Soltint: High Performance BIPV Design Customization

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Abstract

Building-integrated photovoltaic (BIPV) systems significantly enhance the energy efficiency of buildings. This paper introduces a novel coloring technology for BIPV that merges aesthetic appeal with high energy performance through the use of doliquid crystal-based colored interference coatings. These coatings selectively reflect and transmit light, aiming to optimize both color vibrancy and solar power efficiency. The study unfolds in two segments: initially, we discuss transmission measurements that evaluate the optical properties of these coatings in comparison to traditional BIPV systems. These measurements indicate a theoretical power loss ranging from 10% to 35% for most graphic design customizations, using standard black modules as a benchmark. Subsequently, we explore I-V measurements of a photovoltaic module laminated with one of these colored films, including graphic elements, to assess its performance, which shows a loss of 16% compared to a black reference model. Following this, a benchmark comparison with other BIPV coloring techniques is provided, highlighting the unique benefits and challenges of our method. The results demonstrate that our approach not only enhances the aesthetic value of building facades but also maintains a robust energy output. By detailing how these coatings manage light and energy, we show their potential to significantly improve energy-efficient building designs.

Keywords

Building-Integrated Photovoltaics (BIPV), Aesthetic Solar Modules, Interference Coatings, Cholesteric Liquid Crystals, Colored Photovoltaics, BIPV facades, Mass customization, Graphic PV module, Solar Facade Design

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1. Introduction

As the global building sector strives to reduce its carbon footprint, the integration of renewable energy systems directly into the building envelope is becoming increasingly vital. Among these, Building-Integrated Photovoltaics (BIPV) offer a compelling dual function: serving as both a power-generating technology and an architectural element. This dual role is particularly aligned with the European Union's Nearly Zero-Energy Building (NZEB) (European Commission, n.d.) directive, which mandates that new buildings consume nearly as much energy as they generate through renewable sources.

Despite the promise of BIPV, widespread adoption remains limited. A central barrier is the longstanding trade-off between aesthetics and energy performance. While traditional PV modules are optimized for efficiency, their uniform dark appearance often conflicts with architectural requirements—especially in highly visible facade applications. Architects, designers, and building owners increasingly seek visual integration in the form of custom colors, graphic treatments, and material textures. However, existing customization techniques often result in significant optical losses, reducing the overall energy yield of BIPV systems.

Recent industry and academic research confirms that aesthetics, performance, and cost are the three most important criteria influencing BIPV adoption (Frontini et al., 2024). This highlights a key innovation gap: the need for solutions that offer visual design flexibility while maintaining acceptable electrical performance and compatibility with industrial production.

This paper introduces a novel approach to aesthetic customization in BIPV using interference-coated PET films layered with digitally applied CMYK graphics. The base color of the film is generated through a cholesteric liquid crystal (CLC) coating, which creates selective reflection via a helical molecular structure. Unlike conventional multilayer interference coatings, CLCs achieve color reflection using only a single layer of self-assembling molecules, resulting in highly tunable, polarization-selective optical effects. Importantly, CLC coatings transmit much of the solar spectrum while reflecting visible light in a narrow band—making them ideally suited for BIPV applications where both color vibrancy and energy transmission are critical (Kessels & Lacaze, 2023).

The CMYK graphic layer, applied to the outer side of the film, enables a high degree of design freedom—including gradients, imagery, and branding—without the need for specialized coated glass. When laminated above photovoltaic cells, this layered configuration aims to achieve the architectural benefits of visual customization with minimized energy penalties.

Objectives of This Study

This study investigates:

1. The optical and electrical performance of interference-coated films with various graphic treatments using transmission measurements and EQE-based modeling.
2. The experimental validation of the technology through I-V testing of both lab-scale IBC prototypes and factory-produced monocrystalline modules.
3. A benchmark comparison with other commercially available BIPV coloring techniques, highlighting the relative strengths and limitations of the proposed approach.

By combining aesthetic versatility with solid electrical performance, this research contributes to advancing the design and commercial viability of next-generation BIPV systems.

2. Methods

The evaluation of the proposed coloring method involved two complementary approaches:

1. Optical and theoretical electrical performance analysis based on transmission measurements of colored films.
2. Experimental validation through fabrication and I-V testing of both laboratory-scale and factory-produced photovoltaic modules.

2.1. Materials and Coating Chemistry

The colored interlayer films were first coated with cholesteric liquid crystal ink, formulated by mixing a liquid crystal base with a chiral dopant and coating additives. For this work the ratio between the LC base material and chiral dopant are adjusted in such a way to obtain red and green reflective CLC coatings as base colours for the designed films. The CLC ink formulations are coated on a 1.6m wide PET substrate using an industrial scale roll-to-roll coating process. The LC base material and chiral dopant have reactive chemical groups due to which they can be polymerized by UV-light after being coated on the substrate and freed from solvent by evaporation, resulting in a hardened CLC coating in which the molecular order and thus the designed reflective colour is frozen in. Hereafter pigments were applied on the opposed side of the film using an inkjet printing technique.

The aesthetic result of the colored film is created by the combination of a base interference color and a digitally printed CMYK graphic layer. The base color is generated by the cholesteric liquid crystal (CLC) interference coating, which reflects a narrow band of visible light due to its helical molecular structure. This reflected color exhibits a distinct angular color shift, a characteristic behavior of interference materials. For example, a red base color viewed at normal incidence will appear red, but as the viewing angle increases, the color gradually shifts through orange, yellow, and green.

The CMYK graphics are printed over this interference coating, meaning they are not applied to a neutral substrate but are instead visually mixed with the underlying interference color. The final perceived color is thus a combination of the CMYK pigment absorption and the spectral reflection of the base layer. This interaction must be considered in the design process, especially for applications requiring precise color control or branding fidelity.

2.2. Transmission Measurements and Theoretical Calculations

To quantify the optical impact of the graphic treatments and CLC coatings, transmission spectra of film samples were measured using a Lambda 1050+ UV/Vis spectrophotometer (PerkinElmer). The spectrophotometer was calibrated against reference samples of transparent and fully opaque (black) materials to ensure accuracy. Spectral measurements were conducted over the wavelength range of 300–1200 nm, with a 10 nm resolution.

The tested films consisted of the PET substrate, with the CLC interference layer facing the photovoltaic cell side, and the digitally printed graphics facing the incoming irradiance (i.e., the exterior of the module). This orientation accurately replicated conditions expected in a real laminated photovoltaic module.

The measured transmission data (T(λ)) were integrated with the AM1.5 global tilt solar spectrum (E(λ)) and the external quantum efficiency (EQE) of a Maxeon SunPower IBC solar cell. The cell's spectral response (SR(λ)) was derived from its EQE data using the relationship:

$$SR(\lambda)=(EQE(\lambda)*\lambda)/1239.9 \qquad (1)$$

Subsequently, the theoretical short-circuit current (Isc) for each color treatment was calculated by integrating over the active cell area (A, 0.015625 m², corresponding to a single cell area of 125 × 125 mm):

$$Isc = \int T(\lambda) * SR(\lambda) * E(\lambda) * A\, dx \quad (2)$$

This allowed systematic quantification of the optical performance penalty associated with each graphic color treatment.

Laboratory Prototype Fabrication and Testing

Two laboratory-scale photovoltaic modules were fabricated manually using Maxeon E66S interdigitated back-contact (IBC) cells. Each prototype module consisted of 12 solar cells arranged into three parallel strings of four series-connected cells. One module served as a control with a standard black background, while the other incorporated the colored, interference-coated PET film with digitally printed graphics.

Current-voltage (I-V) characteristics of both modules were measured under Standard Test Conditions (STC: irradiance of approximately 1000 W/m², cell temperature around 25°C) using an Eternal Sun solar simulator (xenon-based, non-LED type). The resulting I-V data were analyzed using custom Excel-based software to extract key performance parameters: short-circuit current (Isc), open-circuit voltage (Voc), maximum power output (Pmax), and fill factor (FF).

Electroluminescence (EL) imaging was performed on both prototype modules before electrical characterization, allowing visual detection of cell-level defects such as cracks, local shunts, or interconnection issues. This provided additional context for interpreting the electrical performance results.

2.3. Factory Module Manufacturing and Characterization

To validate scalability and real-world feasibility, seven photovoltaic modules were produced by a commercial photovoltaic manufacturer using industry-standard lamination processes. These modules were fabricated using monocrystalline silicon solar cells arranged in an 18-cell layout. The same interference-coated PET films with digitally applied CMYK graphics were laminated onto these modules. The graphic used resembled the image of a corten steel surface. The images of each module were slightly different from each other to create a more natural looking façade effect.

The modules were produced in an 18-cell configuration

Standard I-V measurements were performed on each module under Standard Test Conditions (STC):

- Irradiance: ~1000 W/m²
- Module temperature: ~25°C

Key parameters extracted included:

- Short-circuit current (Isc)
- Open-circuit voltage (Voc)
- Maximum power point (Pmax)
- Voltage and current at Pmax (Vmp,Imp)
- Fill Factor (FF)

Due to practical limitations during production, no black reference module using the same cell type and layout was fabricated. However, theoretical specifications for the equivalent monocrystalline black module were provided by the manufacturer and used as a benchmark for performance comparison.

2.4. Benchmark

To contextualize the performance of the proposed coloring method, we compiled a benchmark of non-transparent BIPV coloring technologies based on published literature. The comparison focuses on three core attributes: optical loss (as a percentage reduction in power output), and design freedom (graphic or tonal flexibility). Data were primarily sourced from a recent comprehensive review by Borja Block et al. (2024), which evaluates aesthetic photovoltaic treatments across commercially relevant techniques.

The coloring method described in this study, which combines interference-based base colors with CMYK graphic overlays, is currently patent pending.

3. Results

The evaluation results of the novel coloring method for BIPV modules are presented in three distinct parts: (1) transmission and theoretical short-circuit current (Isc) calculations, (2) laboratory-scale module electrical performance, and (3) industrially manufactured module performance.

3.1. Transmission and Theoretical Short-Circuit Current (Isc)

Transmission measurements of the colored interference-coated PET films revealed a clear dependency of the optical properties on graphic ink density and pigment combinations. Figure 1 illustrates the relationship between ink density and the calculated short-circuit current (Isc). Single-color pigments, such as cyan or yellow, exhibited minimal transmission losses (approximately 10–15%) even at high ink densities. In contrast, higher-density combinations involving black and CMY pigments showed substantially higher optical losses (up to 35%), primarily due to increased absorption and broad-spectrum reflectivity, significantly impacting theoretical photovoltaic performance.

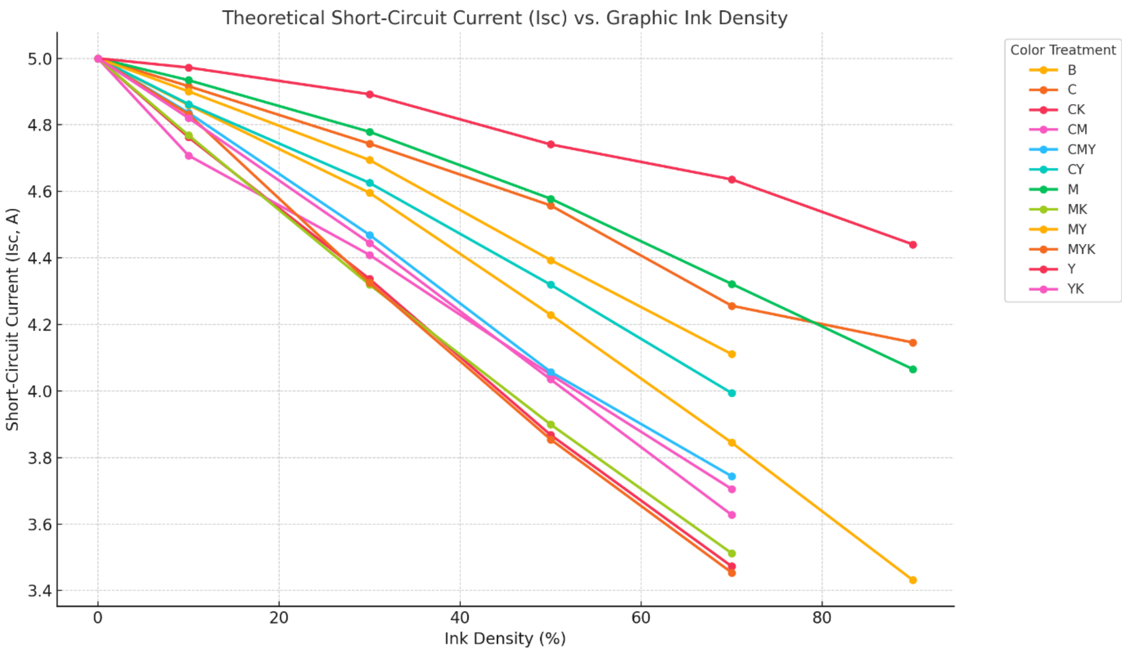

Figure 1: "Theoretical Isc vs. Graphic Ink Density".

These measurements confirm that careful selection and optimization of pigment density and color combination can substantially mitigate optical losses in aesthetically customized BIPV modules.

3.2. Laboratory-Scale Module Results (Handmade Prototypes, IBC Cells)

Electrical performance characteristics of the laboratory-scale prototypes (IBC cells, Maxeon E66S) measured under Standard Test Conditions (STC) are summarized in Table 1. The colored prototype module exhibited a short-circuit current (Isc) approximately 21% lower than the black reference module, directly reflecting the expected optical losses associated with the colored interference film. Open-circuit voltage (Voc) showed minimal degradation (1.5%), indicating the coloring had negligible impact on cell-level recombination or voltage behavior. The maximum power (Pmax) showed a 16% decrease, directly attributable to reduced optical transmission.

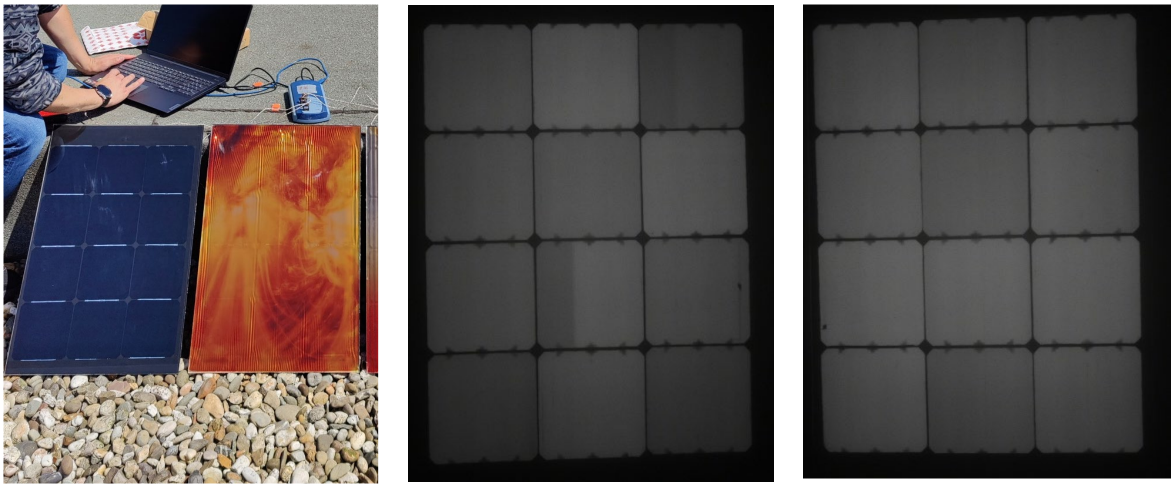

Figure 2: "Photographs of Handmade Laboratory Prototypes" and "EL Imaging Results of Laboratory Modules.") ref. module left, colored module right.

Table 1: Electrical characteristics of the lab-scale prototypes.

Parameter	Colored Prototype	Black Reference	Relative Loss (%)
Isc (A)	4.43	5.60	20.8%
Voc (V)	8.55	8.68	1.46%
Pmax (W)	28.96	34.43	15.9%
Fill Factor (%)	76.4	70.9	-7.8% (gain)

Interestingly, the fill factor (FF) of the colored module was notably higher than that of the reference module. Electroluminescence (EL) imaging (Figure 2) revealed minor cell-level defects, including slight cell cracks and local shunts in both modules, but defects appeared more pronounced in the reference module. These defects likely caused the lower fill factor observed in the reference, thus explaining the improved FF observed for the colored module.

3.3. Industrial Module Results (18-cell Monocrystalline Modules)

Seven 18-cell modules with monocrystalline silicon cells were produced at a commercial photovoltaic manufacturing facility, incorporating the colored interference-coated films with digitally printed graphics. The performance characteristics measured under STC showed consistent electrical parameters across all modules (Table 2).

Table 2: Electrical characteristics of industrially produced modules.

Parameter	Mean	Rel.Std Dev	Min	Max
Pmax (W)	65.32	±2.9%	62.58	67.35
Voc (V)	12.04	±0.95%	11.98	12.30
Isc (A)	7.40	±0.31%	6.80	7.70
Fill Factor (%)	73.3	±4.2%	72.0	74.8

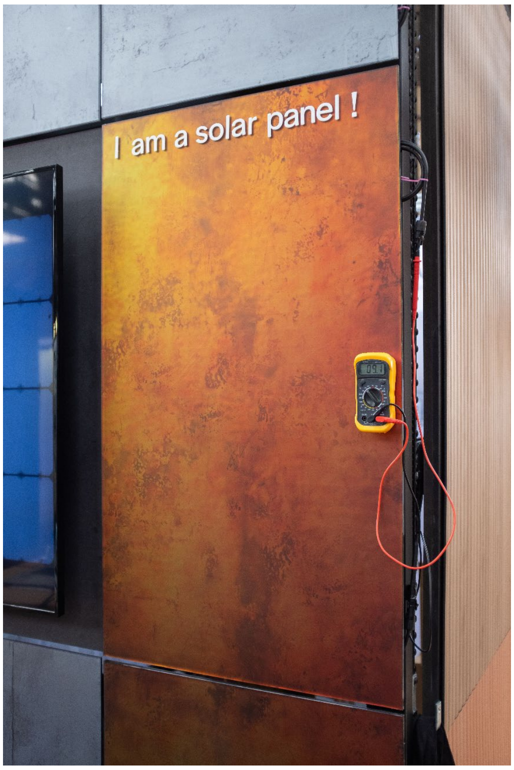

Figure 3: One of the seven industrially manufactured PV modules with the colored interlayer provided with a "corten steel" image.

Compared with theoretical specifications provided by the manufacturer for an identical black reference module, the colored modules exhibited a 21.3% relative reduction in maximum power (Pmax) on average, primarily due to reduced short-circuit current (14.9% reduction). Voltage losses (1.8%) and fill factor reductions (5 .6%) were relatively modest, indicating that the main contributor to power loss remained optical.

Table 3: Factory Module Performance Comparison (Colored vs. Black)").

Parameter	Colored Modules (Mean)	Theoretical Black Module	Relative Loss (%)
Pmax (W)	65.32	83.00	21.3%
Voc (V)	12.04	12.26	1.76%
Isc (A)	7.40	8.70	14.9%
Fill Factor (%)	73.3	77.6	5.6%

Due to the limited number of modules tested (N=7), formal statistical significance testing was not performed. However, low standard deviations indicate good reproducibility of the manufacturing process.

3.4. Benchmark

A comparative benchmark of non-transparent BIPV coloring techniques is presented in Table X. The results demonstrate that the proposed method, based on cholesteric interference coatings combined with digitally printed PET films, provides a unique balance of high design freedom and moderate optical loss (15–30%). While certain interference-based techniques such as Kromatix or MorphoColor achieve lower optical losses (<10%), they are limited to fixed color palettes. By contrast, the method presented in this study offers a high degree of graphical customization with performance that is competitive with existing commercial solutions.

Table 4. Benchmark with other PV color technologies.

Technology	Optical Loss (%)	Design Freedom
This Study (CLC + CMYK)	10–30	Moderate, graphics applied on base color. Bright colors with low eff. Loss.
Digital Ceramic Printing (DCP)	10 (dark)–50 (bright)	High, low loss for dark images, high loss for bright colors.
ColorQuant (Wolbring)	≤20	Low, solid colors or repetitive patterns (screenprint)
Kromatix (Swissinso)	2–8	Low, fixed Palette
MorphoColor (Fraunhofer)	3–7	Low, fixed Colors
Solaxess (interlayer foil)	10–45	Low, fixed Colors
Colored Encapsulants (Freesuns)	30–35	Low, Fixed Tone
Coloured Cells (Lofsolar)	15–30	Single Color individual cells

4. Discussion

This study evaluated a novel BIPV customization approach using interference-coated PET films with graphic CMYK treatments, combining high visual design freedom with moderate optical losses. The method was validated through both theoretical modeling and experimental testing of lab-scale and industrially produced PV modules. The results demonstrate that it is possible to achieve architecturally compelling aesthetics without unacceptably compromising photovoltaic performance.

4.1. Optical Losses and Color Design Trade-offs

Transmission measurements and theoretical Isc calculations showed that optical loss is strongly dependent on pigment choice and ink density. Graphic treatments using light single-color pigments (e.g., yellow or cyan) led to minimal current loss (~10–15%), while high-density black or CMY combinations incurred losses of up to 35%. This highlights the importance of strategic color planning during the architectural design process. For example, lighter or sparsely applied graphics may be prioritized on high-insolation facades to maintain energy yield, while bolder graphics may be positioned where shading or overproduction limits justify more expressive aesthetics.

This trade-off between visual expression and efficiency is quantifiable, allowing architects and engineers to make informed design decisions based on the energy impact of various color schemes. The flexibility of the CMYK system enables nearly unlimited design freedom while maintaining a degree of predictability in performance impact.

4.2. Lab-Scale Performance and Module Quality

The colored IBC prototype module exhibited a 20.8% reduction in short-circuit current and a 15.9% reduction in maximum power output compared to a black reference.

Surprisingly, the fill factor (FF) of the colored module was significantly higher than that of the black reference (76.4% vs. 70.9%). This discrepancy was explained by EL imaging, which revealed more pronounced cell-level defects in the black module. These likely contributed to increased series resistance or shunting losses, reducing FF and overall power output. This finding underscores the importance of module quality and handling, especially for handmade prototypes, and illustrates how process variation can interact with optical performance to affect final module efficiency.

4.3. Industrial-Scale Validation

Across seven factory-produced 18-cell monocrystalline modules, electrical performance showed good consistency, with standard deviations of ~2.9% for maximum power, ~0.95% for open-circuit voltage, ~1.3% for fill factor, and ~4.2% for short-circuit current. The higher variation in Isc is likely attributable to differences in light absorption introduced by minor variations in the printed image.

When benchmarked against theoretical black module specifications, the colored modules exhibited:

A 21.3% reduction in Pmax, 14.9% drop in Isc. Only 1.8% loss in Voc and 5.6% in FF.

These results confirm that the dominant mechanism of performance loss is optical, not electrical. Voltage and fill factor remained stable, indicating no evidence of cell degradation or interference with electrical operation due to the film or ink layers.

4.4. Method Limitations

Several limitations should be acknowledged:

- Sample Size: With only one black lab reference module and seven factory modules, the statistical power of performance comparisons is limited. While standard deviations are low and trends consistent, larger sample sizes would improve confidence in observed trends.
- No Measured Factory Black Module: For the factory prototypes, black module performance was estimated using manufacturer data. While reasonable, a directly fabricated reference under the same process would offer more rigorous benchmarking.
- Spectral Simplifications: The calculation of theoretical Isc assumes perfect EQE behavior across the module and ignores potential angular, polarization, or encapsulant effects that may arise in laminated modules under field conditions.
- No Durability or Aging Data: This study did not include weathering, UV exposure, or mechanical stress testing. While CLCs are polymerized for stability, the long-term integrity of both the interference coating and printed graphics under environmental exposure remains to be validated.

4.5. Future Work

Based on these findings, several directions are recommended for future research:

- Durability Testing: Accelerated aging studies (UV, humidity, thermal cycling) are needed to confirm the long-term viability of both optical and mechanical properties.
- Optimization of Graphic Coverage: Development of design tools or software to simulate energy loss from different graphic layouts would empower architects and engineers to make data-driven aesthetic decisions.
- Color Performance Modeling: Integration of angular-dependent transmission and polarization effects into optical models would further improve accuracy.
- Real-World Monitoring: Field testing of modules installed in architectural settings would provide valuable insights into seasonal performance, glare, and visual integration.

5. Conclusions

This study presents and evaluates a novel coloring approach for building-integrated photovoltaic (BIPV) modules that combines liquid crystal-based interference coatings with digitally applied CMYK graphics. The method addresses one of the primary limitations of BIPV adoption—lack of aesthetic flexibility—by enabling full-color, high-resolution designs while maintaining acceptable photovoltaic performance.

Transmission measurements and EQE-based modeling demonstrated that optical losses range from 10% to 35%, depending on the color density and pigment combinations. Lab-scale prototype testing showed a 16% reduction in maximum power relative to a black reference, while factory-produced monocrystalline modules exhibited a 21% loss, confirming scalability and alignment with theoretical expectations.

Compared to other BIPV coloring technologies, this method offers a unique balance of:

- High design freedom, supporting full graphical customization;
- Moderate optical loss, competitive with or better than existing solutions;
- Seamless integration into standard manufacturing processes via PET film lamination.

The results indicate that this technology can play a pivotal role in enabling visually compelling, architecturally integrated photovoltaic facades, especially in applications where both aesthetics and energy performance are essential.

Future work should explore long-term environmental durability, refinement of color-performance trade-offs, and real-world field validation to fully realize the potential of this approach in commercial BIPV systems.

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The coloring technology described in this paper is currently patent pending.

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