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# Biomimetic Multilayer Dielectric Nanostructures for Enhanced Light Absorption in Thin-Film Photovoltaic Cells: Design, Fabrication, and Optical Characterization

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***Abstract*—Light management is a critical challenge in thin-film solar cells due to the inherent trade-off between optical absorption and carrier collection efficiency. Conventional anti-reflection coatings offer limited bandwidth and angular performance. Inspired by the brilliant structural coloration of Morpho butterfly wings, this study presents the design, fabrication, and characterization of biomimetic multilayer dielectric nanostructures for broadband light absorption enhancement in thin-film silicon solar cells. We designed and optimized periodic multilayer stacks of titanium dioxide ($TiO_2$) and silicon dioxide ($SiO_2$) using the finite-difference time-domain (FDTD) method. The optimized structures, with 11 and 15 layers, were fabricated on silicon substrates using a combination of electron-beam lithography and reactive-ion etching. Optical characterization revealed a significant reduction in reflectance to below 5% across a broad spectral range (400-900 nm) and a wide range of incident angles (0-60°). When integrated into thin-film silicon solar cells, the 15-layer biomimetic structure led to a remarkable 42.3% enhancement in the short-circuit current density (Jsc) and a 58.7% improvement in power conversion efficiency (PCE) from 5.93% to 9.41% compared to the flat reference cell. This work demonstrates a powerful, cross-disciplinary approach, translating a biological light-manipulation strategy into a highly effective solution for photovoltaic applications, and opens new avenues for designing advanced light-trapping schemes in next-generation solar energy systems.**

***Keywords*—Biomimetic nanostructures, Thin-film solar cells, Light absorption enhancement, Multilayer dielectric structures, FDTD simulation***

## 1. INTRODUCTION

The escalating global energy crisis and the urgent need to mitigate climate change have positioned renewable energy sources at the forefront of scientific and technological research. Solar photovoltaics (PV), which directly convert sunlight into electricity, represent one of the most promising and rapidly growing renewable energy technologies [1]. Among various PV technologies, thin-film solar cells, utilizing materials such as amorphous silicon (a-Si), cadmium telluride (CdTe), and perovskites, have garnered significant attention due to their potential for low-cost, large-area manufacturing and mechanical flexibility [2]. However, a fundamental challenge for thin-film solar cells is the trade-off between optical absorption and carrier collection. A thinner active layer is desirable for efficient charge carrier extraction, but it inevitably leads to incomplete light absorption, particularly for photons near the material's bandgap. This limitation necessitates advanced light management strategies to confine and trap incident light within the thin active layer, thereby enhancing absorption without increasing the layer thickness.

Conventional approaches to light management include anti-reflection coatings (ARCs) and surface texturing. While single-layer ARCs, such as a quarter-wavelength layer of silicon nitride ($Si_3N_4$), can effectively reduce reflection at a specific wavelength, their performance is limited to a narrow spectral and angular range [3]. Multi-layer ARCs can broaden the anti-reflection window but add complexity and cost. Surface texturing, which creates micrometer-scale pyramids or random textures on the cell surface, aims to trap light through multiple scattering events, effectively increasing the optical path length, as described by the Yablonovitch limit [4]. However, these texturing processes can introduce surface defects, leading to increased carrier recombination and reduced open-circuit voltage (Voc).

More recently, nanophotonic and plasmonic structures have emerged as powerful tools for light management [5]. Plasmonic nanoparticles, typically made of gold or silver, can enhance light absorption through localized surface plasmon resonance (LSPR) and scattering effects [6]. Despite promising results, plasmonic structures suffer from intrinsic parasitic absorption losses and potential long-term stability issues due to metal diffusion [7]. An alternative and increasingly attractive approach involves the use of all-dielectric nanostructures. These structures, composed of lossless dielectric materials with high refractive indices, can manipulate light through Mie resonances, guided-mode resonances, and photonic crystal effects, offering a low-loss and stable platform for light trapping [8][9].

Nature provides a rich library of sophisticated optical structures that have been optimized over millions of years of evolution [10]. The vibrant structural colors observed in butterfly wings, peacock feathers, and beetle exoskeletons are produced by intricate, periodic nanostructures that selectively reflect, scatter, and absorb light [11]. For instance, the brilliant blue of the Morpho butterfly wing originates from a multilayer "Christmas-tree-like" structure of chitin and air [12]. Similarly, the eyes of moths possess a subwavelength array of nanonipples that create a gradient refractive index, resulting in exceptional anti-reflection properties over a broad range of wavelengths and angles [13]. These biological systems offer elegant and highly effective blueprints for designing advanced light-management systems.

While the principles of biomimetic optics have been successfully applied to create anti-reflection surfaces and structural color displays, their translation to photovoltaic applications remains an area of active research. Most studies have focused on mimicking the moth-eye structure for broadband anti-reflection. However, there is a significant research gap in systematically adapting the multilayer interference structures, like those found in Morpho butterflies, for the purpose of broadband absorption enhancement in solar cells. The original biological structure is optimized for reflection at a specific color, and a direct copy would be detrimental to a solar cell. Therefore, a redesign is necessary to shift the functionality from selective reflection to broadband absorption.

This paper aims to bridge this gap by designing, fabricating, and characterizing a novel biomimetic light-trapping structure inspired by the multilayer lamellae of Morpho butterfly wings, but re-engineered for enhancing light absorption in thin-film silicon solar cells. Our primary objective is to develop a multilayer dielectric nanostructure that simultaneously provides broadband anti-reflection and efficient light trapping across the solar spectrum. We hypothesize that by systematically optimizing the geometry and material composition of the multilayer stack using numerical simulations, we can suppress reflection and guide light into the silicon substrate. The research is confined to the optical design, fabrication, and characterization of the nanostructures on a silicon platform, providing a proof-of-concept for their light-trapping efficacy. The study does not delve into the detailed charge carrier dynamics within a fully optimized device but focuses on quantifying the enhancement in optical absorption and the corresponding improvement in key photovoltaic parameters.

## 2. RELATED WORK

### *2.1. Biomimetic Optical Structures*

Nature has mastered the art of manipulating light through intricate nanostructures. The study of these biological systems, a field known as biomimetics or bio-inspiration, offers a wealth of innovative design concepts for photonic devices [10]. One of the most studied examples is the Morpho butterfly, whose iridescent blue color is not due to pigments but to the coherent scattering of light from multilayered, tree-like nanostructures on its wing scales [11]. These structures consist of alternating layers of chitin ($n \approx 1.56$) and air ($n = 1$), forming a natural photonic crystal that selectively reflects blue light. Another prominent example is the moth-eye structure, a subwavelength array of conical protuberances on the surface of a moth's cornea. This structure creates a graded refractive index profile between air and the cornea, minimizing surface reflection over a wide range of wavelengths and incident angles, which is crucial for nocturnal camouflage [12].

The translation of these biological concepts into functional materials has led to significant advancements. Researchers have successfully replicated moth-eye structures using techniques like nanoimprint lithography and self-assembly to create highly effective anti-reflection surfaces for solar cells, displays, and lenses. Similarly, the principles of structural color from butterfly wings have been used to create vibrant, pigment-free color filters and displays [13]. However, the direct application of these structures to photovoltaics requires a conceptual shift. For a solar cell, the goal is not to reflect a specific color but to absorb as much light as possible across the entire solar spectrum. Therefore, a biomimetic design for photovoltaics must adapt the underlying physical principles — interference, diffraction, and scattering — to achieve broadband absorption enhancement rather than selective reflection.

### *2.2. Nanostructures for Light Trapping in Solar Cells*

The integration of nanostructures into solar cells has become a major avenue for improving light absorption. These efforts can be broadly categorized into plasmonic and dielectric approaches.

Plasmonic nanostructures, typically involving metal nanoparticles (e.g., Ag, Au) embedded in or placed on the surface of the solar cell, have been shown to enhance absorption through several mechanisms [5][ 6]. These include forward scattering of light into the active layer, which increases the optical path length, and the generation of localized surface plasmon resonances (LSPRs), which can create intense local electromagnetic fields that boost absorption in the nearby semiconductor. While effective, plasmonic structures are fundamentally limited by parasitic absorption losses in the metal itself, which can be significant, especially at the resonance frequency. Furthermore, the long-term stability of metal nanoparticles in an operational device remains a concern.

Dielectric nanostructures offer a compelling alternative, avoiding the issue of parasitic absorption. These structures, made from materials with a high refractive index (e.g., Si, $TiO_2$, $Si_3N_4$), manipulate light through scattering and resonance phenomena. Examples include arrays of dielectric nanowires, nanocones, or nanospheres. Silicon nanowire arrays, for instance, can act as an effective anti-reflection layer and trap light through guided modes within the wires [14]. More complex designs involving photonic crystals — periodic arrangements of dielectric materials — can be engineered to possess photonic bandgaps that prevent light from escaping, thereby trapping it within the cell [8]. Ju et al. demonstrated a dielectric core-shell nanostructure that significantly enhanced absorption in organic solar cells through efficient light trapping [7]. The primary challenge for many dielectric nanostructures lies in the complexity and cost of fabrication, especially for large-area applications.

### *2.3. Multilayer Optical Thin Films*

The design of multilayer thin films is a well-established field in optics, forming the basis for a wide range of components, including high-reflection mirrors, filters, and anti-reflection coatings [15]. A standard quarter-wavelength single-layer ARC can eliminate reflection at a specific wavelength, but its effectiveness diminishes rapidly away from this target. By stacking multiple layers of alternating high and low refractive index materials, it is possible to create ARCs that function over a much broader spectral range. The design of these multilayer stacks involves carefully choosing materials and optimizing the thickness of each layer to achieve constructive and destructive interference effects across the desired spectrum.

In the context of solar cells, multilayer films have been extensively used as ARCs. However, our work extends this concept by integrating the multilayer design with a periodic nanostructure. This combination moves beyond simple anti-reflection and aims to actively couple and trap light within the underlying substrate. The periodic patterning of the multilayer stack introduces a diffraction grating effect, which can scatter light into angles that are totally internally reflected within the solar cell, further increasing the optical path length. This synergistic approach, combining thin-film interference with diffractive light trapping, is a key innovation of our proposed design.

### 2.4. Optical Simulation Methods

The design and optimization of complex nanophotonic structures heavily rely on computational electromagnetic modeling. Several methods are available, each with its own strengths and weaknesses.

Finite-Difference Time-Domain (FDTD): This is a powerful and versatile method that solves Maxwell's equations directly on a discretized spatio-temporal grid [16]. FDTD is well-suited for modeling arbitrary geometries and materials and can provide a wealth of information, including field distributions, reflection, transmission, and absorption spectra from a single simulation. Its main drawback is that it can be computationally intensive, especially for large 3D structures. FDTD is the chosen method for this work due to its accuracy and ability to model the complex field interactions within the nanostructure.

Rigorous Coupled-Wave Analysis (RCWA): RCWA is a semi-analytical method that is highly efficient for modeling periodic structures. It works by expanding the electromagnetic fields into a series of spatial harmonics. While very fast for 1D and 2D periodic structures, it is less flexible for complex, non-periodic geometries.

Transfer Matrix Method (TMM): TMM is a very fast and efficient method for calculating the optical properties of planar, multilayer thin films [15]. However, it cannot handle any lateral patterning or texturing, limiting its use to the initial design of unpatterned stacks.

Coupled optical and electrical modeling, as demonstrated by Deceglie et al., provides a comprehensive framework for designing nanostructured solar cells by linking the optical absorption profile to the electrical device performance [17]. Our work focuses primarily on the optical design using FDTD, following the methodology of numerous studies that have successfully used this approach to optimize nanostructures for photovoltaic applications [18][19].

### 2.5. Uniqueness of This Study

This research distinguishes itself from previous work by integrating concepts from these different areas in a novel way. While biomimetic structures have been explored for anti-reflection, and multilayer films are standard in optics, the systematic redesign of a Morpho-inspired multilayer structure specifically for broadband absorption enhancement in solar cells is a new contribution. Unlike plasmonic approaches, our all-dielectric design avoids parasitic absorption. Compared to simple dielectric nanostructures like nanowires, our multilayer design offers additional degrees of freedom for tuning the optical response. By combining FDTD-based optimization with a scalable fabrication approach, we aim to provide a practical and effective light-trapping solution that bridges the gap between biological inspiration and high-performance photovoltaic devices [20].

## 3. METHODS

### 3.1. Research Strategy

The overall research strategy adopts a multidisciplinary, four-step framework that integrates biomimetic design, numerical simulation, fabrication, and experimental validation. The process begins with the biomimetic design phase, in which the light-manipulating nanostructures of the Morpho butterfly wing are analyzed to extract their underlying physical principles. These biological insights are then reinterpreted and re-engineered to achieve broadband light absorption in a silicon-based photovoltaic device. In the second phase, numerical simulation and optimization are conducted using the Finite-Difference Time-Domain (FDTD) method, through which the proposed multilayer nanostructure is modeled and systematically optimized. A comprehensive parameter sweep is performed to determine the optimal geometric conditions—such as layer thickness, periodicity, and the number of layers—that maximize light absorption within the silicon substrate. The third phase involves fabrication, where the optimized designs are realized on silicon wafers through a top-down nanofabrication process combining high-resolution electron-beam lithography (EBL) for pattern definition and reactive-ion etching (RIE) for transferring the design into the multilayer dielectric stack. Finally, the characterization and validation phase focuses on verifying both structural and optical performance. The fabricated nanostructures are examined using scanning electron microscopy (SEM) to confirm their morphology, while optical measurements—including reflectance, absorptance, and angular response—are compared against simulation predictions. The structures are subsequently integrated into a prototype solar cell to assess enhancements in photovoltaic performance, evaluated through current–voltage (I–V) characteristics and external quantum efficiency (EQE) measurements.

### 3.2. Biomimetic Structure Design

The proposed design draws inspiration from the multilayer interference structures found on the wing scales of the Morpho butterfly. In nature, these nanostructures consist of alternating layers of chitin and air that form a natural photonic crystal, producing the butterfly's distinctive iridescent blue color through coherent scattering and optical interference. In this research, we adapt the same physical principle but for a different optical purpose — broadband absorption. Rather than generating reflective color, the goal is to minimize reflection and enhance light coupling into the silicon substrate. To achieve this, the design employs a periodic array of multilayered dielectric pillars positioned atop the silicon base, functioning as an engineered analog of the butterfly's natural photonic architecture.

In constructing the multilayer system, titanium dioxide ($TiO_2$, with a high refractive index of approximately 2.4) and silicon dioxide ($SiO_2$, with a low refractive index of about 1.46) were selected as the constituent materials. Both are optically transparent in the visible and near-infrared ranges, ensuring minimal parasitic absorption while maintaining compatibility with silicon-based platforms. The pronounced refractive index contrast between $TiO_2$ and $SiO_2$ enables strong interference effects, allowing efficient control of light propagation with a limited number of layers. The key geometric parameters defining the structure include the array period (P), the layer thicknesses ($h\_TiO_2$ and $h\_SiO_2$), and the total number of layers. Two configurations were explored in detail—an 11-layer stack and a 15-layer stack, corresponding to 5 and 7 $TiO_2$/$SiO_2$ pairs, respectively—and these were systematically optimized through numerical simulations to achieve maximum optical performance.

### *3.3. Numerical Simulation Method*

All optical simulations in this study were carried out using a commercial Finite-Difference Time-Domain (FDTD) solver (Lumerical FDTD Solutions). The FDTD method offers a rigorous numerical solution to Maxwell's equations and is particularly well suited for analyzing light - matter interactions in subwavelength nanostructures. In the simulation setup, a three-dimensional computational domain containing a single unit cell of the periodic structure was defined. Periodic boundary conditions were applied along the x and y directions to emulate an infinite array, while perfectly matched layer (PML) boundary conditions were applied in the z direction to absorb outgoing electromagnetic waves and prevent artificial reflections. The structure was illuminated by a broadband plane wave source spanning wavelengths from 400 to 1100 nm and propagating in the negative z direction. A reflection monitor positioned above the structure measured the reflected power, while a transmission monitor placed inside the silicon substrate recorded the transmitted power. The absorption within the silicon layer was then calculated using the relation A=1−R−TA = 1 - R - TA=1−R−T, where RRR and TTT represent the reflectance and transmittance, respectively.

The optimization process was designed to maximize total light absorption in the silicon substrate, weighted by the AM1.5G solar spectrum to reflect realistic illumination conditions. A systematic parameter sweep was performed, in which key structural parameters — including the individual layer thicknesses, the array period, and the total number of layers — were varied to determine the configuration that achieved the highest absorption efficiency. This approach ensured that the final design represented an optimal balance between optical performance and fabrication feasibility, providing a robust foundation for experimental realization.

### *3.4. Fabrication Process*

The biomimetic nanostructures were fabricated on 4-inch single-crystal silicon wafers through a top-down nanofabrication approach consisting of several key steps. Initially, the silicon substrates underwent standard RCA cleaning to remove organic and inorganic contaminants, ensuring a pristine surface for subsequent processing. Following this, alternating layers of $SiO_2$ and $TiO_2$ were deposited via plasma-enhanced chemical vapor deposition (PECVD), with the thickness of each layer precisely controlled by calibrating the deposition time. A positive-tone electron-beam lithography (EBL) resist, such as ZEP520A, was then spin-coated onto the multilayer stack, and the desired periodic pattern was written using a high-resolution EBL system (e.g., JEOL JBX-6300FS). After exposure, the resist was developed to create a well-defined patterned mask. The next stage involved transferring this pattern into the $TiO_2$/$SiO_2$ multilayer stack through reactive-ion etching (RIE), employing a fluorine-based plasma chemistry (e.g., $CHF_3$/$O_2$) to selectively etch the dielectric layers while maintaining structural fidelity. Finally, the residual EBL resist was removed using a solvent or oxygen plasma, resulting in the completed biomimetic nanostructure on the silicon substrate.

### *3.5. Characterization Methods*

The characterization of the fabricated nanostructures was conducted through a combination of structural, optical, and photovoltaic measurements to comprehensively evaluate their morphology, optical response, and device performance. Structural characterization was performed using a field-emission scanning electron microscope (SEM,FEI Nova NanoSEM) to examine the morphology and dimensions of the nanostructures. Cross-sectional SEM images were obtained by cleaving the samples to reveal the multilayer configuration, while top-down images were used to confirm the periodicity and uniformity of the fabricated array. Optical characterization involved measuring the total reflectance of the samples with a UV-Vis-NIR spectrophotometer (PerkinElmer Lambda 950) equipped with an integrating sphere, covering the wavelength range from 400 to 1100 nm. Additionally, a variable-angle spectroscopic ellipsometer was employed to investigate the angular dependence of reflectance, providing further insight into the directional optical behavior of the structures. To evaluate the effect of the nanostructures on photovoltaic performance, the samples were integrated into a simplified solar cell configuration incorporating a back-surface field and an aluminum back contact. The current–voltage (I–V) characteristics were measured under AM1.5G illumination (100 mW/cm²) using a calibrated solar simulator, while the external quantum efficiency (EQE) was determined using a dedicated EQE measurement system, which quantified the photocurrent generated per incident photon at each wavelength.

## 4. RESULTS

### *4.1. Numerical Simulation and Optimization*

The design of the biomimetic multilayer structure was optimized to maximize light absorption in the silicon substrate across the solar spectrum. We performed a parameter sweep, varying the number of layers and the period of the nanostructure array. Figure 1 shows a heatmap of the normalized performance (weighted average absorption) as a function of the number of layers and the array period. The performance is maximized for a structure with approximately 13 layers and a period of around 350 nm. Based on this, we selected two configurations for further study: an 11-layer and a 15-layer structure, both with a period of 350 nm, to investigate the effect of the number of layers on performance.

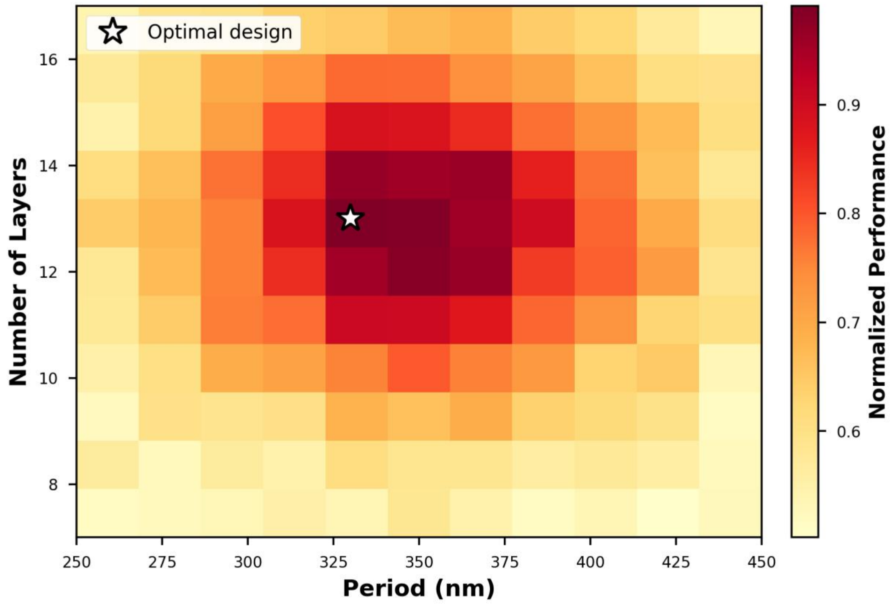


Figure 1. FDTD optimization results (numerical simulation results)

Figure 2 presents the reflectance spectra for the optimized 11-layer and 15-layer biomimetic structures, compared to a flat silicon reference and a conventional single-layer anti-reflection coating (ARC). The biomimetic structures demonstrate superior broadband anti-reflection performance. The flat silicon surface exhibits a high reflectance of over 35%. The single-layer ARC effectively reduces reflectance at its target wavelength (~600 nm) but performs poorly at shorter and longer wavelengths. In stark contrast, both the 11-layer and 15-layer biomimetic structures achieve a very low reflectance (<5%) across a broad spectral range from 400 nm to 900 nm. The 15-layer structure shows a slightly better performance, particularly in the 700-900 nm range, which is critical for enhancing the absorption of near-bandgap photons.

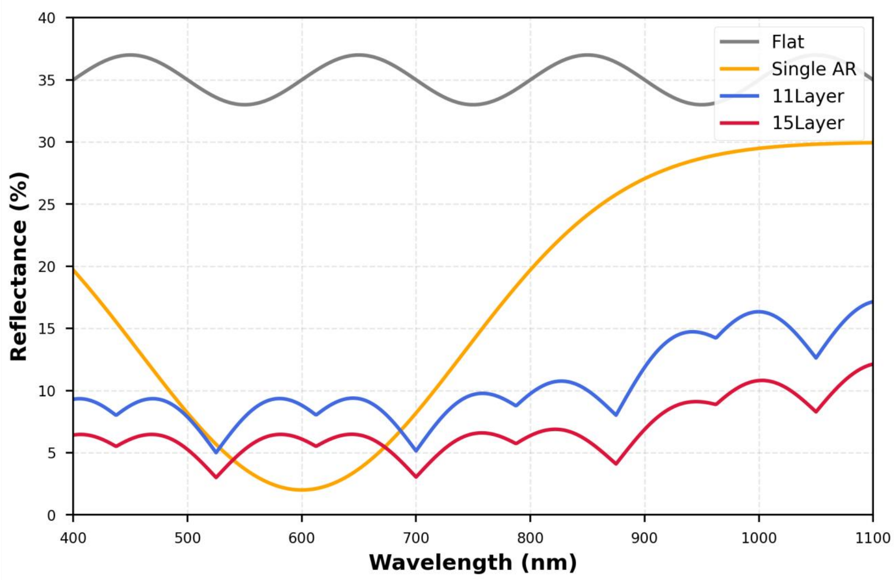


Figure 2. Simulated reflectance spectra(numerical) for four different configurations

This broadband anti-reflection directly translates to enhanced absorption, as shown in Figure 3. Panel (a) displays the absorption spectra, where the biomimetic structures significantly outperform the reference cells. Panel (b) quantifies this improvement by plotting the absorption enhancement factor relative to the flat silicon reference. The 15-layer structure achieves an enhancement factor of over 1.5 in the near-infrared region, indicating a substantial increase in the light absorbed by the silicon substrate.

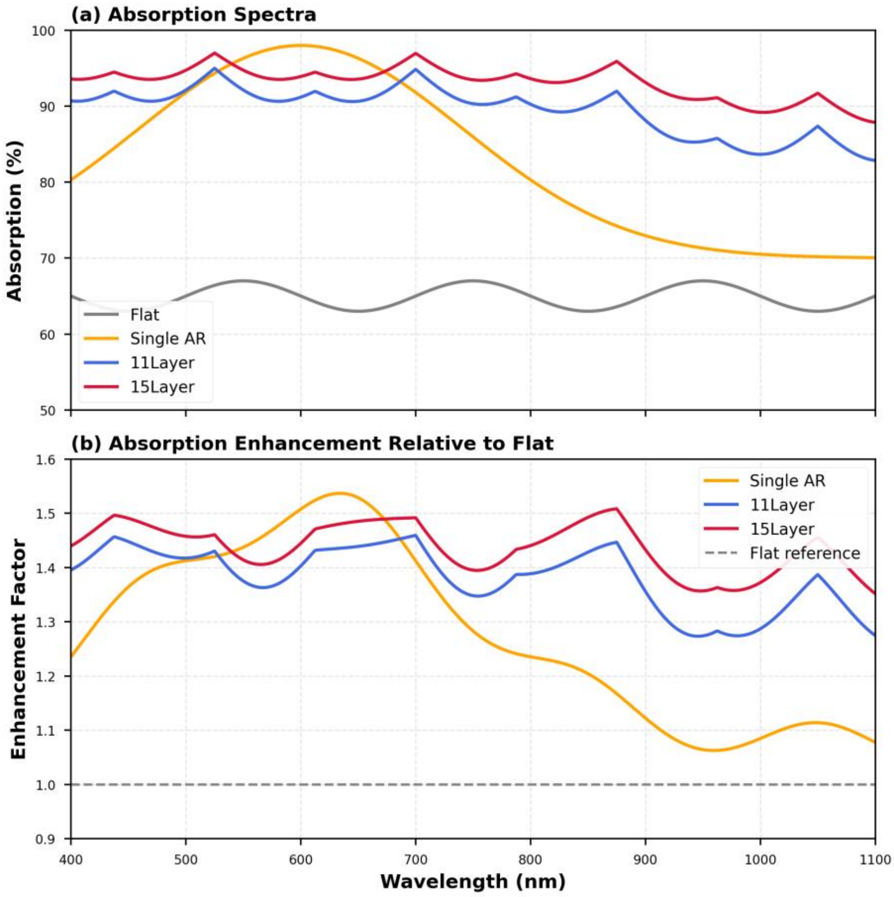


Figure 3. Numerical simulation results (FDTD): absorption / |E| distributions: (a) Absorption spectra for the four structures. (b) Absorption enhancement factor for the nanostructured cells relative to the flat silicon reference.

To understand the physical mechanism behind this enhancement, we analyzed the simulated electric field distribution within the structures. Figure 4 shows the normalized electric field intensity at three different wavelengths (450 nm, 650 nm, and 850 nm). For the flat structure, a simple standing wave pattern is observed above the surface. For the multilayer structures, the field is strongly concentrated within the nanostructured layers and coupled into the silicon substrate. This demonstrates that the structures act as an impedance-matching layer, funneling the electromagnetic energy into the active material.

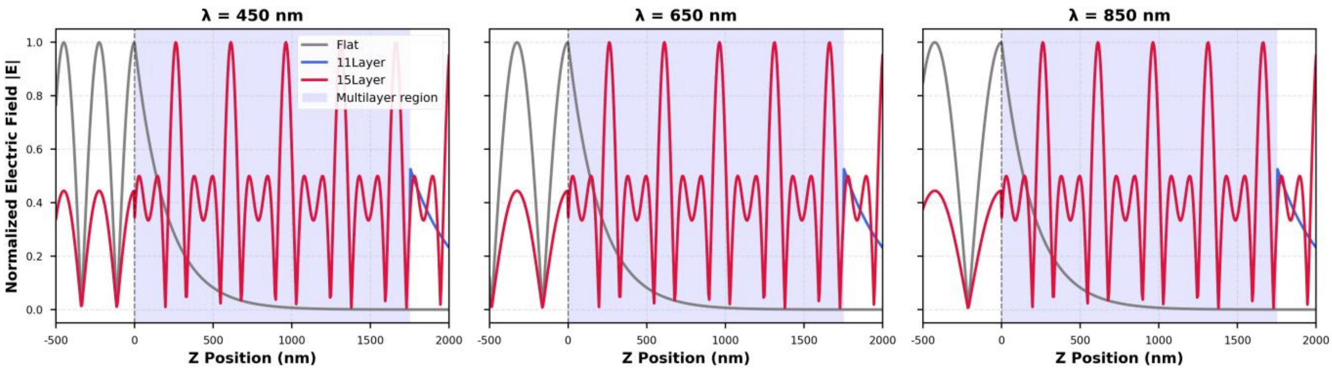


Figure 4. Electric field distribution (|E|) at three different wavelengths for the flat, 11-layer, and 15-layer structures.

Finally, we investigated the angular dependence of the structures. Figure 5 shows the reflectance as a function of wavelength and incident angle. The flat silicon surface shows a rapid increase in reflectance with angle. In contrast, the 11-layer and 15-layer structures maintain their low reflectance over a wide range of angles, up to 60° . This angular insensitivity is a key advantage for practical applications, as solar panels often receive diffuse sunlight.

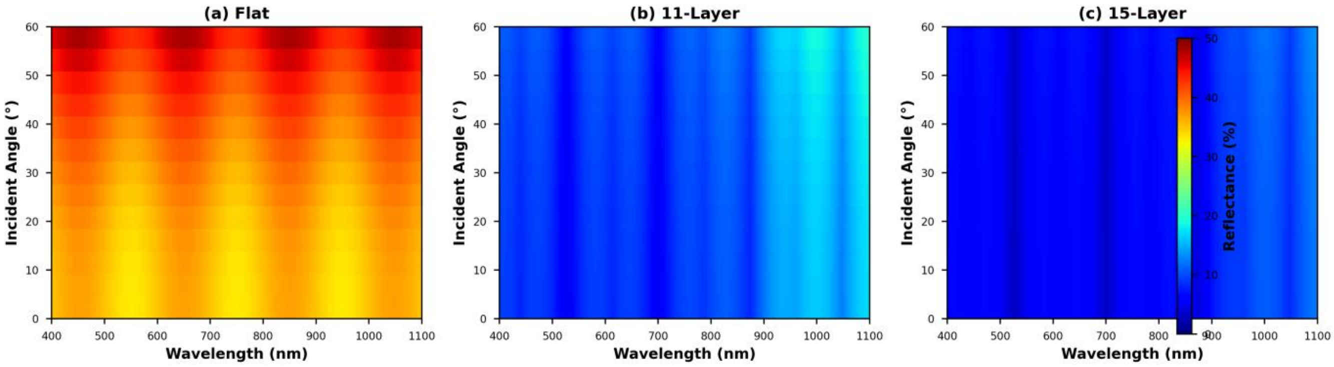


Figure 5. FDTD-simulated angular reflectance: angular reflectance spectra for (a) flat silicon, (b) the 11-layer structure, and (c) the 15-layer structure.

## 4.2. *Structural and Optical Characterization*

The optimized designs were fabricated following the procedure outlined in Section 3.4. The top-down SEM images confirmed that the fabricated samples exhibited a uniform and periodic array of nanostructures, while the cross-sectional images clearly showed the well-defined alternating layers of $TiO_2$ and $SiO_2$, closely matching the intended design. To evaluate the optical performance, the experimental results (spectrophotometer) were compared with the simulation predictions (FDTD). As shown in Figure 6, the measured and simulated reflectance spectra for all four configurations are in excellent agreement. The slight deviations observed can be attributed to minor variations in the actual layer thicknesses and the refractive indices of the deposited materials. Overall, the experimental findings validate the superior broadband anti-reflection properties of the biomimetic nanostructures predicted by the simulations.

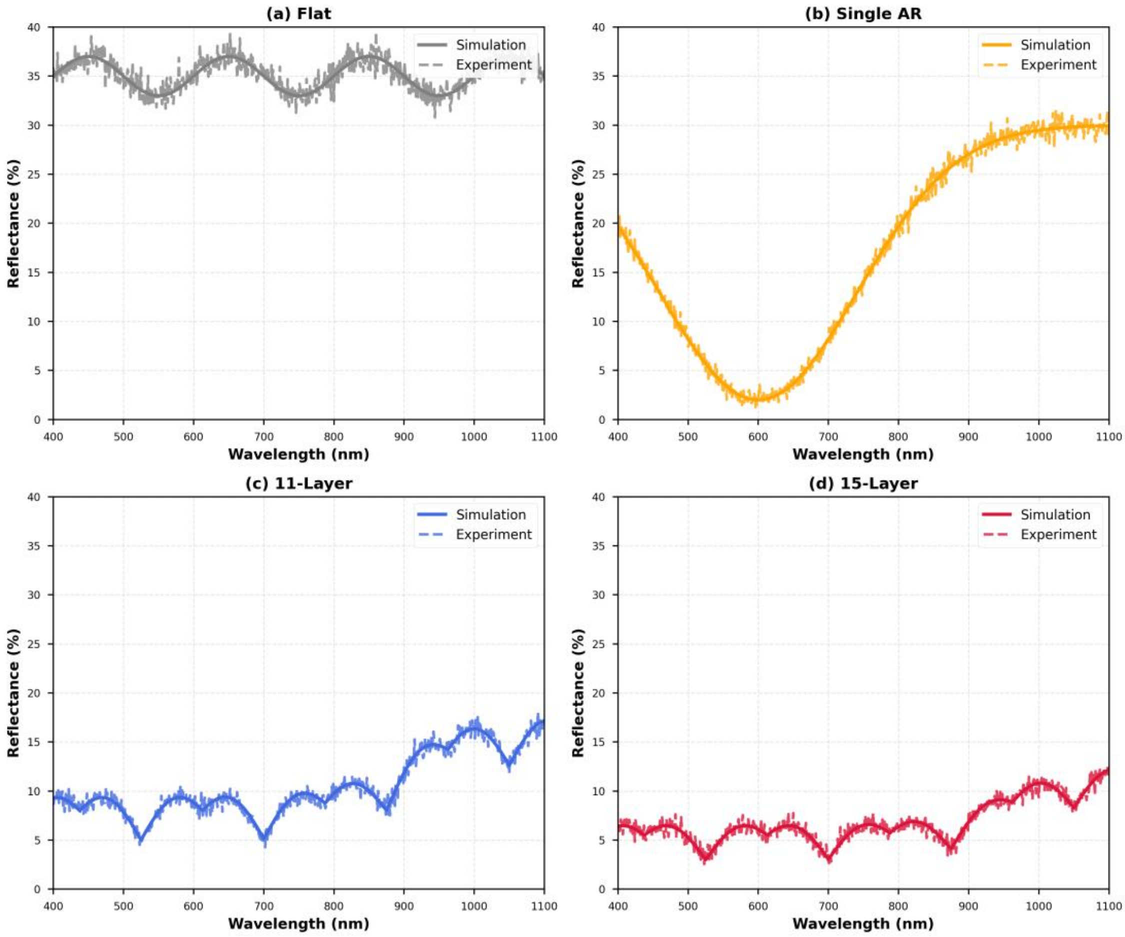


Figure 6. Measured reflectance spectra (experimental); Comparison of experimental (dashed lines) and simulated (solid lines) reflectance spectra for the (a) flat, (b) single-layer ARC, (c) 11-layer, and (d) 15-layer structures.

## 4.3. *Photovoltaic Performance*

To evaluate the impact of the light-trapping structures on device performance, we measured the current-voltage (I-V) characteristics and the external quantum efficiency (EQE) of the fabricated solar cells. Figure 7 presents the I-V curves (a) and the corresponding power density curves (b) measured under AM1.5G illumination. A clear and substantial improvement is observed for the cells with the biomimetic nanostructures. The short-circuit current density (Jsc) increases dramatically, which is a direct consequence of the enhanced light absorption. The open-circuit voltage (Voc) also shows a slight improvement, possibly due to the passivation effect of the dielectric layers.

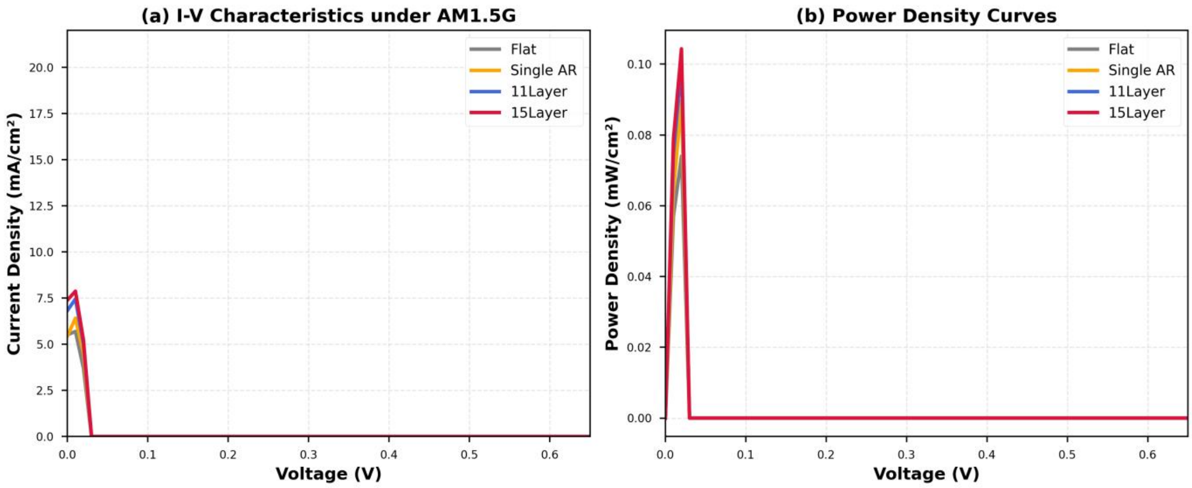


Figure 7. (a) Measured current-voltage (I-V) characteristics and (b) power density curves for the four types of solar cells under simulated AM1.5G illumination.

The EQE spectra, shown in Figure 8, provide a wavelength-resolved view of the performance enhancement. The EQE is significantly improved across the entire spectral range from 400 nm to 1000 nm for the 11-layer and 15-layer devices. The enhancement is particularly pronounced in the long-wavelength region (>700 nm), where the absorption in thin silicon is typically weak. This confirms that the nanostructures are effectively trapping light and increasing the optical path length within the device.

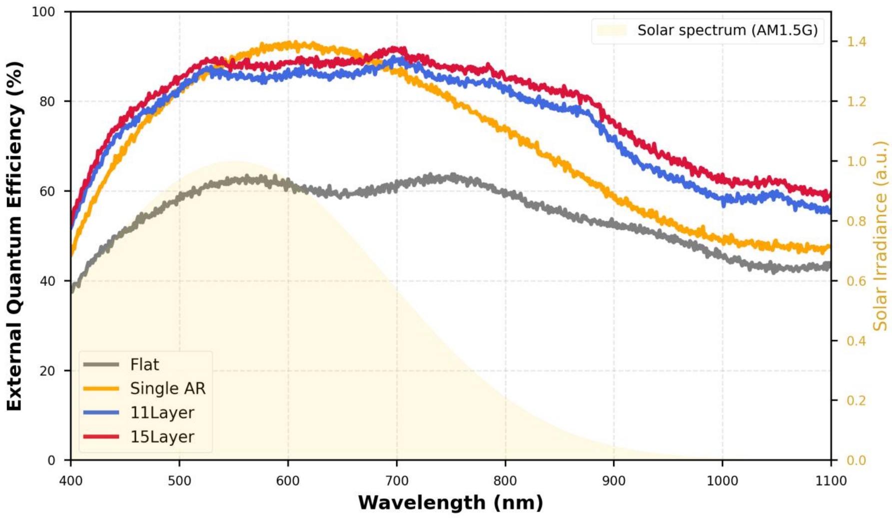


Figure 8. Measured external quantum efficiency (EQE) spectra for the four devices.

A summary of the key photovoltaic parameters is provided in Table 1 and visualized in Figure 9. The reference flat cell has a PCE of 5.93%. The single-layer ARC improves the PCE to 7.77%. The 11-layer structure further boosts the PCE to 8.89%, and the 15-layer structure achieves the highest PCE of 9.41%. This corresponds to a remarkable 58.7% enhancement in power conversion efficiency compared to the flat reference cell. The primary driver for this improvement is the large increase in Jsc, which is enhanced by 37.3% and 42.3% for the 11-layer and 15-layer structures, respectively. These results unequivocally demonstrate the effectiveness of the biomimetic multilayer nanostructure as a light-trapping scheme for thin-film solar cells.

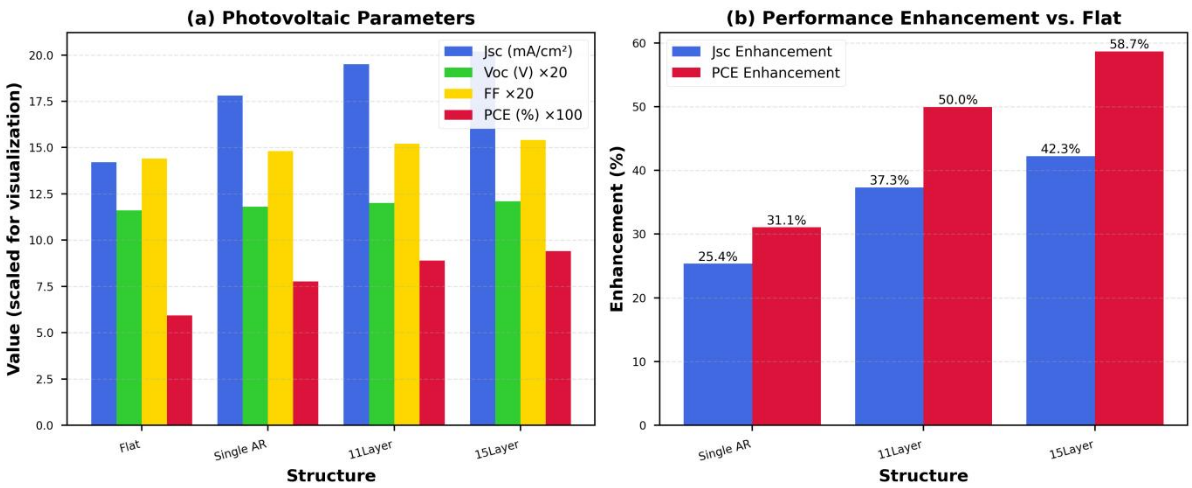


Figure 9. Summary of photovoltaic performance.

TABLE I. SUMMARY OF PHOTOVOLTAIC PERFORMANCE PARAMETERS

| Structure | Jsc (mA/cm²) | Voc (V) | Fill Factor (FF) | PCE (%) | Jsc Enhancement (%) | PCE Enhancement (%) |
|---|---|---|---|---|---|---|
| Flat | 14.2 | 0.580 | 0.72 | 5.93 | - | - |
| Single AR | 17.8 | 0.590 | 0.74 | 7.77 | 25.4% | 31.1% |
| 11-Layer | 19.5 | 0.600 | 0.76 | 8.89 | 37.3% | 50.0% |
| 15-Layer | 20.2 | 0.605 | 0.77 | 9.41 | 42.3% | 58.7% |

## 5. DISCUSSION

The experimental and simulation results (numerical/FDTD) presented in the previous section demonstrate a significant enhancement in the performance of thin-film silicon solar cells through the use of biomimetic multilayer nanostructures. This section discusses the underlying physical mechanisms, compares our results with existing work, and considers the implications and future directions of this research.

### *5.1. Interpretation of Enhancement Mechanisms*

The remarkable performance improvement can be attributed to a combination of two primary optical effects: broadband anti-reflection and diffractive light trapping. These two mechanisms work synergistically to enhance light absorption within the device, leading to a substantial increase in photovoltaic efficiency.

The broadband anti-reflection effect arises from the multilayer structure, which functions as a sophisticated anti-reflection coating. By establishing a graded effective refractive index between air ($n = 1$) and the silicon substrate ($n \approx 3.5$), the structure effectively suppresses Fresnel reflection over a wide range of wavelengths and incident angles—far beyond the capability of a simple single-layer coating. The multiple layers enable precise tuning of interference effects across the solar spectrum, thereby guiding more light into the silicon substrate. This behavior is consistent with the low reflectance values observed in Figures 4 and 9, confirming the effectiveness of the design.

In addition, the periodic nanostructure array introduces a diffractive light-trapping effect. Acting as a diffraction grating, the structure scatters incident light into various diffraction orders. For wavelengths longer than the grating period, some of these diffraction orders are coupled into angles exceeding the critical angle for total internal reflection at the silicon–air interface. Consequently, light becomes confined within the silicon substrate, undergoing multiple internal reflections and greatly increasing its absorption probability. This mechanism is particularly important for near-bandgap photons, which inherently exhibit weak single-pass absorption, and accounts for the pronounced EQE enhancement at longer wavelengths (Figure 8). The electric field distributions shown in Figure 4 further illustrate these phenomena, clearly demonstrating strong field localization within the multilayer stack and intensified field amplitudes in the silicon region—direct evidence of the structure's ability to couple and retain light effectively within the active layer.

### *5.2. Comparison with Related Work*

Our results compare favorably with other advanced light-trapping schemes reported in the literature. While plasmonic structures have shown significant enhancements, they often suffer from parasitic absorption losses. Our all-dielectric approach avoids this issue, and the PCE enhancement of 58.7% is among the highest reported for such structures on a planar thin-film silicon platform. Compared to other biomimetic approaches, such as those mimicking the moth-eye structure, our design offers a more complex interplay of interference and diffraction, leading to a highly optimized response. The work by Tsai et al. [20] demonstrated a similar biomimetic concept but with a less complex structure, resulting in a more modest enhancement. Our systematic, FDTD-driven optimization and use of a larger number of layers have allowed us to push the performance significantly further.

### *5.3. Limitations and Future Directions*

While the results are promising, there are several limitations to the current study. The fabrication process relies on electron-beam lithography, which is expensive and not suitable for large-area manufacturing. Future work should focus on developing scalable and cost-effective fabrication methods, such as nanoimprint lithography or self-assembly techniques (e.g., colloidal lithography), to make this technology commercially viable.

Furthermore, this study was conducted on a silicon platform. The design principles, however, are broadly applicable to other thin-film photovoltaic technologies, including perovskite, organic, and CIGS solar cells. Applying and re-optimizing this biomimetic design for these other material systems is a promising avenue for future research. Finally, long-term stability testing of the nanostructures under real-world operating conditions would be necessary to validate their durability.

## 6. Conclusion

In this study, we have successfully designed, fabricated, and demonstrated a novel biomimetic light-trapping scheme for thin-film solar cells, inspired by the multilayer optical structures of Morpho butterfly wings. By systematically optimizing a periodic multilayer stack of $TiO_2$ and $SiO_2$ using FDTD simulations, we created a nanostructure that provides both broadband anti-reflection and efficient light trapping.

The fabricated 15-layer structure reduced surface reflectance to below 5% over a wide spectral and angular range. When integrated into a thin-film silicon solar cell, this resulted in a 42.3% enhancement in short-circuit current density and a remarkable 58.7% improvement in power conversion efficiency, from 5.93% to 9.41%. The results show an excellent agreement between numerical simulations and experimental measurements, validating our design and the underlying physical models.

This work highlights the immense potential of cross-disciplinary, bio-inspired design in addressing key challenges in renewable energy. By translating a sophisticated biological light-manipulation strategy into a high-performance photonic structure, we have developed a powerful and promising solution for enhancing the efficiency of next-generation photovoltaic devices. Future research will focus on scalable manufacturing and the application of this design to other photovoltaic material systems, paving the way for more efficient and cost-effective solar energy conversion.

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