# **Stretchable and Flexible Crystalline Silicon Photovoltaic Modules Embodying an Auxetic Rotating-Square Structure for Adjustable Transmittance**

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# Abstract

This work describes the segmentation of commercial crystalline silicon solar cells into smaller sections and their subsequent restructuring into interconnected arrays, based on an auxetic rotating-square architecture, to produce a lightweight, flexible and stretchable solar module. As expected, the sectioning of the solar cells reduces their power conversion efficiency due to increased carrier recombination at the sawn edges. However, average cell section efficiencies are shown to be less than 1.8% lower than the original cells. Output voltage and current can be tailored according to the combination of series or parallel connections between solar cell sections in the design. Due to the negative Poisson's ratio of the auxetic structure, bi-directional expansion with uniaxial stretching is achieved, opening gaps in the module which allows the light transmittance to be adjusted. Mechanical tests reveal that the structures are robust to repeated cycles of expansion and relaxation, aided by the joint rotation mechanism of expansion that avoids excessive strain on the joint material. The modules are fully expanded when each cell section is rotated by 45°. In this expanded state, modules made of 31.75 mm × 31.75 mm solar cell sections have a strain of 67% and transmittance of 41.9%. Modules incorporating the smaller 20 mm × 20 mm cell sections have a maximum strain of 60%, with a corresponding transmittance of 49.5%. A geometric model is used to show that by varying the design parameters, the transmittance maximum, minimum and range can be tuned, opening up various potential applications include BIPV (e.g. partially shaded windows), AgriPV (e.g. greenhouse roofs), portable PV devices and wearables.

*Keywords: Auxetic Rotating Square Structure, Stretchable Solar Cell Module, Adjustable Transmittance*

## Introduction

To protect fragile crystalline silicon (c-Si) solar cells from mechanical damage and degradation by the external environment, c-Si solar modules are typically assembled by laminating and mounting them within an aluminium frame using a rigid backsheet, frontal glass, and Ethylene Vinyl Acetate (EVA) encapsulant [1-3]. As a result, solar panels are typically rigid and flat, which limits these devices to applications in large-scale solar farms or flat building surfaces [4-6]. Thin film PV technologies can offer greater flexibility through the use of appropriate substrates, although power conversion efficiencies and long-term stability of such devices tends to be lower than their c-Si counterparts [7]. To further expand their applications in building integrated photovoltaics (BIPV), agricultural PV (AgriPV) and portable/wearable devices, researchers have investigated various methods to make c-Si solar modules lighter in weight and able to cover surfaces with curvature [8-12]. The most common approach is to bend c-Si wafers within their fracture limits, suitable only for simple, single-axis curvatures like pillars or wings of aircraft [11,12]. Alternatively, full-sized c-Si solar cells can be diced into smaller solar cell sections and reconnected with flexible interconnects, allowing them to be individually orientated parallel to the surface plane of a small segment of the curved surface [13-14]. This enables conformal coverage of complex surfaces through adapting the geometries and interconnections of the solar cell sections. [15-16]. Such flexibility depends on the design of elastomer-coated interconnects and their pre-stretched structures, such as wavy metal foils and serpentine metal wires [17-20]. However, enhancing stretchability requires more interconnects, increasing weight, size, production complexity, and reducing the active solar cell area, lowering power output per unit area. Longer interconnects also raise internal resistance, further reducing energy conversion efficiency.

The auxetic rotating polygon structure holds great potential for addressing the aforementioned challenges in designing flexible and stretchable solar modules. Rather than stretching and compression of pre-stretched metallic interconnects, the stretching mechanism of the auxetic rotating polygon structure uses the counter-rotation and separation of adjacent units around the vertices of the polygons [20-21]. During expansion, adjustable gaps form between polygons, allowing unobstructed light transmission. The overall light transmittance can be adjusted by stretching or relaxing the structure to meet practical needs. Another unique attribute is a negative Poisson's ratio, meaning that under uniaxial tensile load, the array expands both along and perpendicular to the tensile load direction by rotating around the vertices of the polygon sections. This avoids the need for control of multidirectional stretching mechanisms of traditional stretchable interconnects [22-25]. In addition, recent studies have shown that during stretch-rotation, the stress concentration occurs at the joints between the polygon sections, while the stresses inside the polygons are very low [26]. Moreover, the strain at the joints in the direction of the tensile load is small [27], a feature which could potentially confer durability in repeated cycles of expansion and relaxation. Recently, auxetic rotating polygon structures have been applied in a variety of flexible and stretchable devices. Examples include bioinspired electronic armour for soft robotics [22], adaptive curvy imagers for tuneable lensing [28] and self-powered strain sensors for structural health monitoring [29]. Here, we study the novel application of such auxetic structure designs to c-Si photovoltaic modules, analysing their electrical, mechanical and optical characteristics, including quantification of their tuneable optical transmittance.

In this work, prototype solar modules were fabricated by interconnecting small square solar cell sections into an Auxetic Rotating Square (ARS) structure. The prototype modules use polyurethane rubber to provide joints with sufficient out-of-plane flexibility to allow conformal coverage of highly curved surfaces, as well as corrugated or folded morphologies. The flexible joints also allow full rotation of the cells upon the application of uniaxial tension, expanding the structure and opening up gaps within the array. The 2×2 modules fabricated of 20 mm and 31.75 mm square solar cells in this work were able to cover complex curved surfaces while achieving light transmittance adjustments of 38.7%-49.5% and 26.3%-41.9% in the 0°-45° rotation range. In addition, the geometrical model developed in this work provides a reference transmittance range for larger modules over a range of unit-cell size ratios. Figure 1 illustrates an example of an ARS PV array in a real-world application: an application on a gabled greenhouse roof. The ability to control the amount of light penetrating through the PV module has potential applications in AgriPV where plant growth depends strongly on the degree of shading [30-32]. By controlling the light intensity and temperature experienced by the plant leaves, the rate of photosynthesis and water loss through the stomata of the plant can be optimised for maximum yield [34-36]. In BIPV, dynamically adjustable light transmittance modules can compensate for the limitations of window-integrated PV modules with fixed projection areas. By modulating the intensity of transmitted light, these modules can balance lighting and temperature control needs, supporting the goals of sustainable and smart buildings [37].

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Figure 1. Schematic of a solar module with adjustable transmittance on curved surface of a greenhouse.

# Methodologies

## Prototype Fabrication

An overview of the fabrication process for the prototype 2 × 2 ARS solar module developed in this work is presented in Figure 2. The individual steps of the process are described in the proceeding sections.

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Figure 2. Illustrations of fabrication workflow from cell sawing to final 2×2 array module using casting method.

### **Solar cell dicing**

The solar cell sections were cut out from 158.75 mm × 79 mm mono-facial PERC cells (half-cell, 5-busbar) using a wafer dicing saw (DAD341, Disco, Blade ZH05-SD2000-N1-90EG, kerf width 55.0±5μm). These solar cell sections are squares of two sizes: 20 mm × 20 mm and 31.75 mm × 31.75 mm, with dicing paths configured as shown in Figure 2 to include a busbar in each cell section. The solar cell sections are cleaned with DI water after dicing.

### **Wiring and Soldering**

Tinned copper tabbing wires were soldered onto the busbars on the front and the soldering pads on the rear of the solar cell sections. Single-core tinned copper wires with diameter of 0.28 mm (30AWG) were then soldered to the tabbing wires to form the electrical connections between the solar cell sections. Circuit diagrams of a 2-line parallel connection and a 4- cell series connection are shown in Figure 3.

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Figure 3. Circuit diagrams: 2-line parallel (top) and 4-cell series (bottom).

### **Mould Fabrication**

The general design for the 2×2 array mould is shown in Figure 4, with specifications for the two cell sizes given in Table 1. The rear side of the model is designed with grooves to accommodate the back support made of UV curable epoxy and the soldered tabbing wire. *L0* is the side length of the square unit and *L1* is the width of the part containing the solar cell section. *α* represents the initial rotation angle of the ARS. *d* is the joint width of the connecting part between the square units. *H* is the thickness of modules, while *h1*, *h2* and *h3* are heights of different regions of the grooves. The moulds used were made of Shore’s hardness 10A silicone rubber (Mold Max 10, Smooth-on) moulded onto 3D printed rigid (Photon D2 DLP, Anycubic) templates. The surface of the mould was sprayed with a mould release agent (Universal Mold Release, Smooth-on) before casting to reduce adhesion to the mould and avoid cure inhibition.

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Figure 4. (a) Workflow of moulding process. (b) Schematics of the mould design.

| Table 1. The specifications of mould design for the two different solar cell section sizes used in this work (refer to Figure 4) | | |
| --- | --- | --- |
|  | 20 mm × 20 mm | 31.75 mm × 31.75 mm |
| *L0* (mm) | 28 | 38.5 |
| *L1* (mm) | 25 | 36.75 |
| *d* (mm) | 1.5 | 1.5 |
| α (°) | 0.5° | 0.5° |
| *H* (mm) | 2 | 2 |
| *h1* (mm) | 0.8 | 0.8 |
| *h2* (mm) | 0.6 | 0.6 |
| *h3* (mm) | 1.4 | 1.4 |

### **Encapsulation**

Encapsulation was performed by casting pre-mixed and degassed two-component liquid polyurethane rubber CF50 (ClearFlex50, Smooth-on) into the mould in which soldered solar cell sections were placed. After the CF50 was fully cured, the front side of the module in the mould was coated with 0.6-0.8 mm thick clear UV curable epoxy (UV Resin, Apex Resin) according to the size and position of the solar cell sections and cured with a 60 W 405 nm UV lamp, to form a protective layer and to avoid fracturing of the solar cell sections during the demoulding process. The module is removed from the soft mould and then UV epoxy is applied to the grooves on the backside and fully cured to form a rigid back support.

## Electrical Characterization

The electrical performance of the solar cell sections and modules under illumination was investigated using a current-voltage measurement setup comprising a solar simulator (Sun3000 AAA Solar Simulator, Abet Technologies) with Xenon arc lamps (550W, AM1. 5G spectrum), a source meter (Keithley 2400), and a probe station with temperature control (water cooling and Peltier) and vacuum chuck. A 4-wire probing method is used to measure I-V curves of the original solar cells, solar cell sections, and modules under standard conditions of 25°C and 1 sun (AM1.5) irradiance. Before the measurements, the solar simulator was calibrated using a reference cell from Radboud University Nijmegen. The calibration involved adjusting the lamp current to correct the light intensity and optimizing the position of the sample cell on the probing stage.

To assess the damage caused to solar cell sections during sawing, soldering, and demoulding, photoluminescence imaging (PL, CellSpot PL, BrightSpot Automation) was performed on cells before and after sawing and on the final module after encapsulation. The PL images were processed using MATLAB for edge profile analysis. Sampling was performed along rows/columns within the sampling window set across an edge. The average value of the sampled pixel brightness along the profile curve was then calculated. The averaged profile curves were then normalized by dividing the brightness of each point by the maximum value on the curve. PL brightness profiles were thus plotted across sawn solar cell section edges and compared with profiles taken across original cell edges.

## Mechanical Characterization

To investigate the stretchability and tensile response of the ARS solar modules, a universal tensile tester (H2KS, Tinius Olsen) with a 25N tension load cell was used to conduct tensile tests on 2×2 arrays of 20 mm and 31.75mm solar cell sections. To test the durability of the joints, a 2×2 module of 20 mm encapsulated solar cell sections was subjected to 1000 cycles of extension and relaxation from the initial state of 0° rotation to the fully expanded state of 45° rotation at 25℃.

## Optical Characterization

The degree of transmittance of an ARS module at a specified degree of in-plane expansion is defined here (see equation 1) as the area of the transparent (air) regions (*Agap*) plus the area of the semi-transparent (encapsulant) regions (*Acf50*), weighted by its average optical transmittance (*Tcf50*), divided by the initial area (*Aini*) which is calculated from the edge of module encapsulation. In all analyses that follow, only changes to light transmission within the initial area covered by the unexpanded module are considered and the expanded module and the initial area are configured to be concentric.

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Figure 5. The illustrations of fully expanded 20 mm 2×2 modules: (a) diagram of simplified geometric model, (b) image rendered from COMSOL mechanics simulation and (c) photograph for pixel counting analysis

The measurement of transmittance of CF50 (*Tcf50*)was conducted by mounting a sample of the material on the side of an integrating sphere within an in-house built Variable Angle Reflectance (VAR) measurement system. Details of the set-up are available in reference [36]. The samples used for transmittance measurements were CF50 sheet cast with 3D printed moulds to a thickness of 2 mm to match the thickness of the CF50 encapsulant regions in the constructed modules. Measurements were taken with light at normal incidence to the sample, using the empty integrating sphere port as a reference (100% transmittance). The area terms in equation 1 were determined in three different ways as illustrated in Figure 5 and described in the sections below.

### **2.4.1** Geometric Model

For transmittance calculations, a MATLAB script was developed to compute the areas from an ideal geometric model of the ARS, as shown in Figure 5(a). The ideal geometric model has unit squares connected at the vertices, i.e., joint widths are 0. Additionally, the supporting ribbons present in the fabricated modules are not included. The code has been made available on MATLAB Central File Exchange, under the name “ARS\_TransmittanceCalc ” [39].

### COMSOL Model

Finite element method simulations of the ARS module were performed using the COMSOL Multiphysics Solid Mechanics module, with results exported for each step of 5° from 0° to 45° rotation. A Boolean difference operation was applied to the COMSOL geometry module and a square with size equal to the initial state. An example of the output from this, for the fully expanded state (i.e. 45° rotation), is shown in Figure 5(b). The area of each region was then extracted using functions within COMSOL.

### Measured from Photograph

Photographs were captured of the modules from above at various degrees of expansion with camera (Canon EOS 250D, 35mm lens), an example of which is shown in Figure 5(c). For this, a manual micrometre translation stage with clamps was used to expand the ARS with rotations of the square solar cell sections from 0° to 45° in steps of 5°. The photographs were then analysed to determine the proportions of semi-transparent (encapsulant) and transparent (air gaps) areas at each expansion step. This was done by first converting the photographs to grayscale, defining pixel threshold values for each region and then determining the areas by counting pixels.

# Results

## Electrical

The current-voltage (I-V) characteristics of the original cells, sawn solar cell sections and modules under 1 sun irradiation were measured with the set-up described in section 2.2 and the Fill Factor (FF) and Power Conversion Efficiency (PCE) were calculated. The average open-circuit voltage (Voc), short circuit current density (Jsc), FF, PCE and PCE degradation with respect to the original cell are presented in Table 2, for the two sizes of sawn solar cell sections. The spreads of values are presented in Figure 6 (a-b). The results show PCE degradation compared to the original cell, which is likely due to increases in carrier recombination at un-passivated sawn edges of the solar cell sections and mechanical damage during the sawing process and handling. By comparing the electrical performance of the two sizes of solar cell sections, it was observed that there is a potential correlation between the performance degradation and the ratio of the un-passivated edge to the upper surface area of the solar cell sections.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Table 2. The averages of the extracted parameters from the I-V characterization of original cells and cell sections | | | | | |
|  | Voc (V) | Jsc (mA/cm2) | FF | PCE (%) | PCE percentage point decrease (%) |
| Original Cells | 0.676 | 40.04 | 0.746 | 20.33 |  |
| 20 mm Solar cell sections | 0.662 | 38.59 | 0.712 | 18.58 | 1.75 |
| 31.75 mm Solar cell sections | 0.675 | 39.38 | 0.706 | 18.79 | 1.54 |

For modules, the average values of the measured parameters are presented in Table 3, with the ranges illustrated in Figure 6 (b-f). Also shown in Figure 6 (c-f) are the current density and voltage at maximum power point (Jm and Vm) for the various module types. For conversion from current to current density, the total module area was used. Encapsulated module performance is affected by optical losses due to the encapsulation material, shading by tabbing wires, and the resistance of the interconnects, in addition to the reduction of the proportion of the total area taken up by cells. The performance attenuation of parallel modules is more significant, which is likely to be due to the ~20% greater total wire length compared to series modules.

| Table 3. The averages of the extracted parameters from the I-V characterization of modules | | | | | |
| --- | --- | --- | --- | --- | --- |
|  | | Voc (V) | Isc (mA) | Pmax (mW) | FF | PCE (%) |
| 20 mm (2×2) Series ARS | | 2.643 | 144.16 | 381.01 | 0.697 | 16.46 |
| 20 mm (2×2) Parallel ARS | | 1.327 | 296.44 | 393.38 | 0.655 | 14.65 |
| 31.75 mm (2×2) Series ARS | | 2.663 | 357.66 | 952.45 | 0.696 | 16.59 |
| 31.75 mm (2×2) Parallel ARS | | 1.336 | 712.90 | 964.46 | 0.650 | 15.35 |

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Figure 6. The I-V characterization results: (a)The Voc and Jsc of solar cell sections and original cells; (b)The PCE of original cells, cell sections and modules; (c)(d) Jsc and Jm of modules with series and parallel connections; (e)(f) Voc and Vm of modules with series and parallel connections.

Examples of cell PL images and a plot of normalized PL intensity vs. distance across edges are presented in Figure 7. Two main types of mechanical damage that can occur during the cutting process are chipped off corners and microcracks (see red arrows in Figure 7 (b) and (e)). In Figure 7(f), the graph shows a more prominent decrease in PL intensity at the un-passivated sawn edges compared to the original cell edges, indicating an increase in defect-mediated, non-radiant recombination occurring there. The dip in the intensity profile for the original cell edge at a distance of about 0.3 mm is due to the metal finger present there. Scrutiny of the PL images of modules in Figure 8 reveals that the module fabrication process did not noticeably add mechanical damage, but the tabbing wires increased the proportional shading on the surface of the solar cell sections besides busbars and fingers, and this effect was more pronounced in the 20 mm modules given the fixed width of the tabbing wires.

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Figure 7. The PL imaging results with sampling windows: (a) the original solar cell; (b)(c) 20 mm cell sections, (d)(e) 31.75 mm cell sections, red arrows pointing at a missing corner and a microcrack. (f) The plots of normalized PL imaging intensity vs. sampling distance for sawn and original edges, red arrows on inset image represent sampling directions at each edge.

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Figure 8. PL images of encapsulated modules: (a) 20 mm module; (b) 31.75 mm module.

## Mechanical

The assembled 2×2 ARS solar module is designed with supporting ribbons for easy stretching and control of the rotation angle of the solar cell sections. Expansion of the module is achieved by applying a uniaxial displacement to this symmetric set of ribbons, as shown in Figure 9(a-c). The elasticity of the polyurethane rubber causes the modules to quickly revert to their initial state after the stretching force is removed. Figure 9(d-f) demonstrates the out-of-plane flexibility of 2 × 2 modules, where the sections can be reversibly folded into a variety of configurations.

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Figure 9. (a-f) Fabricated modules with 20 mm × 20 mm cell sections at (a) initial state of 0° rotation, (b) 30° rotation and (c) full expansion state of 45° rotation. (d-e) folded out-of-plane, (f) folded into stacked configuration with small form factor.

Force-strain graphs from the tensile test experiments on the 2×2 ARS solar modules are presented in Figure 10 (a). In the tensile test, the initial state of the module, as shown in Figure 9(a), is defined as 0% strain. The strain required to bring the 20 mm and 31.75 mm modules from initial state to full expansion at 45° rotation is 60.0% and 67.3%, respectively. Continued increase in the strain after reaching the fully expanded state will cause the cells to continue to rotate until 90°, accompanied by the contraction of the array perpendicular to the applied force. Further stretching beyond this causes elastic deformation of the joints, leading to eventual fracture. The tensile force-strain curve of the module durability test is shown in Figure 10 (b), which shows that there is no significant degradation of the mechanical properties after 1000 cycles. Figure 11 (a)(b) presents photographs of the module encapsulation and embedded wires before and after testing. No visible damage was evident after testing, except for a slight breakage at the clamped ribbons. Subsequent I-V characterization showed no significant degradation of the electrical performance after the durability test, as shown in Figure 11(c).

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Figure 10. The force-strain curves of (a) 2×2 ARS modules from initial state to full-expansion state and over-stretched state and (b) durability test on 20mm 2×2 module over 1000 cycles of 0° to 45° rotations.



Figure 11. The photographs of the tested module: (a) before durability test and (b) after 1000 cycles. (c) The I-V curves and P-V curves of the 20mm 2×2 module before and after 1000-cycle durability test.

## Optical

The CF50 exhibited an average optical transmittance (*Tcf50* in equation 1) of 0.8 over the wavelength range of 350 nm to 1000 nm. Transmittance calculation results based on measurements from photographs of the fabricated 2×2 ARS modules (section 2.4.3) are plotted in Figure 12. They show that the maximum transmittance of the modules, reached at 45° rotation of the solar cell sections, is 49.5% for the 20 mm modules and 41.9% for the 31.75 mm modules. Results from the two other methods of determining transmittance (the geometric model, section 2.4.1, and the COMSOL model, section 2.4.2) are also plotted in Figure 12. There are some differences observed when comparing the results from the 3 methods. This is partly due to imperfections in the fabrication process of the modules, causing irregularities in the polyurethane rubber at the edge of the modules during the casting process, and the imperfect alignment of the solar cell sections with the centre of each unit. The deformation of the supporting ribbons during the stretching process is also not uniform in the fabricated samples. There are also errors associated with the identification of the three materials using thresholding on the photographs. Nevertheless, there is general agreement on the overall trend, demonstrating how the transmittance of the module can be varied by stretching from initial state to expanded state.

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Figure 12. The rotation angle vs. transmittance curves of transmittance results for 20 mm and 31.75 mm modules.

A correlation study was conducted between array module size and optical transmittance based on the geometric model outlined in Section 2.4.1, with the aim of evaluating how transmittance evolves when the array is scaled to cover a larger area while maintaining a constant ratio of unit square side length (L0) to solar cell section side length (L1). Figure 13 presents the simulated transmittance values for m×n array modules ranging from 2×2 to 126×126 under a 45° rotation configuration. The L0/L1 values used in the simulation correspond to those of the fabricated prototypes: 1.40 for the 20 mm module and 1.21 for the 31.75 mm module. Among the tested configurations, the 5×5 array exhibited the highest transmittance, while the 2×2 array showed the lowest. Specifically, for arrays comprising 20 mm solar cell sections, the maximum and minimum transmittance values were found to be 75.5% and 53.1%, respectively. For the 31.75 mm cell arrays, the corresponding values were 65.3% and 45.8%.

Extended analysis, increasing the array size range to 512×512 reveals a periodic fluctuation in transmittance as the array size increases, with the transmittance values exhibiting a convergence trend. Figure 14 illustrates such behaviour for array sizes from 2×2 to 126×126. To further investigate the convergence behaviour and limits, a moving standard deviation analysis was performed with a window size corresponding to one fluctuation period. The moving standard deviation of transmittance in the final window was 0.04% for the 20 mm module and 0.049% for the 31.75 mm module, the moving standard deviation values exhibit a decreasing trend with increasing module size, approaching zero, indicating progressive convergence. The limit values of transmittance for the 20 mm and 31.75 mm modules were then determined by averaging the data points from array sizes 400×400 to 512×512, yielding 69.6% and 62.8%, respectively.

This periodicity arises from variations in the spatial mapping of solar cell sections within the expanded array relative to the initial area. These findings underscore the design’s inherent tunability for application-specific optimization, whereby the array dimensions (m×n) can be strategically selected to either maximize or minimize optical transmittance within a fixed area based on targeted functional requirements.



Figure 13. Calculated optical transmittance maps for various array module sizes from 2×2 up to 126×126 for ARS modules made with solar cell section side lengths of 20 mm and 31.75 mm.



Figure 14. The variation in transmittance of square array (n=m) modules as the size of the array from 2×2 to 126×126, specified as the number of rows or columns, is varied. Data are shown for modules with solar cell section side lengths of 20 mm and 31.75 mm. The L0/L1 ratios are 1.4 and 1.212 in these examples.

The relationship between the ratio of the unit square side length (L0) to the solar cell section side length (L1) and optical transmittance under fixed array sizes with the geometrical model was then investigated based on the established correlation between array module size and transmittance, as shown in Figure 15. Three representative module sizes, 2×2, 5×5, and 126×126, were selected, corresponding respectively to the previously identified configurations with the lowest transmittance, the highest transmittance, and a large-scale module approaching the transmittance limit value. The results indicate that as the L0/L1 value increases from 1 to 5, the enhancement in transmittance gradually saturates. whilst the overall transmittance range decreases. Under 0° rotation, the transmittance curves of the three module sizes overlap. Since there are no air gaps in the geometric model, and the transmittance is calculated as per equation (2).

As L0/L1 increases, the areal coverage of the solar cell sections within the module decreases, thereby reducing the overall power output of the photovoltaic module. To maximize cell density and thus enhance power output per unit area, the L0/L1 ratio should be maintained close to 1. This configuration also enables a wider transmittance range between the initial and fully expanded states, although it limits the maximum achievable transmittance. In addition, the minimum allowable value of L0/L1 is constrained by structural requirements, particularly the necessary thickness of encapsulation material surrounding each solar cell section, especially at the joints, to ensure mechanical robustness and durability of the module.



Figure 15. Module transmittance vs. unit square side length (L0) and solar cell section side length (L1) ratio for initial state and fully expanded state. Also plotted is the transmittance range from initial to fully expanded state.

# Discussion

A solar module design concept featuring electrically connected sections of commercial crystalline silicon solar cells arranged in an auxetic rotating square structure is presented. Compared to previous stretchable photovoltaic module designs based on pre-stretched interconnects, the ARS structure offers distinct advantages. It achieves excellent out-of-plane flexibility and in-plane stretchability without relying on pre-stretched interconnects. Moreover, it eliminates the need for multidirectional tensile loads to ensure proper module expansion; instead, dynamic adjustment of transmittance can be realized through simple uniaxial control.

Comparing the electrical performance of the original cell before sawing and the solar cell sections after sawing, there is a noticeable performance degradation, which is thought to mainly arise from increased carrier recombination at the un-passivated, sawn edges of the cells. The larger the ratio of un-passivated edge to the total surface area of the cell, the more obvious the performance degradation, with the average PCE degradation of 20 mm solar cell sections being 1.75% while that of 31.75 mm is 1.54%. Nevertheless, it is encouraging that the sawn solar cell sections continue to work reasonably well and recent research suggests that further improvements are possible through the use of more advanced cutting technologies, Thermal Laser Separation (TLS), and the re-passivation of the sawn edges [40].

Modules made from small solar cell sections can be connected in different configurations to adjust the output current and voltage of the modules. The series-connected modules exhibited higher PCEs, at 16.59% for 31.75 mm solar cell sections and 16.4% for 20 mm solar cell sections, compared to the 2-line parallel modules, at 15.35% for 31.75 mm solar cell sections and 14.65% for 20 mm solar cell sections. The PCE difference between series and parallel connection is speculated to be caused by increased interconnecting wire length.

Mechanical tests have shown that the strain required to fully expand the module is less than half the strain required to fracture the joint. Results of durability tests indicate the reliability of the structure to withstand 1000 cycles of 0-45° rotation without degradation of the structure's mechanical and electrical properties. To further enhance the durability at the joints and prevent encapsulation tearing caused by stress concentration, the interconnecting ribbons between units could be removed, and the fillet radius at the joints could be increased. While 2 mm cast CF50 polyurethane served as an encapsulant in this study, tear-resistant elastomers, thermal lamination films with laser perforation, or reinforced bearing-type joints could be adopted for large-scale implementations.

The transmittance of 2×2 modules made with 20 mm square solar cell sections could be varied from 38.7% to 49.5% through the application of uniaxial stress to rotate the squares by 45°. Likewise, the transmittance of similar modules containing solar cells of side length 31.75 mm could be tuned from 26.3% to 41.9%. Based on the geometric model, the effects of both module size and the unit-cell section length ratio (L0/L1) on transmittance were investigated. The calculated relationship between module size and transmittance shows that, under a 45° rotation, the 5×5 array achieves the maximum transmittance. Transmittance exhibits a periodic fluctuation with respect to array size, with a period of 8, and this fluctuation converges as the module size increases. The calculated transmittance limit values are 69.6% for the 20 mm module and 62.8% for the 31.75 mm module. Transmittance increases with the value of L0/L1, converging to a maximum at a ratio of about 5. Combining the findings, it is possible to optimise the design of the module and the cells within to tune the transmittance maximum, minimum and range, along with the power generation properties, according to the needs of various BIPV and AgriPV applications. Although the maximum transmittance remains limited to some extent, the module’s flexibility and foldable characteristics allow it to be fully folded in scenarios where maximum light transmission is required. It should be noted that the present optical analysis is restricted to planar and concentric installation; modelling for transmittance over curved surfaces and non-concentric scenarios remain an essential direction for future work.

Finally, since the concept uses small sections cut from commercial solar cells, it has the potential for use in recycling, extending the life of degraded cells or finding a use for defective cells. Furthermore, the concept is not limited to c-Si solar cells. Integrating organic photovoltaics (OPV), for example, could further extend the applications of this approach to include indoor settings.

# Conclusion

This study presents an ARS photovoltaic module design featuring adaptable electrical configuration, high mechanical compliance and optically adjustable transmittance. Commercial c-Si solar cells were diced into smaller square sections, reconnected, and encapsulated using polyurethane rubber. The resulting prototype modules achieve a wide range of dynamically adjustable transmittance and can conform to surfaces with multi-axis curvature without relying on any pre-stretched interconnects.

Although the prototype modules exhibit slight efficiency losses, the reduction remains within acceptable limits, with PCE degradation kept below 1.8%. Mechanical durability tests demonstrate that the structure withstands at least 1000 full expansion cycles without performance degradation. A geometrical model provides reference evaluation for transmittance as correlated to degree of expansion, module size and unit-to-cell length ratio, demonstrating wide tunability to meet application requirements.

The design is expected to be compatible with various photovoltaic technologies and shows strong potential for repurposing defected c-Si solar cells, contributing to a more sustainable PV lifecycle. Future research could involve advanced edge-passivation, optical modelling on curved geometries and more robust large-area encapsulation strategies to enable the practical deployment of ARS modules in BIPV and AgriPV systems.

# CRediT authorship contribution statement

**Chen Cao:** Conceptualization, Methodology, Visualization, Software, Data curation, Writing – original draft

**Tasmiat Rahman:** Supervision, Writing – review & editing

**Stuart A. Boden:** Conceptualization, Supervision, Writing – review & editing

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