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Design, Development, and Characterization of Highly Efficient Colored Photovoltaic Module for Sustainable Buildings Applications

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Abstract: The building integrated photovoltaic (BIPV) system is one of the contributors which has enormous potential to reach the goal of net-zero energy buildings (NZEB) that significantly reduce the use of fossil fuels that contribute to global warming. However, the limitations of the visual and aesthetic appearance of current BIPV systems make this aspiration unlikely. This study investigates the limitations of the single-color-based PV modules that are dull in appearance and have low photo-conversion efficiency (PCE). In order to solve this issue, we designed, developed, and characterized micro-patterned-based multicolored photovoltaic (MPCPV) modules which are applicable to net-zero building and development. Our newly developed MPCPV module exhibits an aesthetically attractive and flexible building color suitable for industrial application. Furthermore, the MPCPV module possesses an efficiency of 9.6%, which is 4.1% higher than a single-color PV module (5.5%) but closer to conventional thin-film PV modules. In addition, the other output parameters, such as short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum power (P_{max}), and fill factor (FF), indicate that our developed colored PV module is suitable for modern infrastructures that will enable energy generation on-site without compromising the aesthetic appearance. Finally, this research will have a substantial influence on the NZEB and will play an important part in the development of a sustainable environment.

Keywords: BIPV; colored PV module; building applications; solar energy; cadmium telluride PV

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1. Introduction

Modern buildings and infrastructure are dominant candidates for energy consumption nowadays. High-rise buildings and smart cities worldwide require more than 40% of the global energy, and this trend will continue to rise in the near future due to the expansion of the world population, long-term building usage, and an increased desire for greater building comfort levels [1–3]. On the other hand, buildings are linked to the generation of CO_2 in most cases and play a significant role in global warming and climate change, resulting in increasing sea levels due to melting ice caps and ocean acidification. The vision for the global community has been set to achieve net-zero carbon emissions by 2050, to keep the global temperature rise under 1.5 °C, in order to achieve at least a sustainable position with regard to the target of COP26 (the united nations climate change conference, 2021). In this case, innovative and sustainable building infrastructure can be one of the best alternatives for ensuring on-site renewable energy generation to boost the energy supply. Recently, on-site renewable energy generation has attracted the attention of researchers, and several research works have been conducted to design and optimize energy demand and supply for building-scale infrastructure [4–6]. Building Integrated Photovoltaic (BIPV) systems are capable of offering sustainable micro-energy generation to be integrated into a variety of building designs. Several studies have been conducted and reported that the application of BIPV can result in significant energy savings [7–9] and reductions in energy consumption and pollutant sources. BIPV can act as both an element of the building envelope and an energy-source material for modern infrastructure, based on cost-effectiveness and availability to architects. BIPV systems can be more cost-effective simply because their composition and placement replace many of the traditional components, resulting in a variety of benefits, such as material and electricity cost savings, reduced use of fossil fuels, lower carbon and greenhouse gas emissions, and an improved architectural outlook of the building [10,11].

BIPV systems can generate power cost-effectively when considering both the purpose of electricity generators and building materials [12,13]. However, the use of BIPV materials has a negative reputation, mainly because of the limitation of the visual and aesthetic appearance of BIPV systems [14–24]. The current systems mostly display black or dark blue colors, depending on the photovoltaic technology used [17,25], as shown in Figure 1. It is reported [26] that greater than 85% of building designers choose BIPV products for their aesthetic attributes rather than their costs or limited conversion efficiencies. BIPV products featuring visible transparency, coloration, and reasonable conversion efficiency are alluring for the enhancement of public satisfaction and installation proportion [3,12,27,28]. In this regard, researchers have concentrated on coloring the solar cells by changing the thickness of the absorber materials themselves or adding extra optical materials and coatings to them [29]. For example, perovskite, organic, and dye-sensitized solar cells have a wide range of color options due to the wavelength-dependent visible light absorption characteristics of their active materials [30–35], whereas CdTe, black crystalline silicon, and CIGS solar cells can be made colorful by incorporating additional colored materials or photonic structures [36–40].

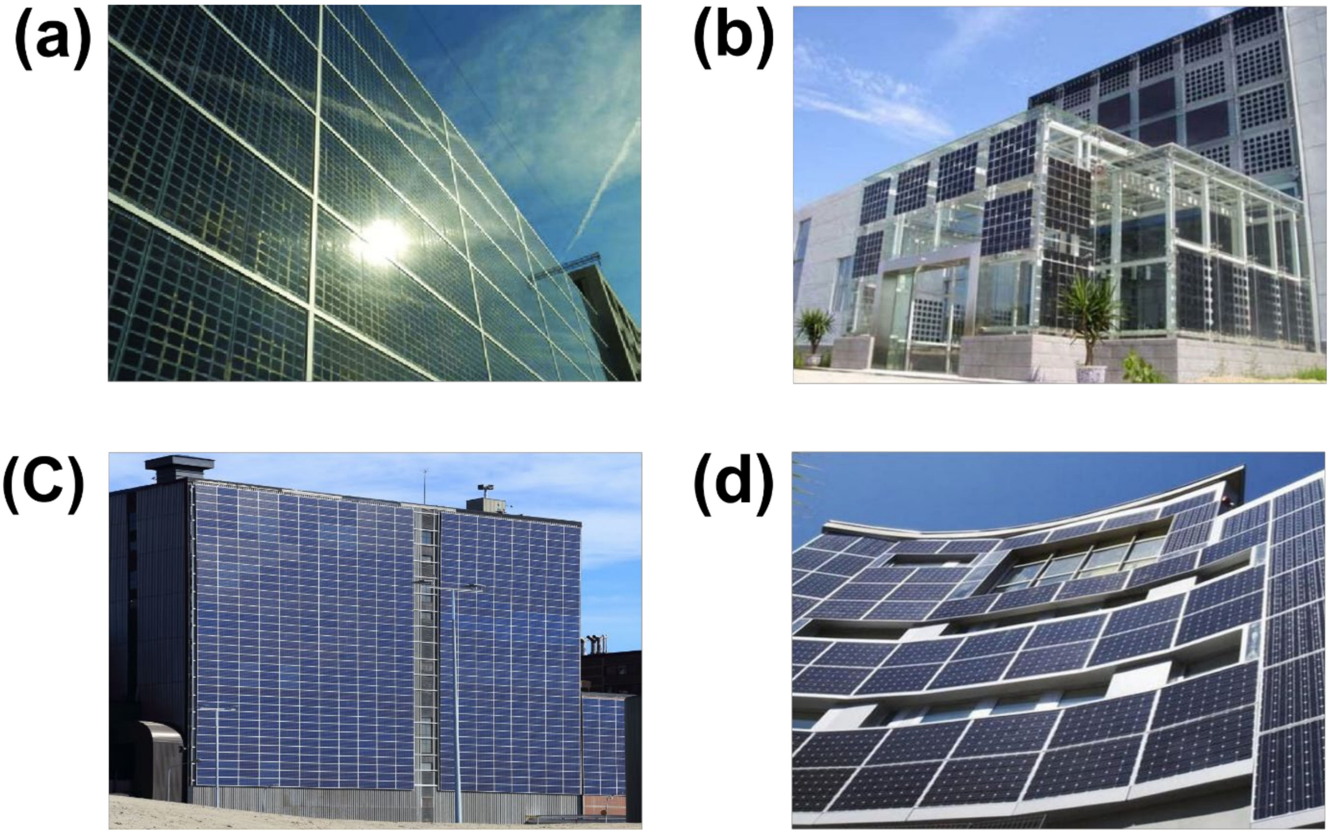

Figure 1. Applications of BIPV products: (**a**) Black facade, (**b**) Blackish facade, (**c**) Bluish facade, and (**d**) blue facade [41–44].

Alternately, several attempts have been made to develop colored high-definition PV panels by coloring the opaque panels, using, for example, distributed Bragg reflectors [40,45], modified antireflective coatings [37,38], resonant dielectric nanoscatterers [46], structures [47], plasmonic particles [28], or luminescent materials [36] that reflect or emit colored light, digitally-printed ceramic inks [48], and sandblasting [12]. Moreover, the external appearance of the traditional opaque PV modules can be altered with colored optical coatings [45,49] and encapsulation with polymer layers or materials [36] applied on their front glass that hide the underlying PV modules while creating the desired colorful appearance [29]. It can be seen from the existing literature that current technologies exhibit only a single color, resulting in a dull appearance and low photo-conversion efficiency (PCE). Currently, no single technology exists where a flexible-colored PV module is produced with high PCE. Therefore, an innovative and cost-effective approach is needed to ensure color flexibility (almost all colors) with high contrast and resolution and a commercially viable PCE.

In this work, we aim to develop and demonstrate a new, superior, cost-effective high-definition colored photovoltaic (PV) technology based on the direct printing of micro-scale-resolution images onto the surface of flat PV panels. To the best of our knowledge, this is the first study focused on designing and developing high-definition, high-efficiency thin-film-based colored PV modules using direct-printing technology. This new thin-film-based high-definition colored PV technology directly addresses the challenges of achieving future zero-net-energy buildings goals through viable and versatile BIPV solutions.

2. Experimental Procedure

Four 13.2 cm x 13.2 cm cadmium telluride (CaTd)-based thin-film PV modules were obtained from Advanced Solar Power Inc., Hangzhou, China). The modules had almost identical physical and optoelectronic properties. One of these PV modules was selected as a reference (black) PV module, with which the performances of the other colored modules were compared. A single-colored PV module was created by directly printing a single ink layer onto the skin of the black PV module. Printing thin layers of ink directly onto a dark solar panel typically yields dark images of very low contrast, making direct printing impractical. To overcome this issue, we printed with white ink on the dark PV module and then brown ink on the white ink using a UV flatbed printer (Model no. BAFUP1325, made in China). This type of printer can print very small to large high-resolution images using cyan (C), magenta (M), yellow (Y), key/black (K), white (W), and clear varnish. The brown ink is a mixture of four different colors: C = 0%, M = 67%, Y = 67%, and K = 50%. The limitation of the single-colored PV module was overcome by printing a multicolor brick wall image onto a black PV module. Placing a high-definition image in front of a PV module typically blocks most of the incident light, significantly reducing the panel efficiency. Finally, the development of a highly efficient colored PV module started with the design of micropatterns (as shown in Figure 2a) using Python, a high-level, general-purpose programming language software. The desired brick image with high resolution shown in Figure 2b was downloaded from open sources [50]. The GIMP, image manipulation and editing software, was used to superimpose the micro pattern onto the wall image. The micropattern acted as a mask for the image shown in Figure 2c, where only the microdots become transparent to the printer. A UV flatbed printer printed the dots on an off-the-shelf thin-film solar module.

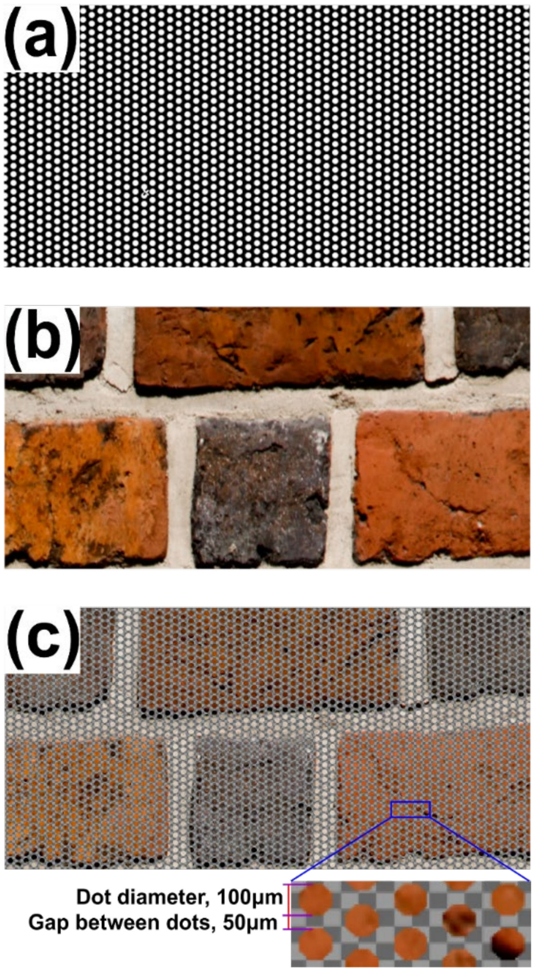

Figure 2. Generation of micropatterned image: (**a**) micropattern produced by Python, (**b**) high-resolution wall image, and (**c**) micropatterned image where the dot diameter is 100µm, and the gap between the dots is 50 µm.

Initially, in the printing process, UV-sensitive white ink was printed on the position of the dot on the PV panel, and then, a colored image (as shown in Figure 2c) was printed onto the white microdots of the PV panel. Generally, if the distance between two objects is smaller than 50 µm, the human eye is not capable of discriminating between them and interprets the picture as a single entity. This concept has been employed to develop colored PV modules by printing micro-scale areas (dots) on the thin-film materials of the PV module. In this process, each image consisted of two layers: (i) a microstructure background comprising semitransparent white micro ink dots (which pass the UV and IR component of sunlight) separated by micro gaps (which pass all sunlight) and (ii) a high-resolution colored image (using thin, semitransparent, durable colored ink) printed over the whole or parts of the solar panel area. From our designed sunlight transmission calculation model (shown in Figure 3), it can be revealed that the total sunlight power transmitted through a high-definition image could potentially exceed 75.5%, which means that the predicted power output of the colored PV panel could be at least 75.5% of the standard (black) PV module output.

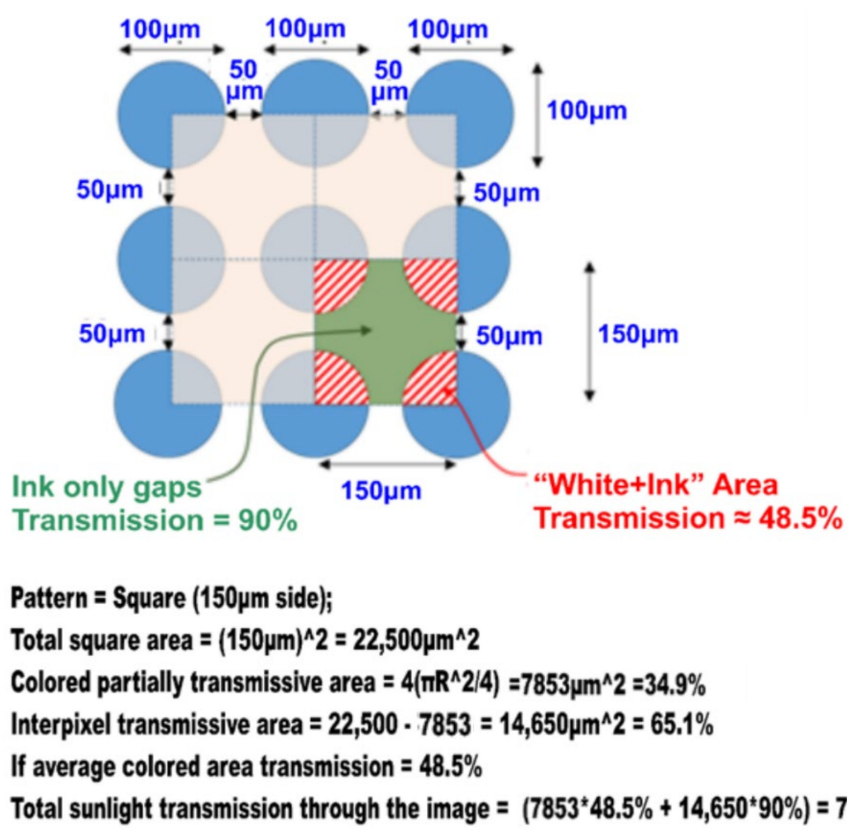

Figure 3. Total sunlight transmission calculation.

The photovoltaic performance, in terms of maximum electrical power and power conversion efficiency, of the colored PV panels was characterized using an outdoor, commercial PV module analyzer (PROVA 200 A, made in Taiwan). This type of PV analyzer is widely used for the measurement of photovoltaic response. Moreover, the evaluation parameters of the PV module were measured and include (1) open-circuit voltage (V_{oc}), the voltage at which no load connected to the PV module; (2) short circuit current (I_{sc}), the current through the solar cell when it is short-circuited; (3) maximum current (I_{max}), the current at which maximum power occurs; (4) maximum voltage (V_{max}), the voltage at which maximum power occurs; (5) fill factor (FF), the ratio of maximum power to the product of the short-circuit current and the open-circuit voltage of a solar cell; and (6) power conversion efficiency (PCE), the ratio of the output electrical power to the input optical power [51].

3. Results and Discussion

High-efficiency, aesthetically appealing BIPV products have become one of the interesting research topics in the renewable energy sector nowadays and are getting more attention by architects for the design of modern infrastructures towards the implementation of net-zero energy buildings (NZEB). BIPV provides an attractive, cost-effective, and technically feasible way to integrate multi-functional components into a building's surface, such as roofs and facades [52]. However, the current BIPV products provide only minimal colors, which are not favored by architects, urban planners, and building owners. The color vision of the human eye is based on the cone cells' spectral sensitivity to a particular wavelength of light, which peaks at specific frequencies in the visible spectrum [53,54]. The CIE 1931 XYZ standard, which defines colors using X-, Y-, and Z-coordinates, often known as the XYZ tri-stimulus values, quantifies human color perception [55,56]. By computing the chromaticity coordinates of the colors, they were converted into the CIE xyY color space to examine the efficiency constraints of different colors in the CIE 1931 chromaticity map (Y-value) at the same relative brightness [29]. However, the CIE color perception standard is only suitable for a single color and is unable to define multicolored images. In this work, we have developed a multicolored building faced PV module which exhibits both color flexibility and higher efficiency. Prior to this, we developed a single-color PV module by using a standard (black) PV module to analyze its limitations. The physical appearance and current-voltage (I-V) characteristics of the standard (black) and single-colored PV (SCPV) modules are shown in Figure 4.

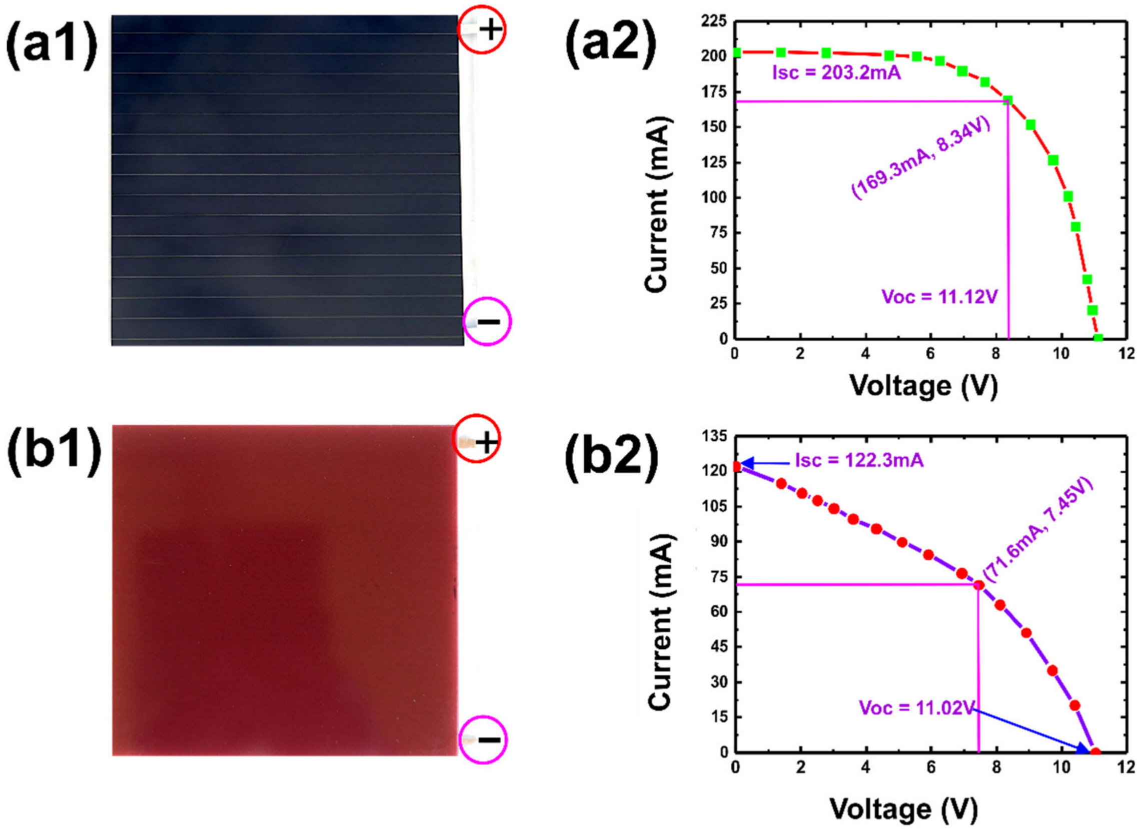

Figure 4. Physical appearance (**a1**) and its I-V characteristics diagram (**a2**) of the standard PV module and visual appearance (**b1**)1 and its I-V curve (**b2**) of single-colored PV modules.

The appearance and functionality of a solar module are based on the two spectra: visible spectrum and solar spectrum. The visible spectrum is the range of frequencies over which the cone cells in human eyes are sensitive, or in other words, it is the range of wavelength visible to the human eye, which spans from 390 to 700 nm. On the other side, the solar spectrum refers to the range of wavelengths (300 to 1200 nm) over which the conventional solar cell absorbs light [54]. From Figure 4a1, it can be seen that the standard PV module looks completely black since it absorbs almost all the wavelengths of the solar spectrum, thus exhibiting maximum electrical output. On the other hand, when sunlight falls on the single-colored PV module, most of the incident light is absorbed or reflected, and the remaining light is transmitted through the color ink layer. The reflected light allows the human eye to visualize the printed image [54].

It can be seen from Figure 4b1,2 that the color ink layer severely affects the performance of the PV module. The single-colored PV module exhibited a PCE of only 5.49%, which is significantly lower than that of the reference (black) module (14.5%). This colored PV module produced 876.58 mW less power than the reference (black) PV module (1410 mW). It is also observed that the color layer has a significant impact on the short-circuit current (122.3 mA), with less effect on the open-circuit voltage (11.02 V). From the perspective of physical appearance, this single-colored PV module looks more aesthetic compared to the reference (black) PV. However, multicolored patterns are typically and consistently more aesthetic to architects and urban planners. Therefore, this single-colored PV module was deemed unsuitable for developing BIPV products due to its low power output performance and aesthetically less-appealing look. We developed a multicolored brick-look PV (MCPV) module to overcome these limitations, as shown in Figure 5a1.

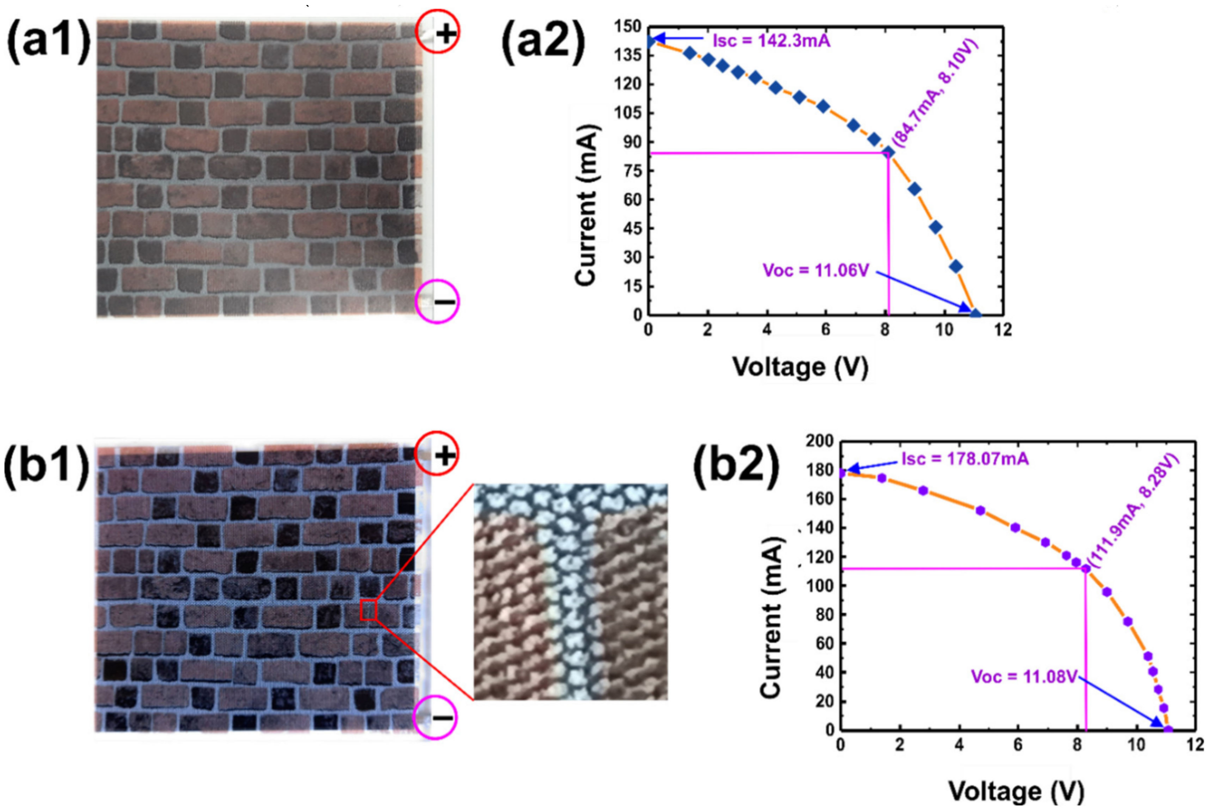

Figure 5. Multicolored brick-look PV module (**a1**) and its I-V characteristics diagram (**a2**) and micropatterned-based colored PV module (**b1**) and its I-V curve (**b2**).

In terms of aesthetic appearance, this PV module looks very attractive compared to a standard PV module (black color) or a single-color PV module. On the other hand, this multicolored PV module exhibited an efficiency of 7.07%, which is 48.7% less efficient than the standard (black) PV module (14.5%). Moreover, the maximum power generation for this PV module is 686.07 mW, which is 723.93 mW lower than the standard (black) PV module (1410 mW). However, this MCPV module exhibited better output performance than the single-colored PV. The reason behind this is that the multicolor wall image (Figure 5a1) contains different color blocks whose absorption and reflection properties are different [29,54]. For example, this multicolored image (Figure 5a1) contains many black blocks whose absorption coefficient is extremely high and whose reflectivity is close to zero. That is why the multicolored ink layer allows significant incident light to pass through to the PV module, enabling better electrical characteristics compared to the single-colored PV.

Although this MCPV module is aesthetically appealing, the low output performances make it unsuitable for industrial applications. We have designed and developed a high-resolution MPCPV module to address this issue, as shown in Figure 5b1. The visual appearance of this MPCPV module is very attractive compared to a standard (black) and single-colored PV module. Moreover, it exhibits a comparably better output performance (Figure 5b2) that supports the result of Ref. [57]. It can be seen from Figure 5b2 that the MPCPV has a short-circuit current of 178.07 mA, which is 25 mA lower than the standard (black) module (203.2 mA), but the open-circuit voltage is almost the same for both modules. This is due to the fact that applying color ink reduces the shunt resistance of the module. This MPCPV module exhibited a higher efficiency (9.6%) than the MCPV (7.07%) and SCPV

(5.5%) modules. The micropatterns allow more sunlight to pass through the colored ink layer to the PV module. According to the theoretical calculation shown in Figure 3, more than 75.5% of sunlight passes through the color ink layer. Therefore, the output power of the MPCPV (926.7 mA) should be at least 75.5% of the standard (black) PV module. However, this MPCPV generates 65.7% of the standard PV power. This limitation can be explained by considering the magnified view of Figure 5b1. It is observed that the microdots are not appropriately printed as the distortions outside the dots are present due to over- and under-printing and jagged edges [15]. As the distorted dots block the incoming light and prevent it from being transmitted, the MPCPV module exhibits lower output power than expected theoretically. Table 1 summarizes the output performance of the standard, single-colored, multicolored, and micropatterned-based multicolored PV modules.

Table 1. Electrical parameters of PV modules.

Sample Name	V_{oc} (V)	I_{sc} (mA)	FF (%)	η (%)	P_{max} (mW)
Reference (Black) PV Module	11.12	203.2	62.4	14.5	1410
Single-Colored PV (SCPV) Module	11.02	122.3	39.5	5.49	533.42
Multicolored (MCPV) PV Module	11.06	142.5	43.5	7.07	686.07
Micropatterned-based Multicolored (MPCPV) PV Module	11.08	178.07	46.9	9.6	926.7

It is clear from the above results and discussions that our developed micropatterned-based colored PV module demonstrates an excellent performance in terms of short-circuit current, open-circuit voltage, fill factor, conversion efficiency, and output power. Although a minor distortion takes place with the microdots due to jagged edges and overprinting, this PV module provides both the aesthetic appearance of the building skin and the output performance simultaneously. It is seen that the efficiency of this PV module will be further increased if the black microdots are managed appropriately because the PV panel underneath is completely black. Finally, it is worthwhile to mention that the ability to develop arbitrary image-based, high-resolution PV modules with high efficiency will pave the way towards the realization of the net-zero energy building and hence the reduction in CO_2 emissions.

4. Conclusions

We have successfully designed and developed multicolored and micro-pattern-based PV modules with a high power conversion efficiency of 9.6%. The results have shown that our MPCPV module exhibits both high resolution and aesthetic appearance, and this module exhibits a higher efficiency than the MCPVPV module (7.07%) and SCPV module (5.5%) due to its absorption of more sunlight through the gaps of the micro-pattern color ink layer. The development of this MPCPV module opens the way for developing arbitrarily patterned PV modules, where almost all the color can be produced without compromising the photo-conversion efficiency. This successful development of MPCPV modules will open new possibilities for boosting up the use of BIPV towards achieving the global goal of net-zero buildings, which address many key challenges related to global sustainable development.

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