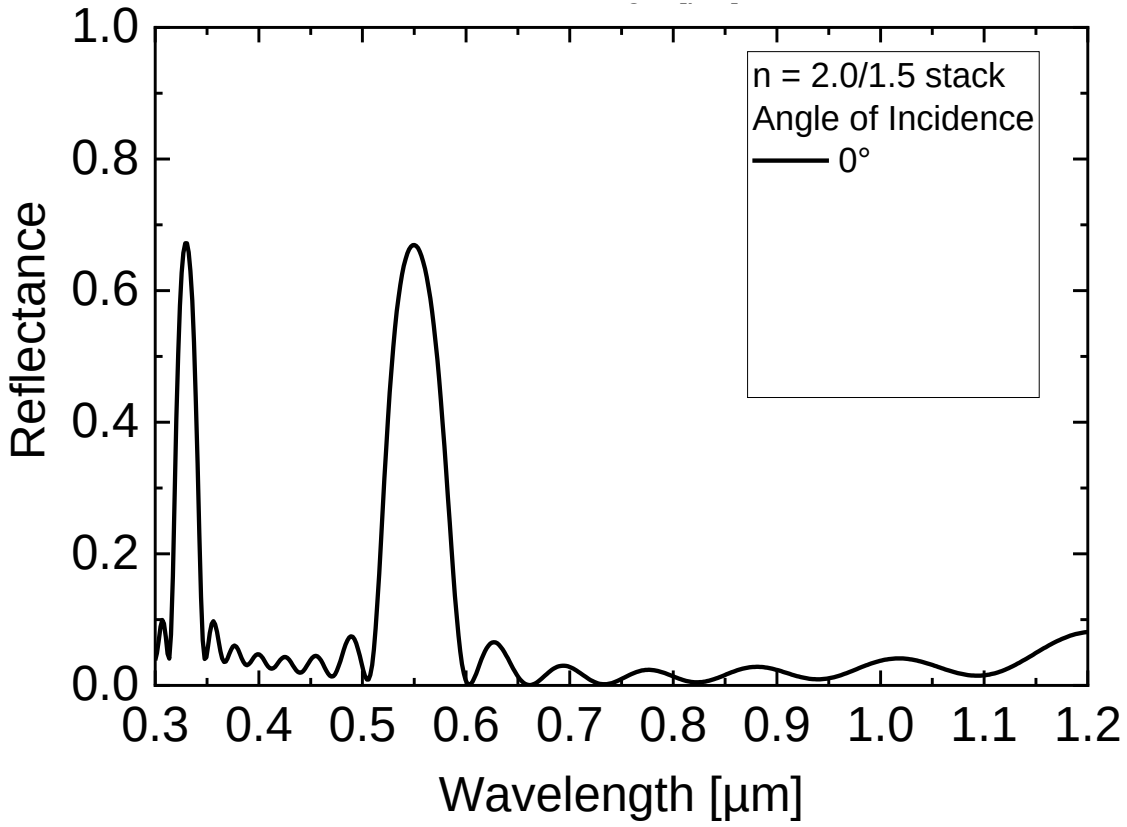
Front side

The MorphoColor™ Concept

How do we get the angular stability?

Two steps

- Step one: high refractive indices in the stack



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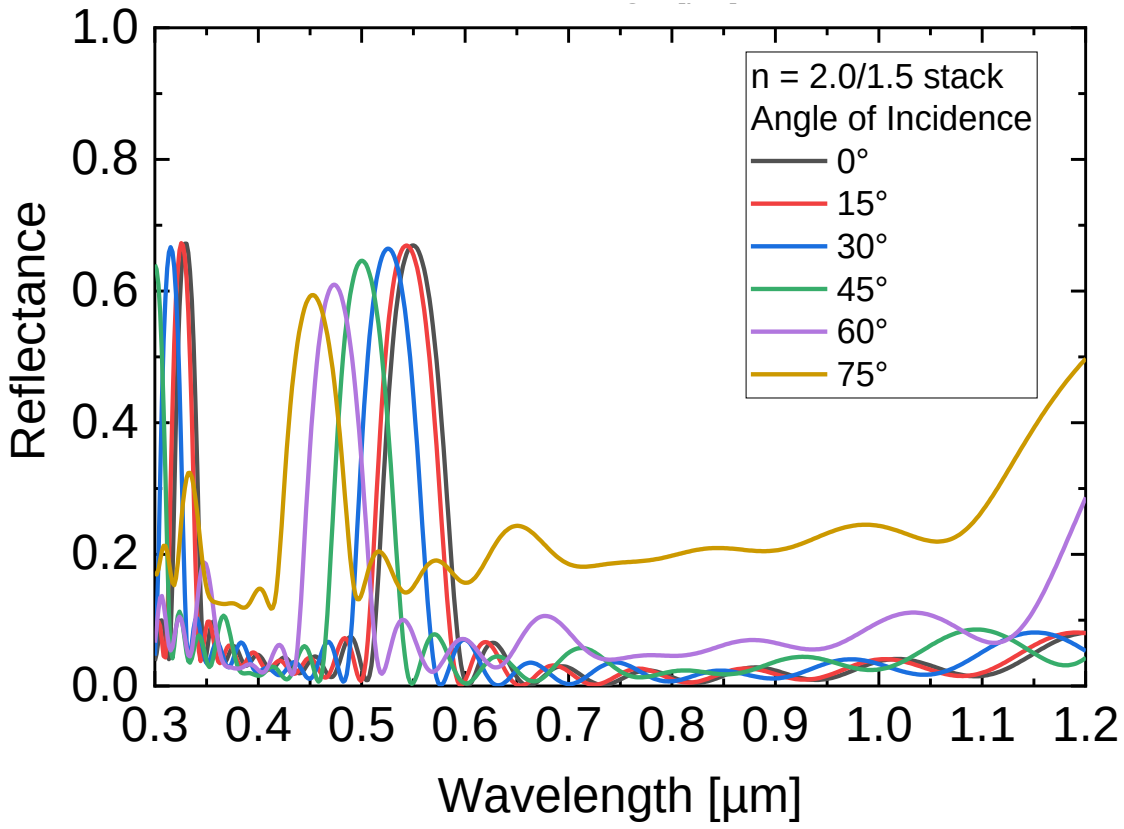
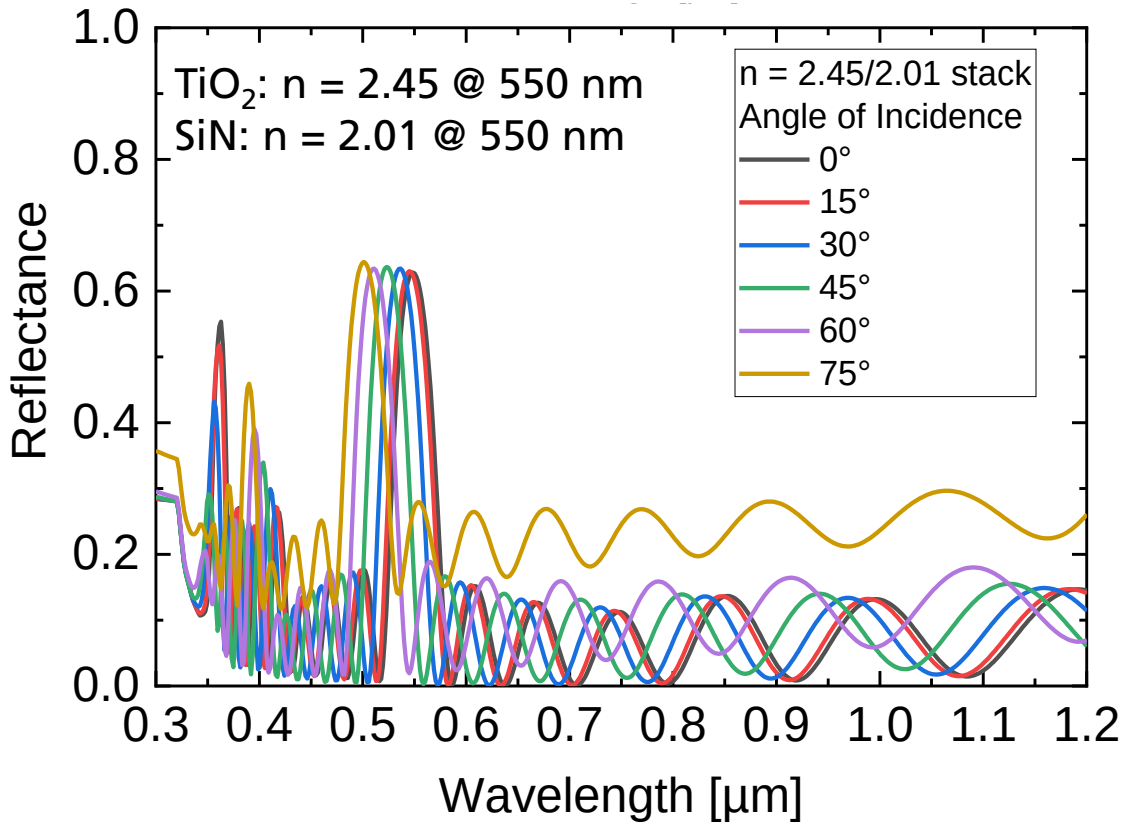




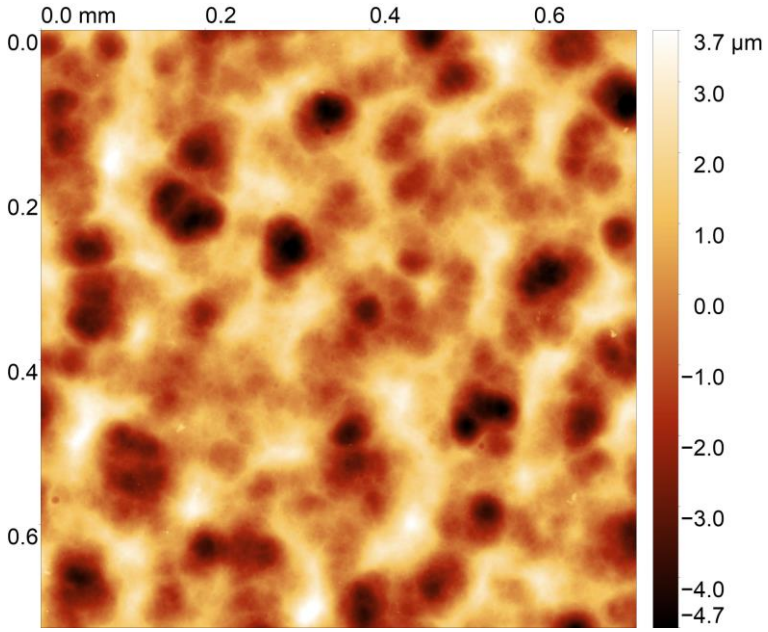
Bläsi, Kroyer, Kuhn, Höhn, „The MorphoColor Concept for Colored Photovoltaic Modules“, IEEE JPV, DOI 10.1109/JPHOTOV.2021.3090158

The MorphoColor™ Concept

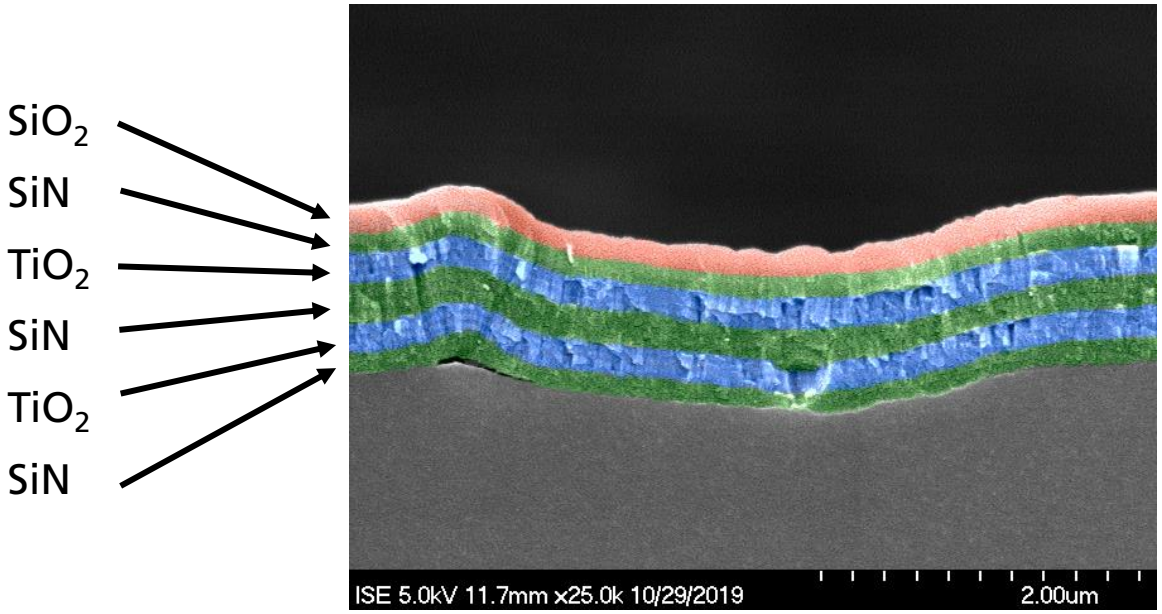
How do we get the angular stability?

Two steps

- Step one: high refractive indices in the stack
- Step two: deposition on a textured glass



Wet chemically etched glass
(confocal microscopy image)



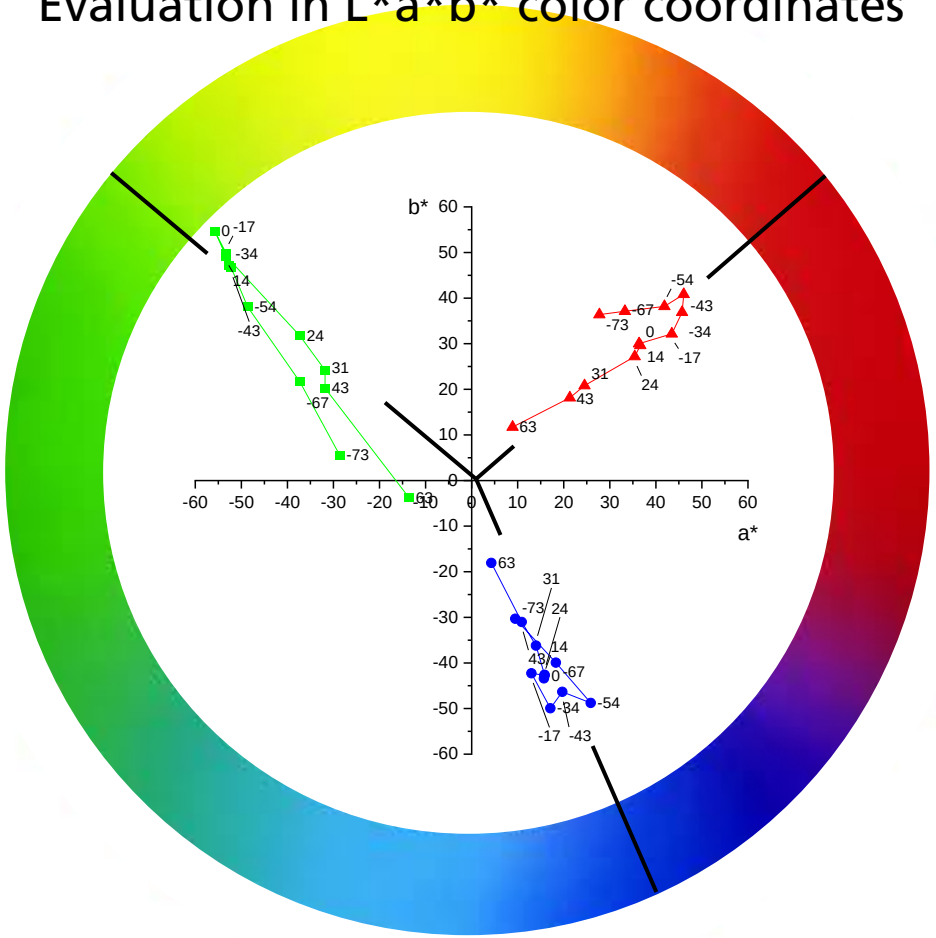
Layer stack on top of glass texture

Bläsi, Kroyer, Kuhn, Höhn, „The MorphoColor Concept for Colored Photovoltaic Modules“,
IEEE JPV, DOI 10.1109/JPHOTOV.2021.3090158

The MorphoColor™ Concept

Color Stability: Photos of the Stele from Different Angles

Evaluation in L*a*b* color coordinates



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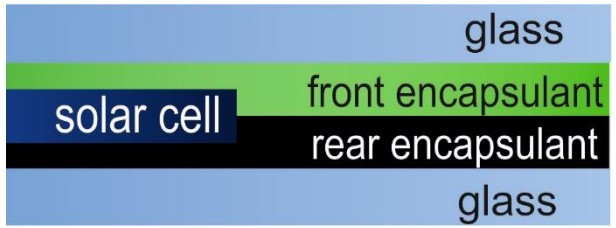
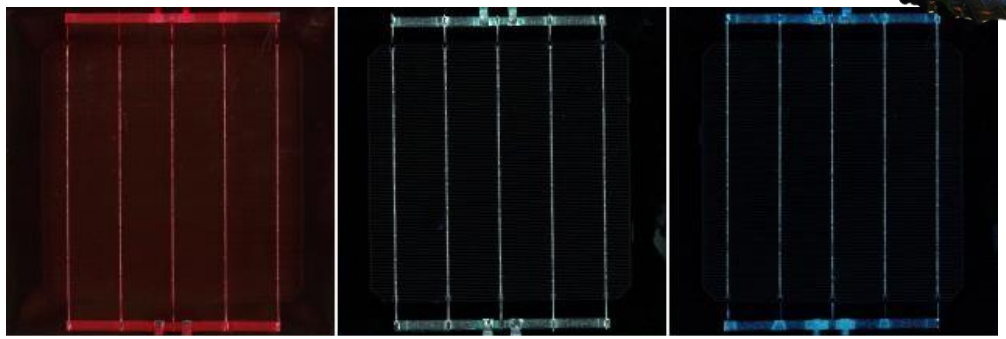
Performance of MorphoColor™ Modules

Comparison to other Color Concepts



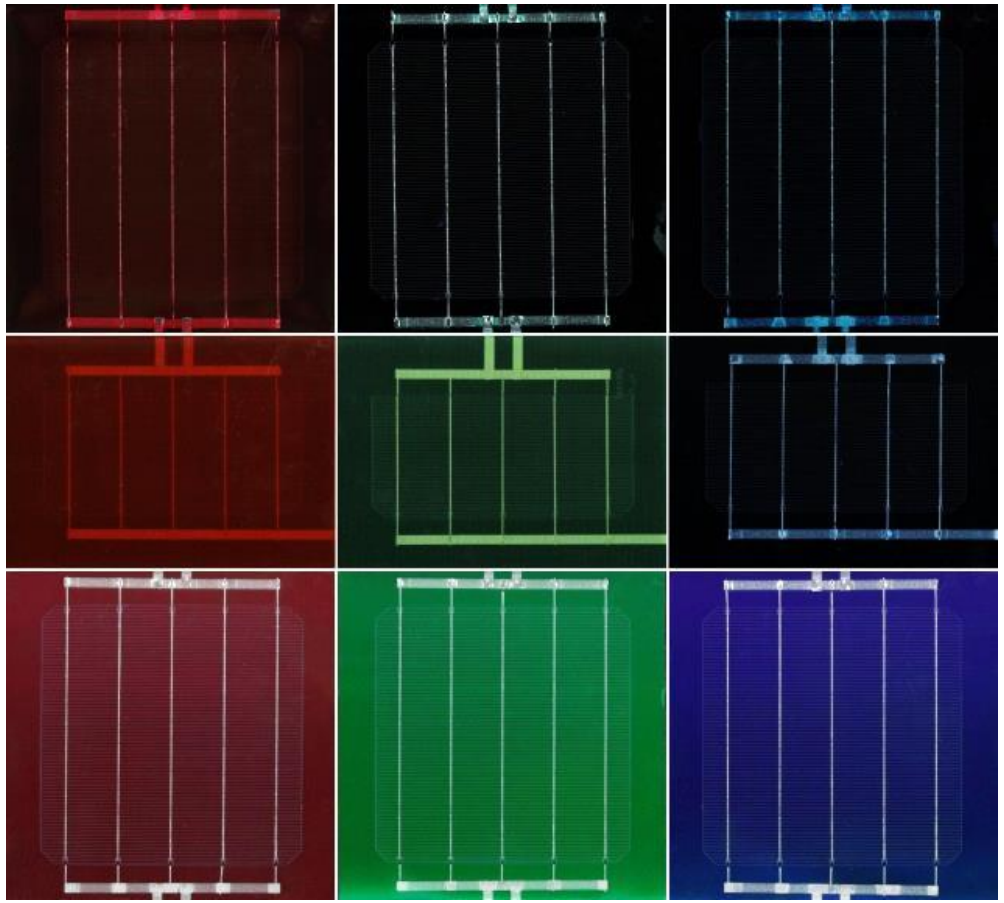
Colored encapsulant

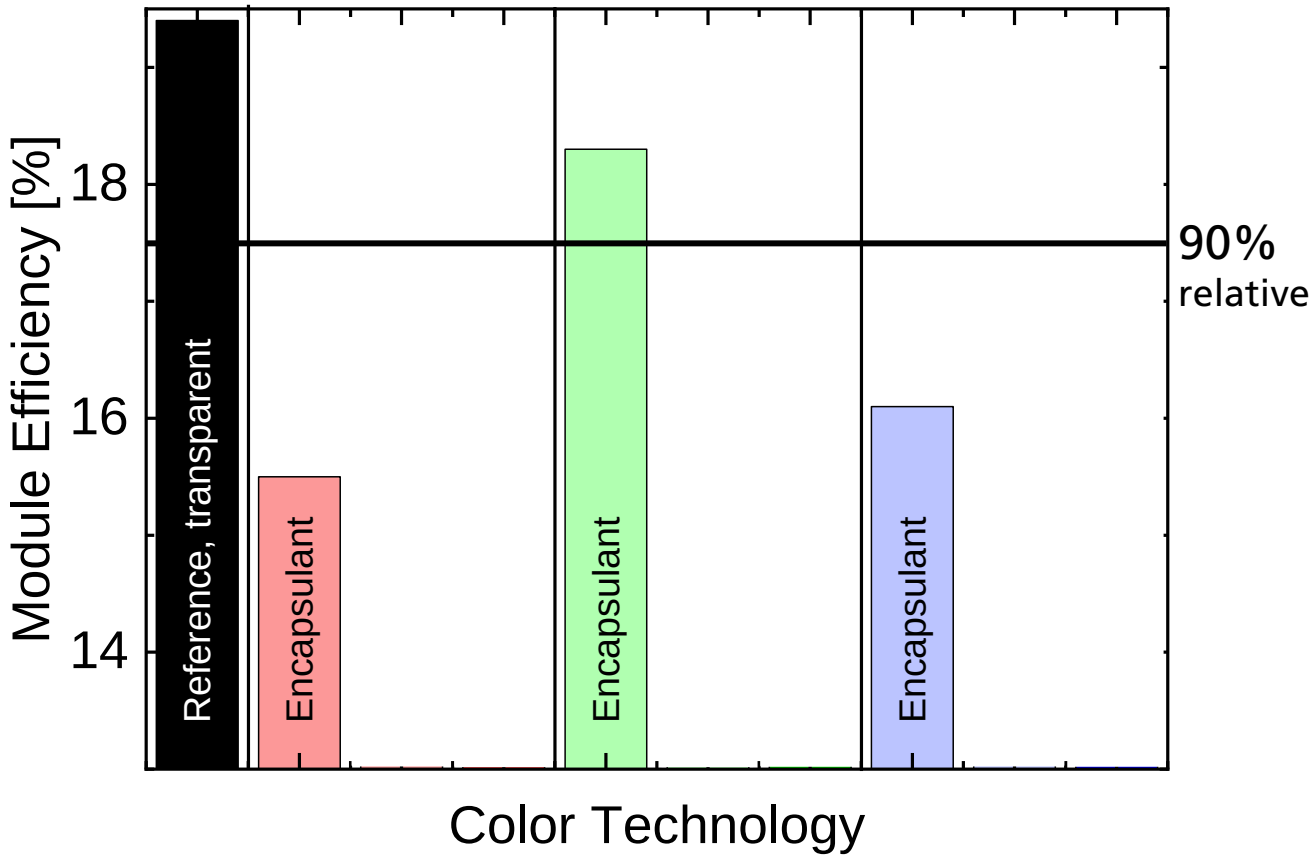


Kutter, et al, Proceedings of the 35th EU-PVSEC, Brussels, Belgium, S. 1488–1492. (2018)

Performance of MorphoColor™ Modules

Comparison to other Color Concepts

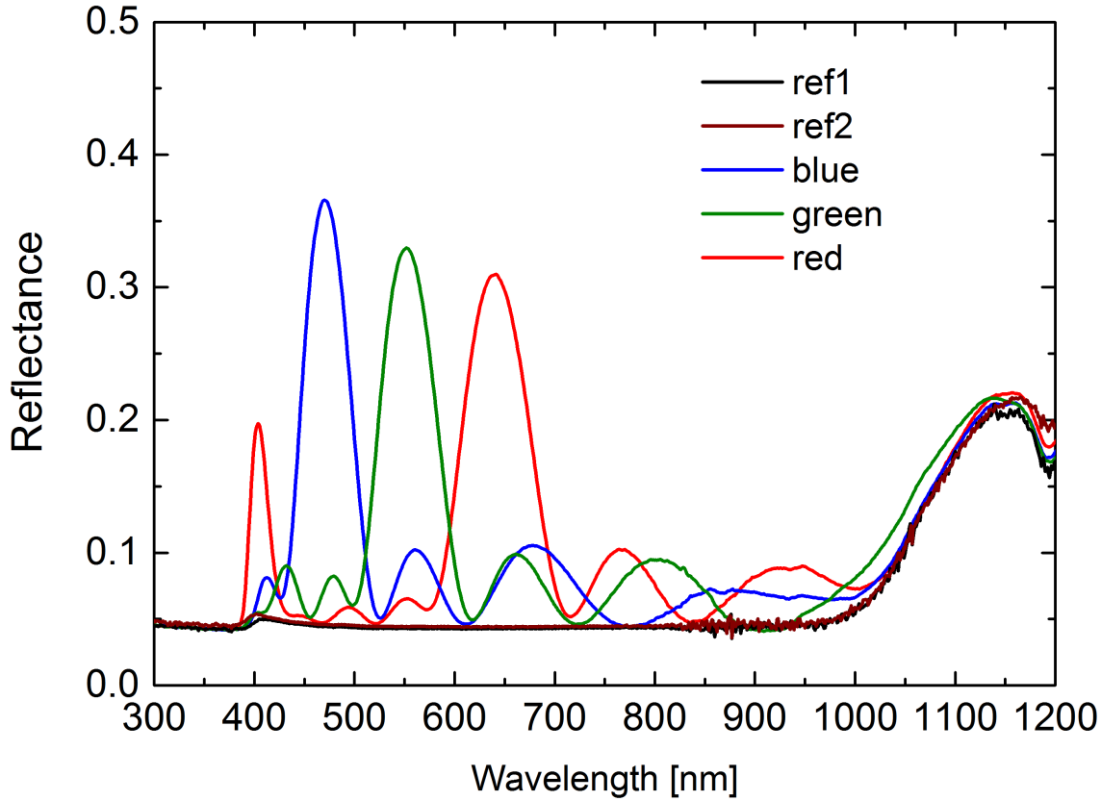


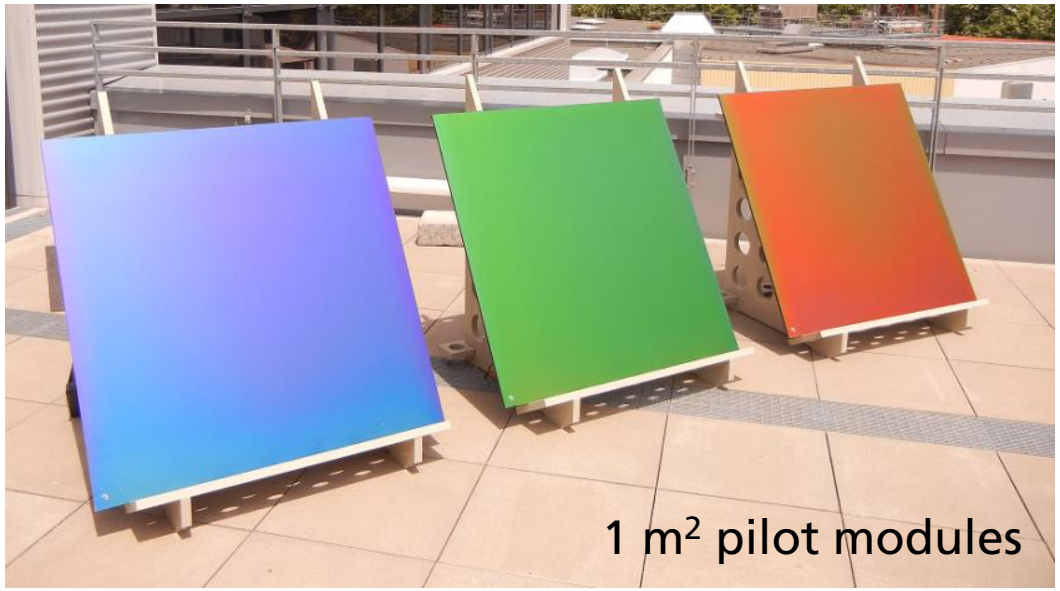


Kutter, et al., Proceedings of the 35th EU-PVSEC, Brussels, Belgium, S. 1488–1492. (2018)

Performance of MorphoColor™ Modules
Prototype modules

- > 93% efficiency
  compared to black reference module





Module	P_{mpp} [W]	I_{sc} [A]	η [%]
Black	156	5.74	15.6
Red	146.7	5.33	14.7
Blue	146.5	5.36	14.7
Green	146.4	5.37	14.6

Potential for CO_2 savings

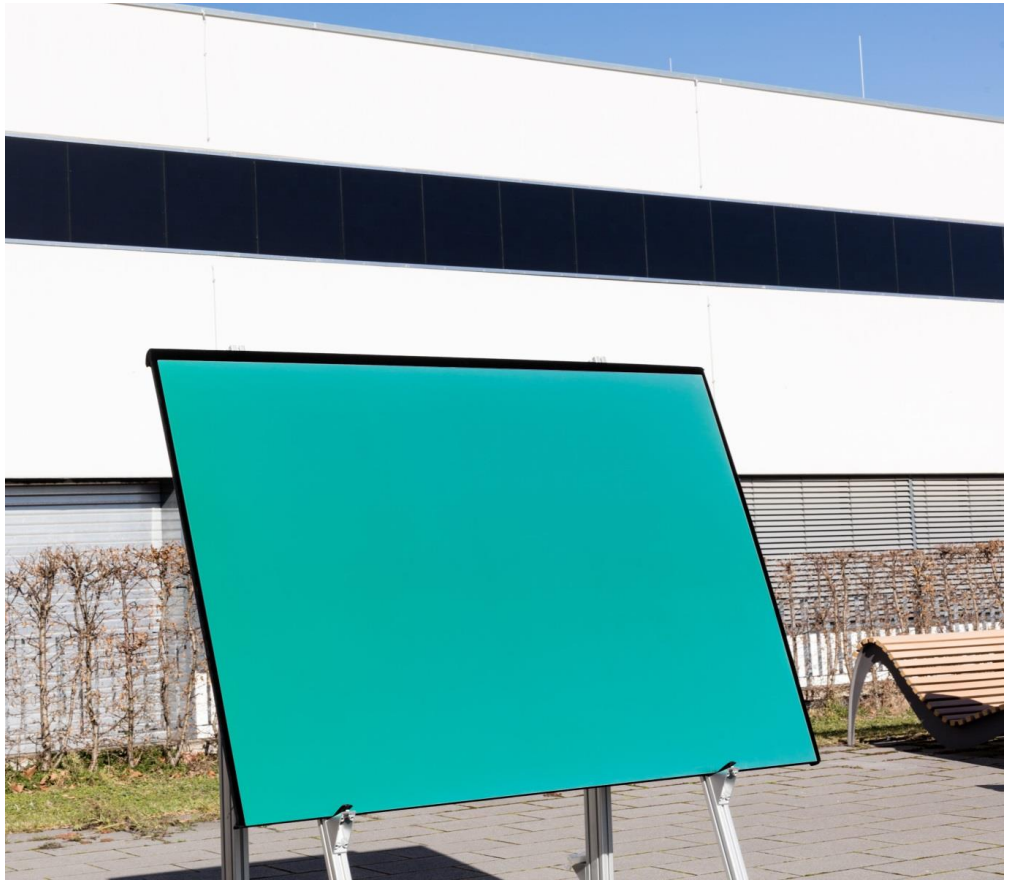
How about IKEA stores with blue PV on the facade?

- 53 department stores
- Average area of approx. 29,000 m² in Germany alone
- Façade area suitable for PV approx. 270,000 m²
- 20,000 tons of CO_2 savings possible per year
- …and that´s just one company and just Germany

Integration in Buildings and Vehicles

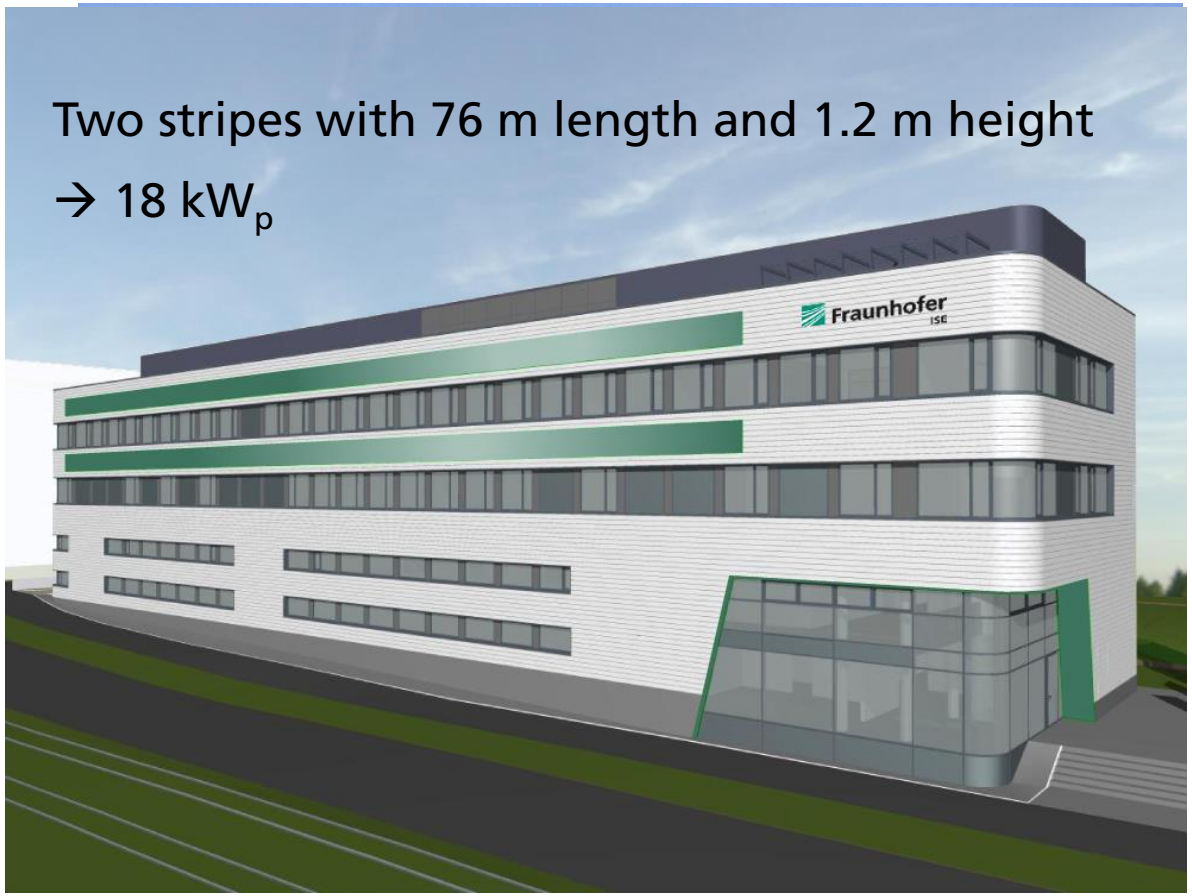
New Center for High-Efficiency Solar Cells at ISE

MorphoColor™ cover glass on black background



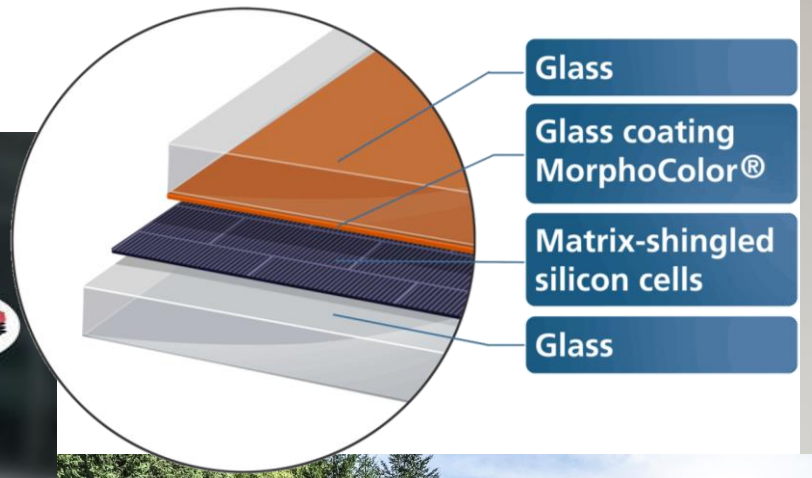
Visualization of the M6 module size: 1.86 x 1.26 m²)

Planned installation (module size: 1.86 x 1.26 m²)



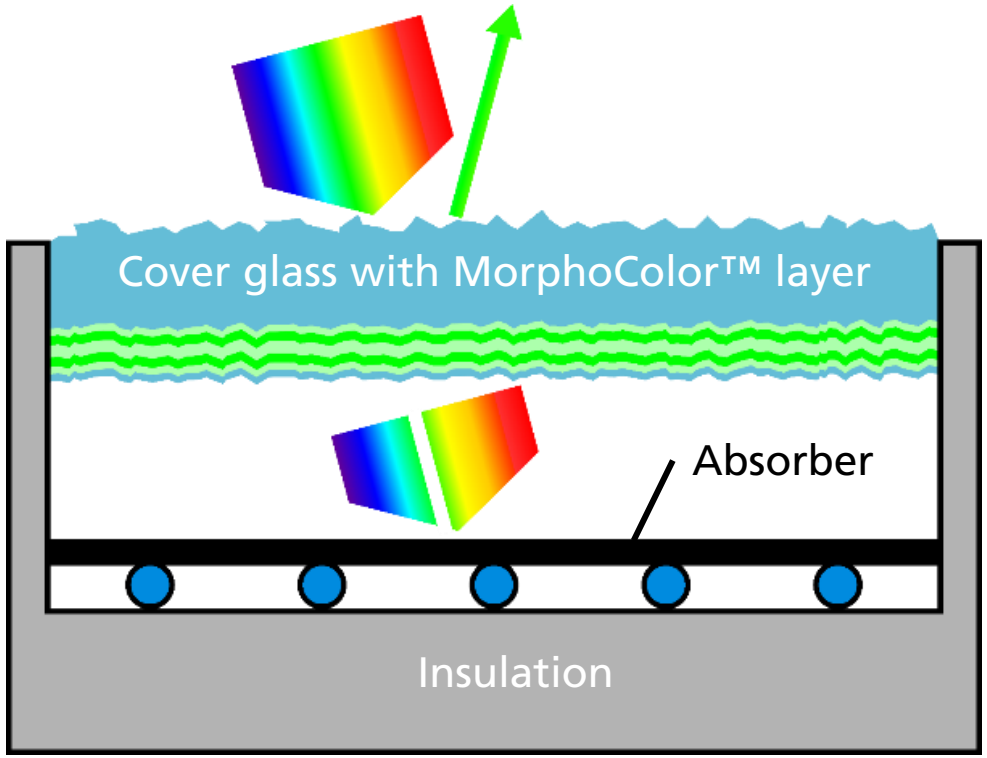
Integration in Buildings and Vehicles

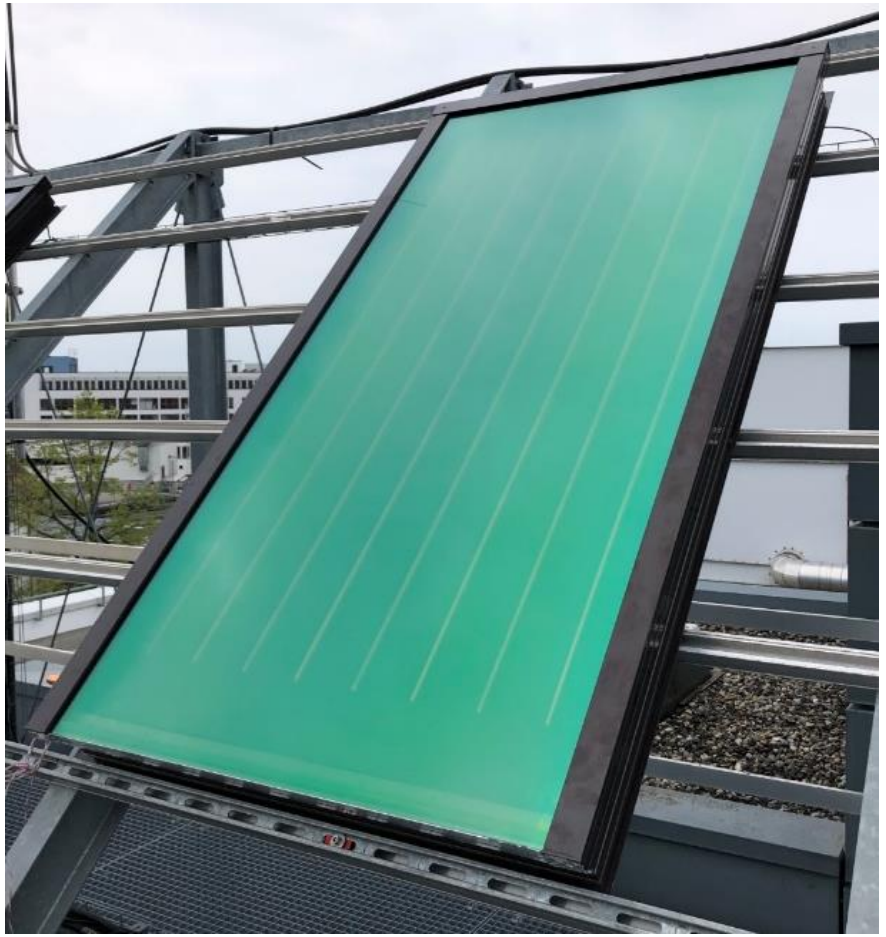
Car Integration



P. Baliozian *et al., PERC-based shingled solar cells and modules at Fraunhofer ISE.* Photovoltaics International, Volume 43 pp. 63 - 79, 2019

Integration in Buildings and Vehicles
Application in Solar Thermal Collector

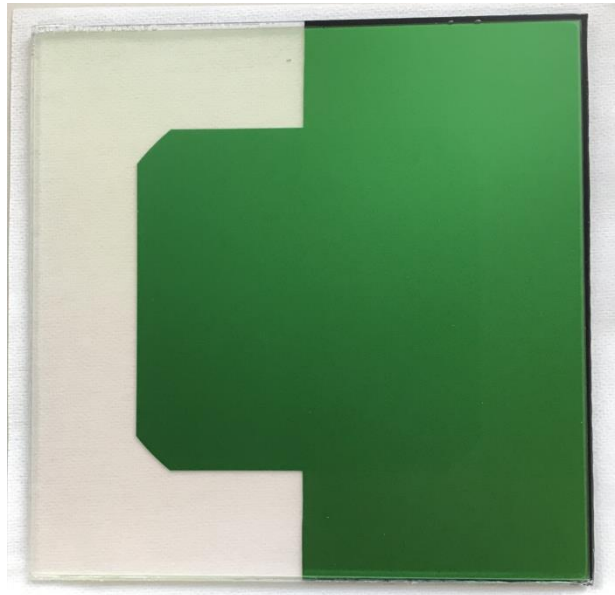


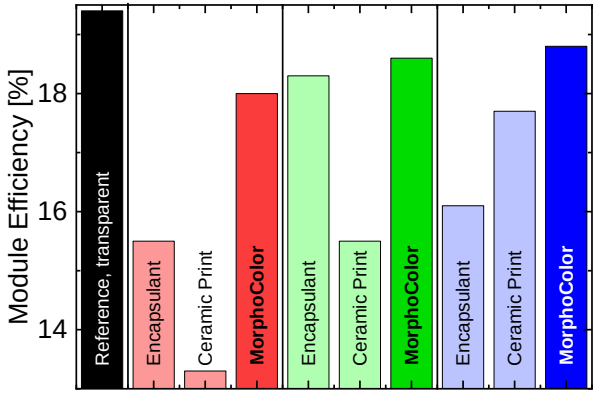


Fraunhofer ISE

Conclusions

- Morpho Butterfly:
  Nature´s wonderful inspiration
- Modifications multilayer + 2nd harmonic:
  saturated colors with high angular stability
- High efficiency maintained:
  > 90% power compared to reference module
- Integration in buildings and vehicles:
  huge potential for solar energy generation





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Thank You Very Much for Your Attention!

Benedikt Bläsi

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