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Aesthetic Micropatterned Photovoltaic Glass for Net-Zero Buildings

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Abstract. Integrating photovoltaic (PV) materials into building components represents a significant advancement toward achieving net-zero energy buildings (NZEBs). However, their widespread adoption is hindered by limited color and opacity options. In this study, we present a comprehensive experimental investigation into the color and transparency characteristics of PV modules, with a focus on their aesthetic appeal and photoconversion efficiency, utilizing advanced micropatterning techniques. Aperiodic micropatterned (AMPV) glass exhibits a lower haze of 3.7% compared to periodic types, which have a haze of 10.7%, while maintaining higher transparency at an AVT of 58.7%. Furthermore, a selectively micropatterned colored PV (SMPCPV) module achieves a power conversion efficiency (PCE) of 11.36%, surpassing both conventional single-color and multi-color designs. These advancements hold promise for the development of building-integrated PV modules that harmonize form and function for sustainable next-generation buildings.

Keywords. Building-Integrated Photovoltaics, Micropatterned Photovoltaic Glass, Net-Zero Energy Buildings, Colored Semitransparent PV, Aesthetic Photovoltaic Modules

1. Introduction

The global movement towards Net-Zero Energy Buildings (NZEBs) has highlighted the challenges faced by traditional building-integrated photovoltaic (BIPV) technologies (Borja Block et al., 2024a; Ghosh, 2020; Kong et al., 2023; Luo et al., 2020; Urge-Vorsatz et al., 2020). Although BIPV systems can reduce the carbon footprint, their low transparency and visually unappealing dark blue or black color present challenges to modern architectural design (Agathokleous & Kalogirou, 2020; Borja Block et al., 2024b; Lee & Song, 2021; Martín-Chivelet et al., 2022; Pelle et al., 2020). To address these limitations, we have developed a suite of photovoltaic glass-based materials that combine efficiency, clarity, and aesthetic flexibility. An overview of the current state of BIPV technologies, their architectural limitations, and integration examples is summarized in Fig. 1, highlighting the visual and functional challenges addressed by this study. We have also evaluated the aesthetic qualities of our printed modules, demonstrating their design flexibility, as any of the printed modules could resemble actual building materials (e.g., brick or concrete). The accompanying figures illustrate the haze performance, printed module visuals, the patterning workflow, and electrical performance metrics.

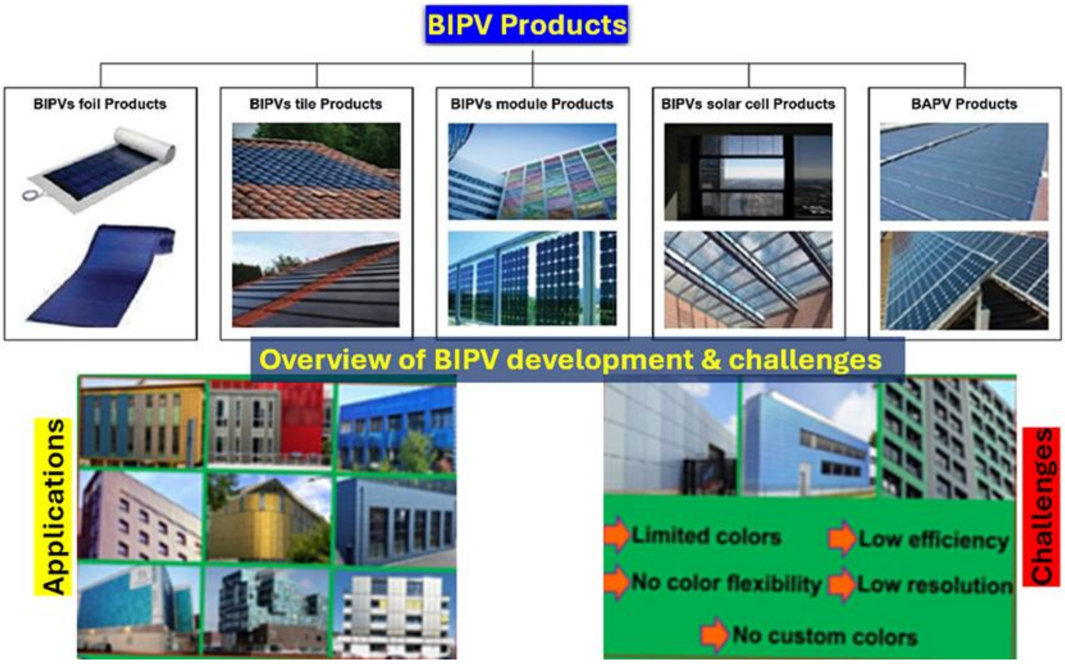

Figure 1. Examples of BIPV products, remaining challenges, and real-world applications of colored BIPV technologies, highlighting limitations in color diversity, efficiency, and resolution, as well as integration in modern facades (Basher et al., 2023; Basher & Basher, 2023).

Therefore, this study aims to develop aesthetically appealing micropatterned photovoltaic glass systems with improved transparency, reduced haze, and enhanced power conversion efficiency for building-integrated photovoltaic applications

2. Methodology

2.1. Fabrication of Aperiodic Micropatterned PV Glass

The initial innovation centers on the development of aperiodic micropatterned glass (AMPV), which enables the creation of non-repetitive transparent stripes through laser micromachining. This glass uniquely replaces the conventional Periodic micropatterned PV (PMPV) glass with AMPV.

2.2. Design of Colored PV Modules

To further expand the design possibilities, single-colored (SCPV), multicolored PV (MCPV), and micropatterned-based colored PV (MPCPV) modules were developed using direct and micropattern image printing, as illustrated in Figure 2 (b, c, d). A high-resolution wall image was micropatterned with 100 µm microdots and superimposed using image editing software prior to printing with a UV flatbed printer.

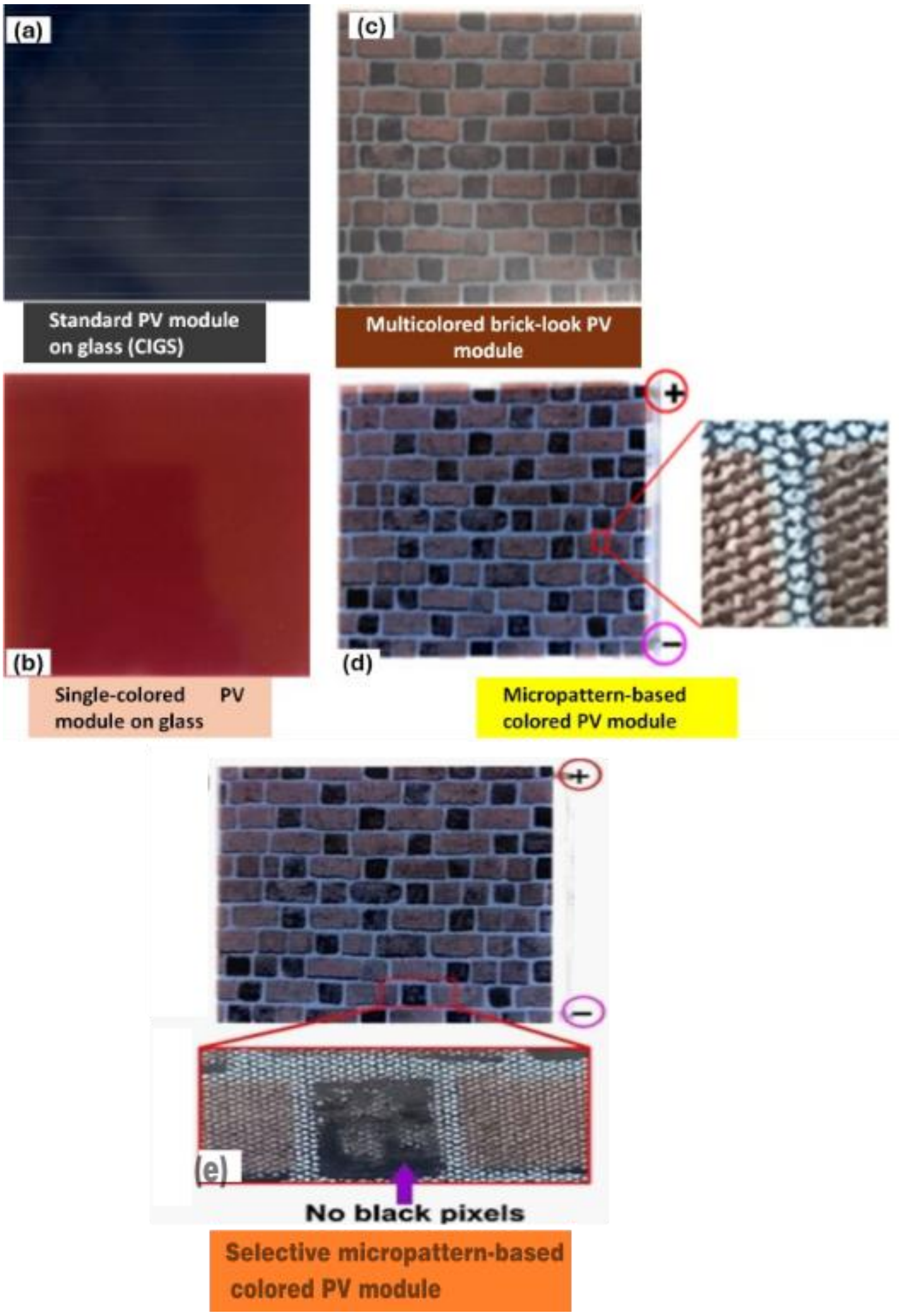

Figure 3. Realistic printed patterns on PV modules demonstrate aesthetic compatibility with architectural materials (Basher et al., 2022, 2024).

2.3. Selective Micropatterning Process

Selective micropatterning was employed to enhance the photoconversion efficiency (PCE) of MPCPV, as depicted in the workflow in Figure 3. Black pixels, which typically obstruct light propagation, were algorithmically removed from the image, thereby increasing light penetration while preserving image quality. This process resulted in a selective micropatterned colored PV (SMPCPV) module, as shown in Figure 2(e).

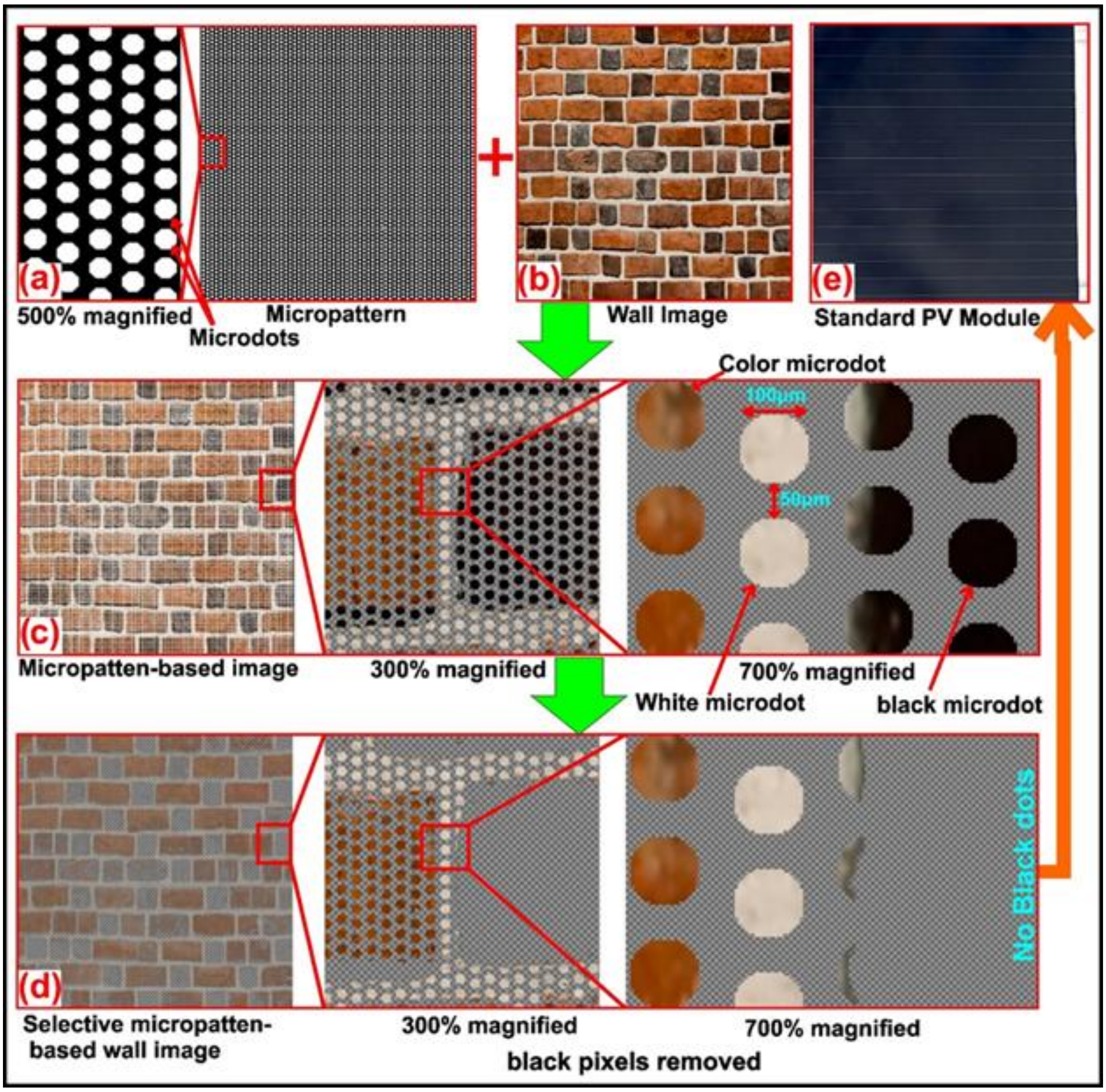

Figure 3. Workflow of the selective micropatterning process used to enhance light transmission through printed color layers (Basher et al., 2024).

3. Performance Evaluation and Discussion

The lower haze observed in AMPV glass (3.7% compared to PMPV's 10.7%) indicates reduced optical scattering, resulting in better visual clarity for architectural glazing applications. The average visible transmittance (AVT) values for AMPV glass were recorded at 58.7%, as shown in Figure 4.

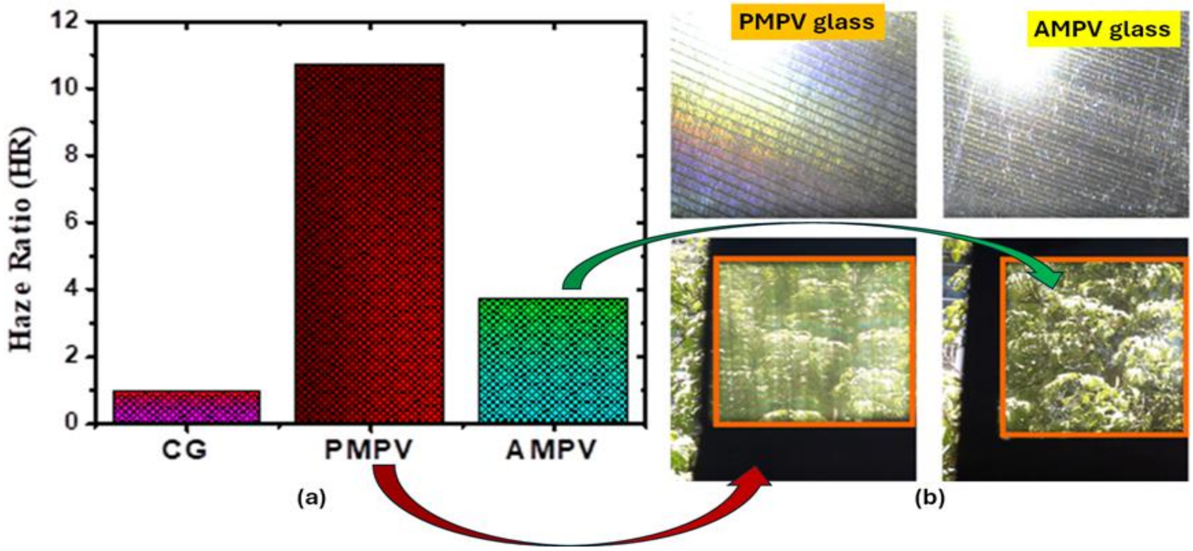

Figure 4. Optical haze comparison of periodic and aperiodic micropatterned PV glass (Basher et al., 2021).

Additionally, an analysis of the CIELAB color space was conducted to verify the color neutrality of the AMPV glass, confirming its suitability for transparent applications such as façades or skylights. The optical properties of micropattern PV glass modules compared with clear glass are summarized in Table 1.

Table 1. Optical performance of micropatterned PV glasses showing AVT and haze values.

Glass Type	AVT (%)	Haze (%)	Visual Clarity
Clear Glass (CG)	82.2	0.9	Excellent
AMPV Glass	58.7	3.7	High
PMPV Glass	43.8	10.7	Moderate

In the context of performance evaluation under actual sunlight conditions, a notable enhancement has been documented (output parameters and performance of tested PV glass modules are presented in Table 2). When comparing a single-color photovoltaic (SCPV) system with an efficiency of 5.49%, a multi-color photovoltaic system with an efficiency of 7.07%, and our SMPCPV system with an efficiency of 11.36%, a substantial contribution to the performance of building-integrated photovoltaic (BIPV) products intended for construction is evident. Additionally, an 18% relative performance improvement has been observed for the SMPCPV system compared to the micropatterned-only modules (MPCPV), achieving efficiencies of 9.6%, as illustrated in Figure 5.

Table 2. Output parameters of tested PV modules under outdoor conditions (Basher et al., 2022, 2024).

Module Type	Voc (V)	Isc (mA)	FF (%)	η (%)	Pmax (mW)
SCPV (Single Color)	11.02	122.3	39.5	5.49	533.42
MCPV (Multi Color)	11.06	142.5	43.5	7.07	686.07

MPCPV	11.08	178.07	46.9	9.60	926.70
SMPCPV	11.09	186.3	53.8	11.36	1111.37
Reference (Black)	11.12	203.2	62.4	14.5	1410.0

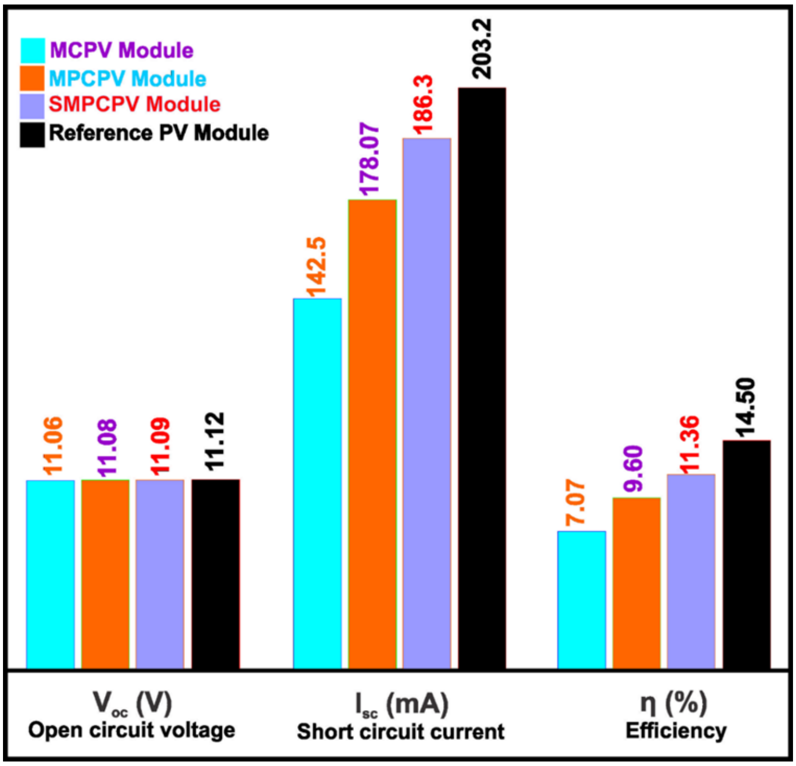

Figure 5. Electrical output performance of various colored PV modules, showing the highest efficiency in the SMPCPV design (Basher et al., 2022, 2024).

The selective removal of black pixels improved photon transmission to the active PV layer, thereby enhancing photocurrent generation and overall conversion efficiency.

4. Conclusion

In summary, we assert that this research illustrates the existence of a model that harmonizes design appeal with energy production in the construction of photovoltaic (PV) modules with energy efficiency. The methodologies presented hold significant potential for integration into contemporary buildings and align with the principles of net-zero construction. Ongoing efforts are focused on refining the selective micropatterning algorithm, particularly to eliminate residual black dots and enhance light transmission without compromising visual quality. These endeavors aim to further optimize the energy yield of patterned modules, thereby advancing the integration of aesthetic and functional elements.

This work also supports carbon reduction in the overall design of buildings by allowing for the increased use of solar energy on the envelope and enhancing the visual and functional performance of photovoltaic (PV) modules. The proposed micropatterning methods allow PV modules to serve as energy-producing components while also allowing them to be used aesthetically. This reduces the need for additional facade materials and decreases the embodied energy of the entire building. This work also has the potential to increase the uptake of PV systems on urban architecture or the use of BIPV systems where visual continuity is desired. The development of BIPV systems is helpful in pushing the energy-use paradigm away from centralized fossil-fuel-derived electricity sourced from the grid to decentralized renewable energy facilities located on buildings, which in turn reduces GHG emissions.

Conflict of interest

The authors declare no conflict of interest.

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