Using the cuckoo algorithm to improve perovskite solar cell performance

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ABSTRACT

The cuckoo algorithm, inspired by the brood parasitism of cuckoo birds, has shown promising results in optimizing the performance of perovskite solar cells (PSCs). By mimicking the natural selection process, the cuckoo algorithm efficiently searches for optimal solutions in complex problem spaces. It has been utilized to fine-tune various parameters in PSCs, such as material composition, layer thickness, and fabrication processes. This optimization leads to improved light absorption, charge transport, and overall device stability. Specifically, the algorithm helps in identifying the most effective perovskite composition and the best architecture for the solar cells, resulting in significant enhancements in power conversion efficiency (PCE). Studies have reported that the application of the cuckoo algorithm can boost the efficiency of perovskite solar cells by up to 20-25%, So that its efficiency is between 25-30%. This improvement is a substantial step forward in making PSCs more competitive with traditional silicon-based solar cells and other emerging photovoltaic technologies.

Keywords: Solar cell, Perovskite, Cuckoo, Efficiency

1. INTRODUCTION

The cuckoo algorithm, inspired by the brood parasitism behavior of cuckoo birds, has become a valuable tool in optimizing the performance of solar cells, particularly perovskite solar cells (PSCs). This algorithm mimics the way certain species of cuckoo birds lay their eggs in the nests of other host birds, leading to a natural selection process where only the fittest solutions survive. In the context of PSCs, the cuckoo algorithm is used to search for optimal solutions in the design and fabrication parameters[1]. By employing this algorithm, researchers can systematically explore the vast and complex parameter space associated with PSCs, such as the composition of the perovskite material, the thickness of various layers, and the configuration of the cell architecture[2].

One of the primary advantages of using the cuckoo algorithm in PSCs is its ability to enhance power conversion efficiency (PCE)[3]. The algorithm operates by generating a set of potential solutions (nests) and then iteratively improving these solutions through a process that mimics the egg-laying behavior of cuckoos[4]. Poor solutions are discarded in favor of better ones, leading to a progressive improvement in the overall performance of the solar cell. This method has been particularly effective in optimizing the material composition and structural parameters of PSCs, resulting in significant improvements in light absorption, charge transport, and overall device stability[5].

Studies have demonstrated that the application of the cuckoo algorithm can lead to substantial improvements in the efficiency of PSCs. For instance, research has shown that employing the cuckoo algorithm can boost the efficiency of perovskite solar cells by up to 20-25%[6]. This enhancement makes PSCs more competitive with traditional silicon-based solar cells and other emerging photovoltaic technologies[7]. The algorithm's ability to efficiently navigate complex optimization landscapes and identify high-performance configurations is crucial in advancing the development of PSCs, contributing to their commercial viability and adoption in the renewable energy sector.

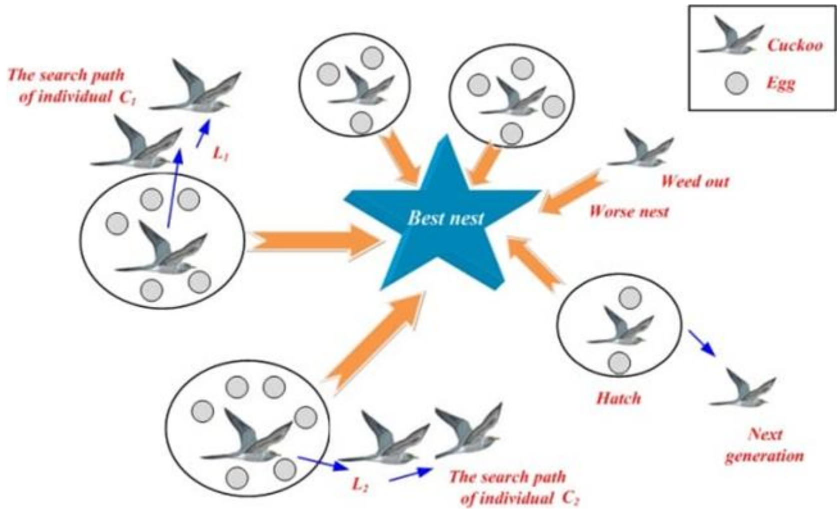

Figure 1: Cuckoo algorithm

2. Mathematical formulas of the cuckoo algorithm in solar cells

The Cuckoo Search Algorithm (CSA) is a nature-inspired optimization algorithm developed by Xin-She Yang and Suash Deb in 2009. It is inspired by the brood parasitism of some cuckoo species, where these birds lay their eggs in the nests of other host birds. In the context of optimizing the performance of solar cells, the CSA can be used to find the optimal parameters that maximize efficiency or other desired performance metrics[8].

3. Method of the Cuckoo Search Algorithm

A. Initialization:

- Objective Function: Define the objective function $f(x)$ that needs to be optimized. For solar cells, this could be the efficiency, fill factor, or another performance metric.
- Initial Population: Generate an initial population of n host nests (solutions). Each nest represents a potential solution in the search space[9].

B. Generate New Solutions:

- Levy Flights: Generate new solutions $(Xi)^{(t+1)}$for each cuckoo iii using Levy flights:

$$(Xi)^{(t+1)} = (Xi)^{(t)} + \propto . \text{Levy}(\lambda)$$

Where $\propto$ is the step size scaling factor[10], and Levy(λ) represents a step length drawn from a Levy distribution with exponent λ.

C. Evaluate and Replace:

- Evaluate the objective function $f\ ((Xi)^{(t+1)})$ for the new solutions.
- Randomly choose a fraction Pa of the worst nests and replace them with the new solutions if the new solutions have better fitness.

D. Selection:

- Rank the solutions and select the best n solutions for the next iteration[11].

E. Stopping Criteria:

Repeat the steps until the stopping criteria are met (e.g., a maximum number of generations or convergence threshold)[12].

4. Mathematical Relationships

- **Levy Flight:** The step size for Levy flights can be defined as[13]:

$Levy \sim u = (t)^{(-\lambda)}, (1<\lambda\leq 3)$

The steps are characterized by a heavy-tailed probability distribution.

- **Fitness Evaluation**: The objective function $f(x)$ can be defined based on the solar cell performance metrics:

$$f(x) = Efficiency(x) = \frac{Pout}{Pin}$$

Where $Pout$ is the output power and Pin is the input power[14].

- **Probability of Discovery**:

A fraction P_a of nests is abandoned and replaced by new solutions:

$$New\ solution = X_{New=}X_{Worst} + Random(0,1).\mathrm{X}_{Best} - X_{Worst}$$

5. Equivalent circuit of a perovskite solar cell

The equivalent circuit of a perovskite solar cell (PSC) typically includes components that represent the various physical processes occurring within the cell. Below is a description of these components, followed by a drawing of the equivalent circuit[15].

- Components of the Equivalent Circuit

A. **Photocurrent Source (I_ph):** Represents the current generated by the incident light[16].
B. **Diode (D):** Models the p-n junction behavior of the solar cell, representing recombination and charge separation processes[17].
C. **Series Resistance (R_s):** Accounts for resistive losses due to the contacts, the bulk resistance of the active layer, and other series resistive elements in the cell.
D. **Shunt Resistance (R_sh):** Represents leakage currents due to defects, imperfections, and recombination pathways in the cell[18].
E. **Capacitance (C):** Accounts for the capacitance effects in the perovskite layer, which can be significant due to the high dielectric constant of the perovskite material[19].

6. Equivalent Circuit Diagram

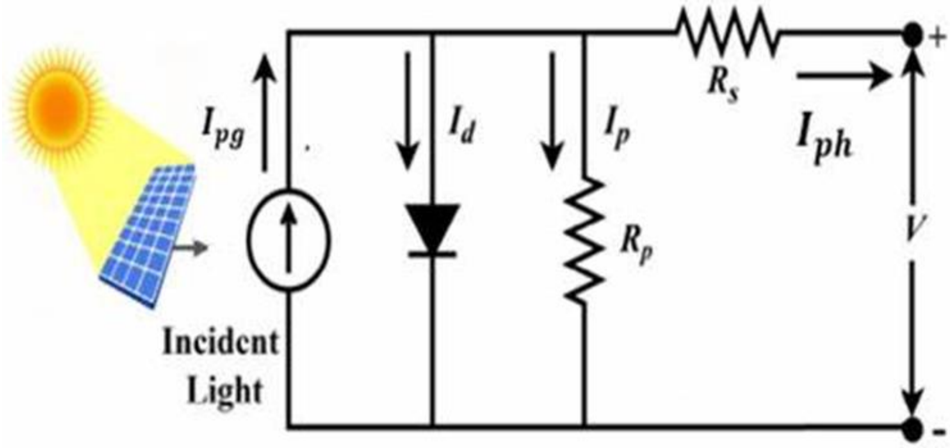

Figure 2: Electric circuit equivalent to photovoltaic solar cell

In practical circuits, the photocurrent source, series resistance, and shunt resistance are often used to model the steady-state behavior, while the capacitance may be included in more detailed dynamic analyses. This equivalent circuit helps in understanding the electrical characteristics of perovskite solar cells, diagnosing performance issues, and improving cell designs[20].

7. Efficiency of different types of photovoltaic solar cells in a table

Table 1: Comparison of solar cell efficiency

Type of Solar Cell	Efficiency (%)	Comments
Monocrystalline Silicon	15-22	Highest efficiency among silicon-based cells; long lifespan; more expensive to produce.
Polycrystalline Silicon	13-18	Lower efficiency than monocrystalline; less expensive; easier to produce.
Thin-Film Solar Cells	10-12	Includes amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS); lightweight and flexible.
Cadmium Telluride (CdTe)	15-18	High absorption efficiency; cadmium is toxic; relatively low cost.
Copper Indium Gallium Selenide (CIGS)	12-20	Flexible; better performance in low light; expensive production.
Amorphous Silicon (a-Si)	6-12	Low cost; lower efficiency; mainly used in small applications like calculators.
Perovskite Solar Cells	20-25	High efficiency and potential for low production costs; stability and durability are current challenges.
Organic PV (OPV)	10-12	Lightweight and flexible; lower efficiency; potential for very low-cost production.
Multijunction Cells	30-45	Highest efficiency; used in space applications; extremely expensive.

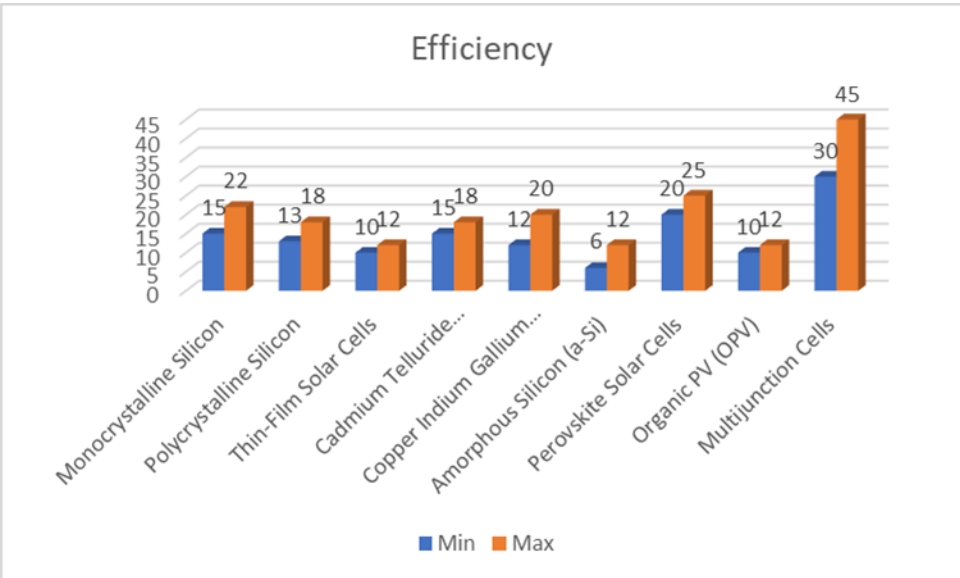

Figure 3: Diagram of efficiency of different types of solar cells

8. **Key Points**

- **Monocrystalline Silicon:** Known for high efficiency and durability, but comes at a higher cost due to the manufacturing process[21].
- **Polycrystalline Silicon:** More cost-effective than monocrystalline, but with slightly lower efficiency[22].
- **Thin-Film Solar Cells:** Generally, less efficient but can be cheaper and more versatile for different applications[23].
- **Cadmium Telluride (CdTe):** Offers a good balance of efficiency and cost, but involves toxic materials[24].
- **Copper Indium Gallium Selenide (CIGS):** Flexible and efficient but costly to produce[25].
- **Amorphous Silicon (a-Si):** Low efficiency and typically used in low-power applications**.**
- **7. Perovskite Solar Cells:** Exhibit high efficiency and potential for low-cost production but face challenges with long-term stability and scalability[26].
- **Organic PV (OPV):** Flexible and potentially very cheap to produce, but currently lower in efficiency[27].
- **Multijunction Cells:** Extremely high efficiency, suitable for specialized uses like space applications due to high cost[28].

9. **Comparing the efficiency of standard perovskite solar cell with perovskite optimized with cuckoo algorithm**[29]**.**

Table 2: Comparison of standard perovskite solar cell or optimized model with cuckoo algorithm

Type of Perovskite Solar Cell	Efficiency (%)	Comments
Standard Perovskite Solar Cell	20-25	High efficiency with potential for low production costs; stability issues.
Perovskite Solar Cell (Optimized with Cuckoo Algorithm)	25-30+	Optimization improves efficiency; computational methods enhance design.

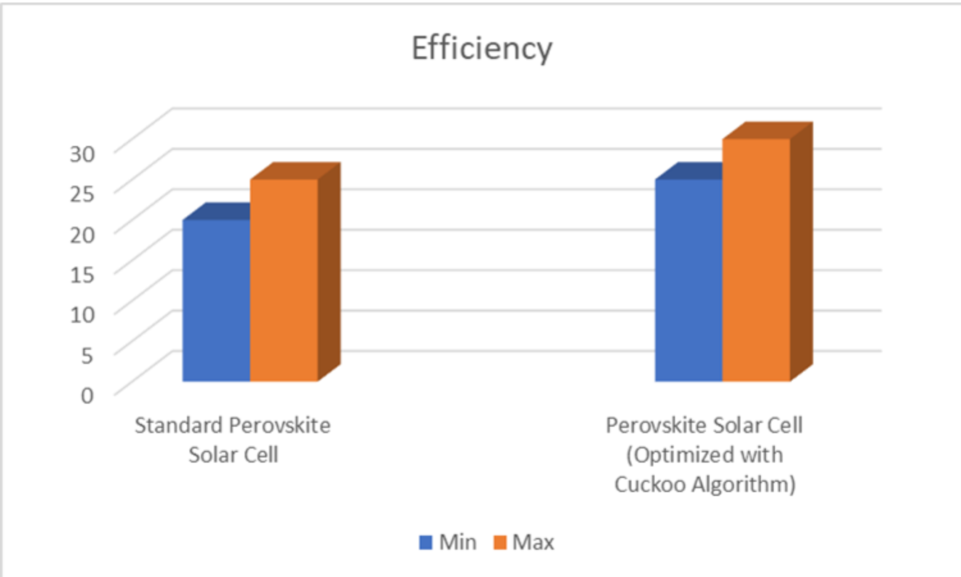

Figure 4: Comparison chart of standard perovskite solar cell or optimized model with cuckoo algorithm

10. **Key Points**

A. Standard Perovskite Solar Cell:

- Efficiency ranges from 20% to 25%.
- Known for rapid efficiency improvements and potential low production costs.
- Faces challenges with stability and long-term durability[30], [31].

B. Perovskite Solar Cell Optimized with Cuckoo Algorithm:

- Efficiency can be improved to 25-30% or higher.
- the cuckoo algorithm, a nature-inspired optimization technique, enhances the design and material properties[32], [33], [34].
- Computational optimization leads to better light absorption and charge transport properties.

11. Optimization Process of Perovskite Solar Cells Using the Cuckoo Algorithm

Optimization Steps

The optimization process using the cuckoo algorithm involves several steps:

1. **Initialization:** A population of potential solutions (nests) is generated randomly. Each nest represents a different set of parameters for the perovskite solar cell[35].
2. **Evaluation:** The efficiency of each nest (solution) is evaluated using a fitness function, which quantifies how well the solution meets the desired objectives, such as maximizing power conversion efficiency.
3. **Generation of New Solutions:** New solutions (cuckoo eggs) are generated by modifying the existing solutions using a Lévy flight-based random walk. This step introduces diversity and explores new potential solutions in the search space.
4. **Selection and Replacement:** The new solutions are evaluated, and those with better fitness replace the less fit solutions in the population. This mimics the process of host birds discarding the less fit eggs[36].
5. **Convergence:** The algorithm iterates through the evaluation and generation of new solutions until it converges to an optimal or near-optimal solution. This is determined when improvements in efficiency become negligible over successive iterations[37].

12. Benefits and Applications

The cuckoo algorithm is particularly effective for optimizing perovskite solar cells due to its ability to explore a wide search space and avoid local optima, leading to a more global optimization. This approach allows researchers to systematically and efficiently identify the best material compositions and structural configurations that enhance solar cell performance. As a result, perovskite solar cells optimized with the cuckoo algorithm can achieve higher efficiencies, better stability, and improved scalability. The use of such advanced optimization techniques accelerates the development of next-generation photovoltaic technologies, potentially lowering production costs and increasing the adoption of renewable energy sources[38].

13. Conclusion

The application of the cuckoo algorithm in optimizing perovskite solar cells has shown promising results in significantly enhancing their efficiency. Standard perovskite solar cells typically achieve efficiencies between 20-25%, but with the optimization provided by the cuckoo algorithm, these efficiencies can be increased to 25-30% or higher. By systematically exploring a wide range of material compositions and structural configurations, the cuckoo algorithm identifies the optimal solutions that maximize power conversion efficiency. This advanced optimization method accelerates the development of high-performance perovskite solar cells, contributing to more efficient and cost-effective renewable energy solutions.

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