Performance degradation and energy loss mechanisms of flexible perovskite mini-modules: An opto-electro-thermal multi-physics analysis

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Introduction

Flexible perovskite solar cells (FPSCs) are bendable and lightweight, making them suitable for curved surfaces, wearable electronics, and building-integrated photovoltaics.In practical operation, they undergo bending deformation and oblique illumination, which lead to significant performance degradation.Most existing studies focus on single bending conditions and lack systematic evaluation of the coupled effects of bending and illumination tilt.This study combines experiments, circuit simulation, and multiphysics modeling to reveal the opto-electro-thermal coupled degradation mechanism.

Methods

1. Experimental Method

Flexible perovskite micro-photovoltaic modules Controlled variables:

Bending central angle θ: 60° / 90° / 120° / 150°

Illumination inclination angle β: 0° / 15° / 45°

Measured parameters: Voc, Jsc, FF, PCE, I–V and P–V curves

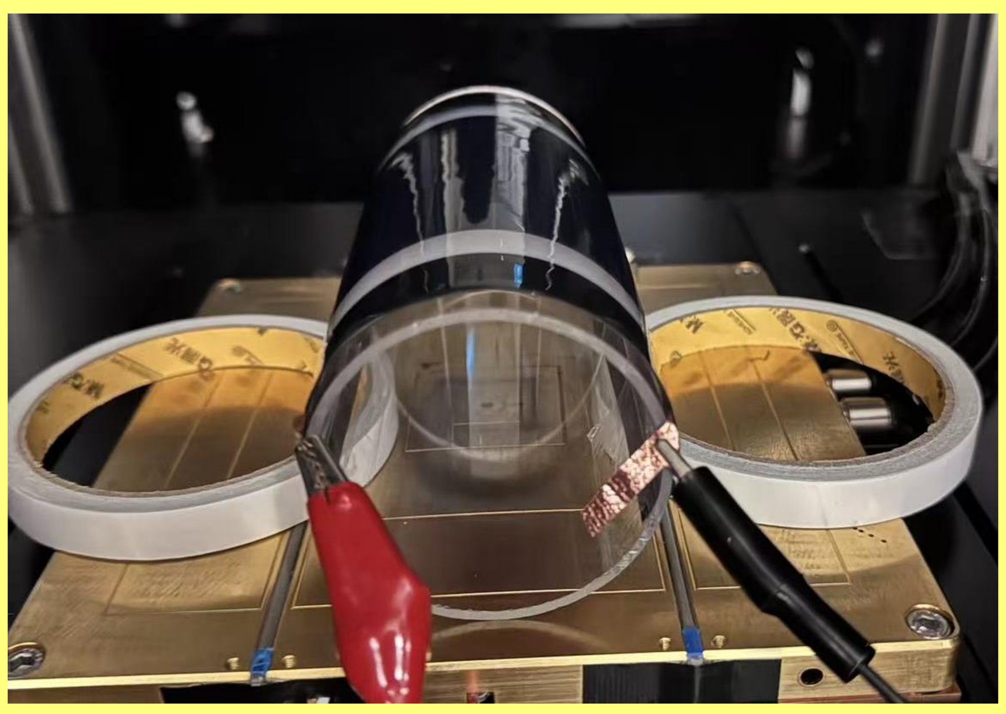

Fig. 1. Flexible photovoltaic cylindrical bending–tilt coupling test bench.

2. Simulink Circuit Simulation Model

Single-diode equivalent circuit model: including photocurrent source (I_{ph}), reverse saturation current (I_0), series resistance (R_s), and shunt resistance (R_{sh}).

Multi-cell series model: current mismatch coefficient between sub-cells is introduced to simulate non-uniform photocurrent caused by bending / tilt.

Outputs: I–V and P–V curves under different working conditions; series mismatch loss and shunt leakage loss are quantified.

3. COMSOL Multiphysics Multi-physics Coupling Model

Coupled physics modules:

Optical module: Solves electromagnetic wave equations via finite element method to calculate light absorption distribution under different bending / tilt conditions.

Electrical module: Uses drift-diffusion equations to simulate carrier transport, electric field distribution, and Joule / recombination heat generation.

Heat transfer module: Solves solid heat conduction equations combined with convection / radiation boundary conditions to obtain device temperature distribution.

Key parameters: Material optical constants, carrier mobility, recombination lifetime, thermal conductivity, etc., are all calibrated using experimental / literature reference values.

Model Validation

Comparison between experimental and simulated I–V curves: The relative errors of key parameters (Voc, Jsc, Pmax) are less than 5%, and the curve trends are in excellent agreement.

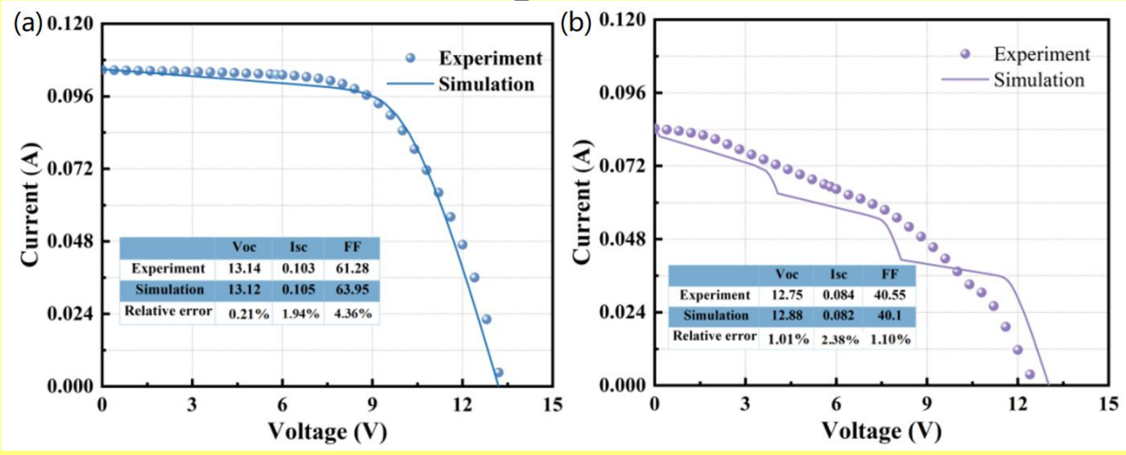

Fig. 2. Comparison of I–V curves between experimental measurement and model simulation:(a) Flat state; (b) Bending state

Optical model validation: The error between simulated reflectance and experimental measurements under different tilt angles is less than 3%, and the light absorption distribution is consistent with literature reports.

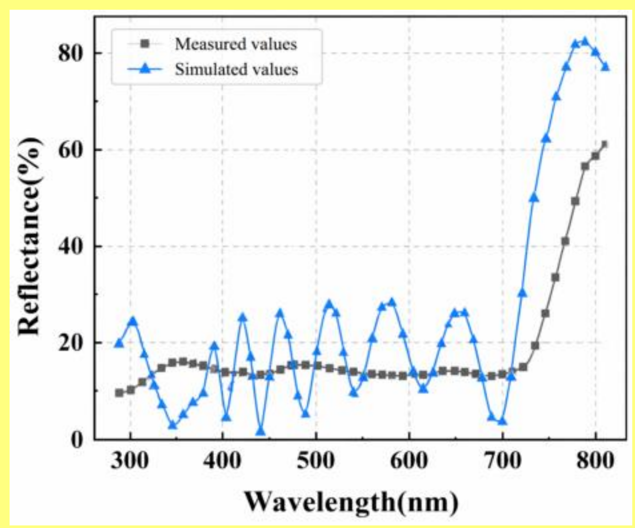

Fig. 3. Comparison of experimental and simulated macroscopic reflectivity.

Electrothermal model validation: The deviation between simulated operating temperature and infrared thermal imaging measurements under standard conditions is less than 2 °C.

Validation conclusion: The multi-physics coupling model can accurately characterize the entire physical process of flexible perovskite modules from light absorption to electrothermal loss, and possesses cross-scale analysis capability.

Results & Analysis

Macroscopic Performance Degradation

1. Performance under Single Bending

Voc: Remains stable during bending, with a maximum reduction of only 3.39% (θ=150°).

Jsc: Decreases continuously with increasing central angle; drops by 18.8% at θ=150°, mainly due to reduced light absorption and increased series resistance.

PCE: Decays linearly; from 14.36% to 11.21% (21.94% reduction) at θ=150°.

2. Performance under Single Illumination Tilt

At β=15°: Degradation is weak, PCE reduction < 5%.

At β=45°: Light absorption drops significantly; Jsc reduces by 22.7%, PCE falls to 10.89% (24.16% reduction).

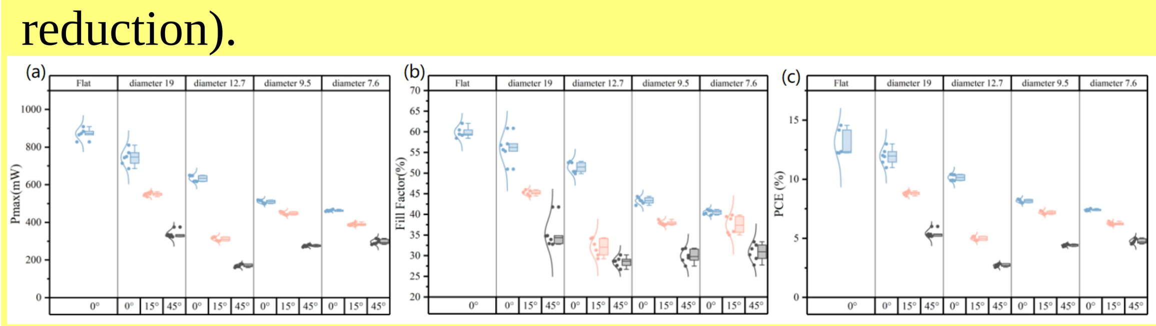

Fig. 4. Comparison of energy output and efficiency under different central angles and offset angles: (a) Maximum power output; (b) Fill factor; (c) Photovoltaic efficiency

3. Synergistic Degradation under Bending–Tilt Coupling

Nonlinear accelerated decay: At θ=120°+β=45°, Jsc reduces by 42.5%, FF drops from 72.3% to 58.1%.

Extreme condition (θ=90°+β=45°): PCE plunges from 14.36% to 2.72%, 81.05% relative degradation.

Key feature: Series I–V curves show severe step distortion; the “bottleneck effect” from subcell current mismatch dominates performance loss.

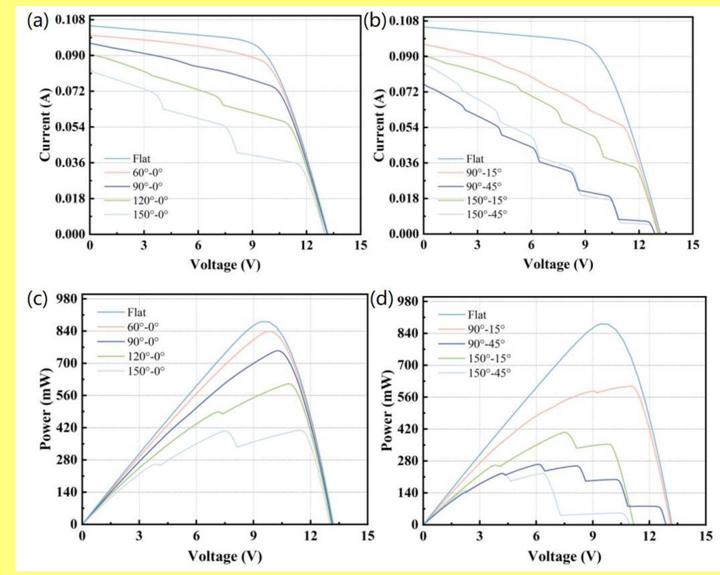

Fig. 5. I–V/P–V characteristics under coupled bending and illumination(a) I–V (β = 0°); (b) I–V (β > 0°); (c) P–V (β = 0°); (d) P–V (β > 0°)

Microscopic Opto-Electro-Thermal Loss Mechanism

1. Light Absorption and Carrier Transport

Bending–tilt causes uneven light absorption among subcells; photocurrent variation up to 35%.

Tensile/compressive stress distorts perovskite lattice, raising non-radiative recombination by 15%.

Series resistance R□ increases by 40% under extreme bending, enhancing Joule heating loss.

2. Electro-Thermal Coupling and Temperature Distribution

Device temperature shows a U-shape versus bias: lowest at MPP, higher at Voc/Jsc.Temperature decreases with bending: 6.2 ℃ lower at θ=150°+β=45° than under standard conditions.

Main reason: Bending suppresses carrier transport and reduces Joule heat; heat-source reduction outweighs weakened heat dissipation.

Heat sources: ~60% Joule heating, ~40% non-radiative recombination (recombination share rises slightly under bending).

3. Quantitative Energy Loss Analysis

Standard condition: Dominated by optical loss (35%) and recombination loss (25%).

Coupled condition: Series mismatch loss (22%) and Joule loss (18%) become major losses; total loss rises to 78%.

Key conclusion: Series subcell current mismatch is the core cause of performance collapse, contributing >50% of total degradation.

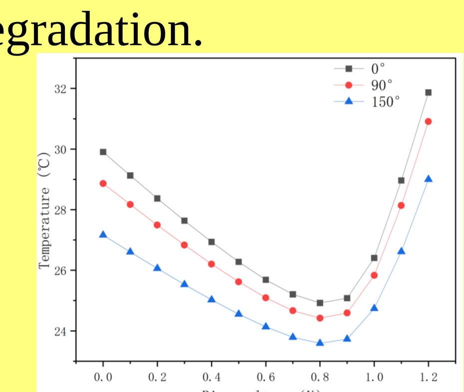

Fig. 6. Variation curves of cell temperature with bias voltage;

Conclusions

The main conclusions drawn from all these work are:

- Bending and illumination tilt show strong synergistic degradation. PCE drops by up to 81.05% under extreme coupling, far exceeding single-factor effects.;
- Series subcell photocurrent mismatch dominates performance loss. I–V distortion and FF decline account for over 50% of total loss;
- Bending lowers device temperature but induces far more current mismatch loss than efficiency gain;

References

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