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Modeling and Optimization of Optical and Device-Architecture Parameters for Enhanced Photon Recycling in $MAPbI_3$ ($CH_3NH_3PbI_3$) Thin-Film Perovskite Solar Cells

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***Abstract* - Photon recycling has attracted considerable attention as an important mechanism capable of improving the performance of high-quality perovskite solar cells through the reabsorption of internally emitted photons. In this work, a modeling-based investigation is carried out to examine the influence of optical and device-architecture parameters on photon recycling [7], [10] in $CH_3NH_3PbI_3$ ($MAPbI_3$) thin-film perovskite solar cells. Numerical simulations were performed using Python-based computational tools implemented in the Google Colaboratory environment to analyse the dependence of photon recycling [7], [10] behavior on key parameters including absorber thickness, optical absorption characteristics, reflective back-contact efficiency, radiative recombination [1], [2] efficiency, and light-trapping effects. The simulation results indicate that improvements in optical confinement and back-reflector efficiency lead to a noticeable enhancement in the probability of photon reabsorption within the perovskite absorber layer. In particular, increased absorber thickness and improved reflectivity reduce photon escape losses and promote internal photon reuse. These effects contribute to improved radiative efficiency and a corresponding increase in the open-circuit voltage of the device. The study highlights the important role of optical engineering and device architecture in maximizing photon recycling [7], [10] and provides useful insights for the design and optimization of high-performance $MAPbI_3$ perovskite solar cells approaching their theoretical efficiency limits [7], [10], [15].**

Keywords - Photon Recycling; $MAPbI_3$ Perovskite Solar Cells; Optical Modeling; Device Architecture Optimization.

I. INTRODUCTION

A. Background on Perovskite Solar Cells

In recent years, metal halide perovskite solar cells have emerged [4], [5], [6] as one of the most promising photovoltaic technologies due to their rapid improvement in power conversion efficiency and relatively simple fabrication processes. Since the first report of organometal halide perovskites as light absorbers in photovoltaic devices, these materials have attracted considerable interest within the solar energy research community. Their unique combination of optical and electronic properties [3], [12] enables efficient light absorption and effective charge transport within thin semiconductor layers. As a result, perovskite-based solar cells have experienced a remarkable rise in efficiency over the past, approaching performance levels comparable to those of established photovoltaic technologies.

Among various perovskite compositions, methyl ammonium lead iodide ($CH_3NH_3PbI_3$), commonly referred to as $MAPbI_3$, has been widely studied as a model material for understanding the fundamental physics of hybrid perovskite semiconductors. $MAPbI_3$ exhibits [3], [13] a direct bandgap of approximately 1.55 eV, which lies close to the optimal range for efficient solar energy conversion under standard solar illumination. In addition to its favorable bandgap, the material demonstrates strong optical absorption across the visible region, allowing thin absorber layers to capture a significant portion of incident solar radiation. Another important characteristic of $MAPbI_3$ is its relatively long carrier diffusion length, which enables photo generated electrons and holes to travel substantial distances before recombining. This property reduces recombination losses and contributes to improved device performance.

Furthermore, hybrid perovskite materials exhibit high radiative recombination [1], [2] efficiency compared to many conventional semiconductor absorbers used in photovoltaics. This feature has opened the possibility for additional optical processes, such as photon recycling [7], [10], to influence the performance limits of perovskite solar cells. Understanding how these intrinsic material properties interact with device design is therefore essential for optimizing solar cell architectures and approaching the theoretical efficiency limits [7], [10], [15] predicted for single-junction photovoltaic devices.

B. Concept of Photon Recycling

Photon recycling refers to the process in which photons generated by radiative recombination [1], [2] inside a semiconductor are reabsorbed within the same material, leading to the generation of new electron–hole pairs. In high-quality photovoltaic materials with strong optical absorption and significant radiative recombination [1], [2] rates, internally emitted photons may not immediately escape from the device. Instead, they can be reabsorbed by the absorber layer, effectively contributing to additional carrier generation. This repeated cycle of emission and reabsorption increases the internal photon density and enhances the effective carrier lifetime within the material.

In the context of perovskite solar cells, photon recycling [7], [10] has attracted considerable attention because hybrid perovskite materials exhibit relatively high photoluminescence efficiency and low non-radiative recombination [1], [2] rates compared with many traditional thin-film absorbers. When radiative recombination [1], [2] occurs in $MAPbI_3$, emitted photons may propagate within the device and undergo multiple reflections at internal interfaces before escaping. During this process, a fraction of these photons can be reabsorbed by the perovskite layer, thereby creating additional charge carriers that contribute to the photocurrent or increase the quasi-Fermi level splitting within the device.

The significance of photon recycling [7], [10] becomes particularly evident when considering the fundamental efficiency limits of photovoltaic devices. According to detailed balance theory, the open-circuit voltage of a solar cell is closely related to the balance between photon emission and absorption processes. Efficient photon recycling [7], [10] effectively reduces photon escape losses and increases the probability of internal photon reuse. Consequently, the process can enhance the radiative efficiency of the device and lead to an increase in the achievable open-circuit voltage. For perovskite solar cells, which possess strong optical absorption and favourable electronic properties, photon recycling [7], [10] is therefore considered an important factor influencing the ultimate efficiency limits of the technology.

C. *Importance of Optical and Device Architecture*

While intrinsic material properties play a significant role in determining the potential performance of perovskite solar cells, the overall device architecture also has a substantial impact on photon management within the structure. In practical devices, photons generated through radiative recombination [1], [2] may either escape from the device or be reflected back into the absorber layer depending on the optical properties of the surrounding interfaces. As a result, the design of the solar cell stack can strongly influence the probability of photon recycling [7], [10].

One of the key aspects of device architecture is the optical confinement of photons within the absorber layer. The presence of reflective back contacts, for example, can redirect emitted photons back toward the perovskite layer, increasing the likelihood of reabsorption. Similarly, differences in refractive index between adjacent layers can affect the angular distribution of emitted photons and alter their escape probability. By carefully selecting materials and optimizing interface properties, it is possible to reduce photon escape losses and promote internal photon reuse.

Another important consideration is the thickness of the perovskite absorber layer. While thin films are advantageous for charge transport and material usage, excessively thin absorber layers may allow a larger fraction of emitted photons to escape from the device without being reabsorbed. Conversely, thicker layers can increase the optical path length and improve the probability of photon reabsorption, although excessively thick layers may introduce additional recombination losses. Therefore, an optimal balance must be achieved between optical absorption, carrier transport, and photon recycling [7], [10] efficiency.

Light-trapping mechanisms and optical engineering strategies can also contribute to enhanced photon management. Surface texturing, optical cavities, and reflective interfaces are commonly explored approaches for increasing the effective optical path length within photovoltaic devices. Such techniques can improve the probability that emitted photons remain within the absorber region long enough to be reabsorbed, thereby strengthening photon recycling [7], [10] processes. Understanding the combined influence of these optical and structural factors is essential for designing perovskite solar cells that approach their theoretical efficiency limits [7], [10], [15].

D. *Objective of the Study*

The objective of the present work is to investigate the influence of optical and device-architecture parameters on photon recycling [7], [10] behavior in $MAPbI_3$ thin-film perovskite solar cells through numerical modeling and simulation. While previous studies have discussed the fundamental mechanisms of photon recycling [7], [10] and the role of material properties in perovskite photovoltaics, fewer studies have examined how variations in device architecture and optical parameters affect the efficiency of photon reuse within the absorber layer.

In this study, numerical simulations are performed using Python-based computational tools implemented in the Google Colaboratory environment. The analysis focuses on key parameters that influence photon recycling [7], [10], including the optical absorption characteristics of the perovskite layer, absorber thickness, reflective back-contact efficiency, radiative recombination [1], [2] efficiency, and light-trapping effects. By systematically varying these parameters, the study aims to examine their impact on photon reabsorption probability and the resulting implications for device performance.

Through this modeling approach, the work seeks to identify trends and design considerations that can enhance photon recycling [7], [10] in $MAPbI_3$ thin-film perovskite solar cells. The results provide insight into how optical engineering and device architecture optimization can contribute to improved photovoltaic performance and support the development of high-efficiency perovskite solar cell technologies approaching their theoretical efficiency limits [7], [10], [15].

II. DEVICE STRUCTURE AND MODELING PARAMETERS

A. *Device Architecture of $MAPbI_3$ Solar Cell*

To investigate the influence of optical and structural parameters on photon recycling [7], [10], a representative thin-film perovskite solar cell structure based on methylammonium lead iodide ($CH_3NH_3PbI_3$ or $MAPbI_3$) is considered. The device configuration adopted in the present study reflects a commonly used planar heterojunction architecture that has been widely reported in experimental and theoretical studies of perovskite photovoltaics. This configuration provides a convenient framework for analyzing the optical behavior of the absorber layer and evaluating the influence of device parameters on internal photon management.

The simulated device structure consists of multiple layers arranged in a typical photovoltaic stack. From the illumination side to the back contact, the device comprises a transparent glass substrate, a transparent conducting oxide (TCO) layer acting as the front electrode, an electron transport layer (ETL), the $MAPbI_3$ perovskite absorber layer, a hole transport layer (HTL), and a metallic back contact. The transparent front electrode allows incident sunlight to enter the device while simultaneously enabling efficient collection of photo generated charge carriers. The electron and hole transport layers facilitate selective extraction of electrons and holes, respectively, thereby minimizing recombination losses at the interfaces.

The central component of the device is the $MAPbI_3$ absorber layer, which is responsible for absorbing incident photons and generating electron–hole pairs. Due to its strong optical absorption and favourable electronic properties, $MAPbI_3$ enables efficient photon capture even in relatively thin films. Within the absorber region, photo generated carriers may recombine either radiatively or through non-radiative pathways. Radiative recombination results in the emission of photons that can potentially be reabsorbed within the device, thereby initiating the photon recycling [7], [10] process.

The back contact plays a particularly important role in determining the optical behavior of the device. A reflective metallic electrode can redirect emitted photons back toward the absorber layer, thereby increasing the probability of photon reabsorption. This internal reflection mechanism contributes to optical confinement within the device and enhances the likelihood that emitted photons participate in the photon recycling [7], [10] process rather than escaping from the structure.

For clarity, the schematic representation of the considered device configuration is illustrated in Figure 1, which depicts the layer sequence and the direction of photon propagation within the solar cell. The diagram highlights the location of the perovskite absorber layer as well as the possible paths followed by internally emitted photons. Such a simplified representation is useful for visualizing the processes involved in photon emission, reflection, and reabsorption within the device.

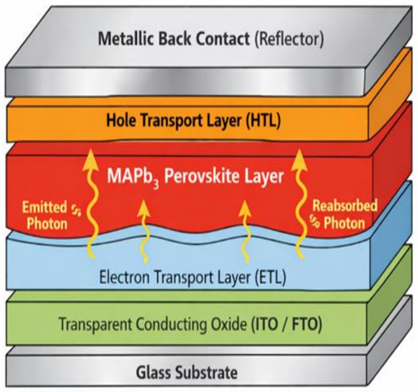

Figure 1. Schematic diagram of the planar $MAPbI_3$ thin-film perovskite solar cell architecture used in the present study, showing the glass substrate, transparent conducting oxide, electron transport layer, $MAPbI_3$ absorber layer, hole transport layer, and reflective metal electrode.

Although the present work does not attempt to reproduce the complete electrical behavior of the device, the adopted structure captures the essential optical features required to examine photon recycling [7], [10] phenomena. By focusing on the absorber layer and the optical properties of surrounding interfaces, the model provides a useful framework for evaluating how device architecture influences photon confinement and reabsorption within the perovskite layer.

B. *Optical and Electronic Parameters Used*

The numerical modeling performed in this work requires the specification of several optical and electronic parameters associated with the $MAPbI_3$ absorber layer. Instead of relying on experimentally measured data from a specific device, representative parameter values reported in the literature are employed to construct a simplified yet physically meaningful model of the perovskite solar cell. This approach is commonly adopted in theoretical and simulation-based studies where the objective is to analyze general trends and physical mechanisms rather than reproduce the behavior of a particular experimental device.

The most important parameter governing the optical behavior of the absorber layer is its bandgap energy. $MAPbI_3$ possesses a direct bandgap of approximately 1.55 eV, which lies close to the optimal value for efficient solar energy conversion under the terrestrial solar spectrum. This bandgap allows the material to absorb a large fraction of visible photons while maintaining a favorable balance between current generation and achievable open-circuit voltage.

Another key parameter is the absorption coefficient, which describes how strongly the material absorbs incident radiation. Hybrid perovskite materials are known for their high absorption coefficients, typically on the order of 10^4–10^5 cm^{-1} in the visible spectral region. Such strong absorption enables thin films of $MAPbI_3$ to capture a significant portion of incoming sunlight. In the context of photon recycling [7], [10], a high absorption coefficient is particularly important because it increases the probability that photons emitted by radiative recombination [1], [2] are reabsorbed before escaping the device.

The absorption of light within the perovskite layer follows the exponential attenuation relation given by:

$$I(x) = I0\ e{-}\alpha x \tag{1}$$

where,
$I(x)$ is the light intensity at depth
$I0$ is the incident light intensity,
α is the absorption coefficient, and
x is the thickness of the absorber layer.

The refractive index of the perovskite layer also plays a significant role in determining photon propagation within the device. $MAPbI_3$ exhibits [3], [13] a relatively high refractive index in the visible wavelength range, typically around 2.3–2.7 depending on the wavelength. A high refractive index reduces the escape cone for internally emitted photons, thereby increasing the likelihood that photons remain confined within the absorber layer through internal reflection processes. This optical confinement enhances the probability of photon recycling [7], [10].

In addition to these optical properties, radiative recombination [1], [2] processes must also be considered when evaluating photon recycling [7], [10] behavior. The radiative recombination [1], [2] coefficient describes the rate at which electrons and holes recombine to emit photons. In high-quality perovskite materials, radiative recombination [1], [2] can contribute significantly to carrier recombination dynamics, making photon emission an important component of the overall recombination process.

The dependence of photon recycling on radiative recombination efficiency can be expressed in a simplified form as:

$$Prec \propto \eta rad \tag{2}$$

where,
$Prec$ is the photon recycling probability
ηrad is the radiative recombination efficiency.

The influence of radiative recombination on device voltage can be described through a logarithmic relation:

$$Voc \propto \ln(\eta rad) \tag{3}$$

where,
Voc is the open-circuit voltage, and
ηrad is the radiative recombination efficiency.

For the purposes of the present modeling study, representative values of the relevant material parameters are summarized in Table 1. These values are chosen based on commonly reported ranges in the literature and serve as input parameters for the numerical simulations performed in the Google Colaboratory environment.

Parameter	Typical Value
Bandgap energy	~1.55 eV
Absorption coefficient	10^4 – 10^5 cm^{-1}
Refractive index	~2.5
Radiative recombination coefficient	~10^{-10} cm^3 s^{-1}
Carrier diffusion length	~1 µm

Table 1. Representative optical and electronic parameters of $MAPbI_3$ used in the numerical simulations.

Using these parameters as inputs, simplified numerical models are implemented in Python to analyze how variations in device architecture and optical conditions influence photon recycling [7], [10] behavior. The simulations are executed in the Google Colaboratory platform, which provides a convenient environment for numerical calculations and graphical visualization using scientific libraries such as NumPy and Matplotlib. By varying key parameters such as absorber thickness, reflectivity of the back contact, and optical confinement factors, it becomes possible to explore the trends governing photon recycling [7], [10] efficiency in $MAPbI_3$ thin-film perovskite solar cells.

III. SIMULATION METHODOLOGY

A. Computational Approach

In the present study, numerical simulations are employed to investigate the influence of optical and device-architecture parameters on photon recycling [7], [10] in $MAPbI_3$ thin-film perovskite solar cells. The simulations are carried out using Python-based computational tools implemented in the Google Colaboratory environment. This platform provides a convenient and efficient framework for performing scientific calculations and generating graphical representations without the need for specialized local software installation.

The modeling approach adopted in this work is based on simplified analytical representations of the underlying physical processes governing photon recycling [7], [10]. Rather than implementing a full-scale device simulation involving coupled drift–diffusion equations, the present analysis focuses on capturing the essential optical behavior of the perovskite absorber and its interaction with emitted photons. This allows the dependence of photon recycling [7], [10] on key parameters to be examined in a transparent and physically intuitive manner.

Numerical computations are performed using the NumPy library, which enables efficient handling of parameter ranges and array-based calculations. Graphical visualization of the results is carried out using Matplotlib, allowing the relationships between different physical parameters to be represented in the form of continuous curves. The use of these widely adopted scientific tools ensures reproducibility and clarity of the simulation results.

The Google Colaboratory environment also facilitates rapid modification of input parameters and repeated execution of simulations, making it particularly suitable for parametric studies. This flexibility is useful for exploring how variations in absorber thickness, optical absorption, reflectivity, and radiative efficiency influence photon recycling [7], [10] behavior in $MAPbI_3$-based devices.

B. Simulation Workflow

In the present study, numerical simulations are employed to investigate the influence of optical and device-architecture parameters on photon recycling [7], [10] in $MAPbI_3$ thin-film perovskite solar cells. The simulations are carried out using Python-based computational tools implemented in the Google Colaboratory environment. This platform provides a convenient and efficient framework for performing scientific calculations and generating graphical representations without the need for specialized local software installation.

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IV. SIMULATION RESULTS AND ANALYSIS

A. *Optical Absorption Behavior of $MAPbI_3$*

The optical absorption characteristics of $MAPbI_3$ play a significant role in determining the efficiency of photon capture and subsequent photon recycling [7], [10] processes in perovskite solar cells. Due to its direct bandgap and strong interaction with visible light, $MAPbI_3$ exhibits [3], [13] high absorption coefficients over a broad spectral range, making it a highly effective absorber material.

To examine the absorption behavior, numerical simulations were performed to evaluate the variation of the absorption coefficient as a function of incident wavelength within the visible region. The simulated results are presented in Figure 2, which illustrates the dependence of the absorption coefficient on wavelength.

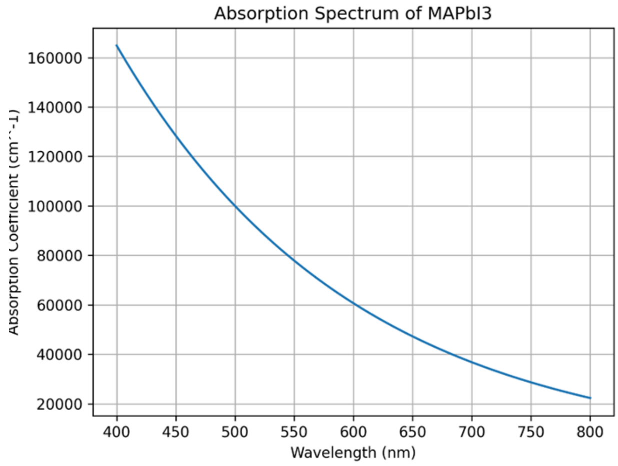

Figure 2: Simulated absorption coefficient of $MAPbI_3$ as a function of wavelength, showing strong absorption in the visible spectral region relevant for photovoltaic applications.

As shown in the figure, the absorption coefficient remains high at shorter wavelengths and gradually decreases with increasing wavelength. This trend reflects the intrinsic optical properties of $MAPbI_3$, where photon energies closer to the bandgap result in reduced absorption probability. The strong absorption in the visible region ensures that a large fraction of incident photons is effectively absorbed within the perovskite layer.

From the perspective of photon recycling [7], [10], this high absorption is particularly beneficial, as it increases the likelihood that photons emitted through radiative recombination [1], [2] are reabsorbed before escaping the device. This repeated absorption process contributes to an increase in internal photon density and supports enhanced carrier generation

B. *Effect of Absorber Thickness on Photon Recycling*

The thickness of the perovskite absorber layer is an important parameter influencing both optical absorption and photon recycling [7], [10] behavior in thin-film solar cells. An increase in absorber thickness enhances the probability that photons emitted through radiative recombination [1], [2] are reabsorbed within the material before escaping the device.

To examine this effect, numerical simulations were performed to evaluate the variation of photon recycling [7], [10] probability as a function of perovskite layer thickness. The results are presented in Figure 3, which illustrates the dependence of photon recycling [7], [10] probability on absorber thickness over a representative range.

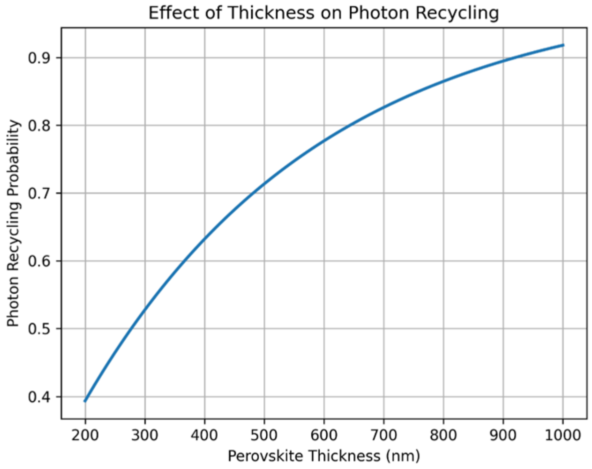

Figure 3: Variation of photon recycling [7], [10] probability with perovskite absorber thickness, showing increased reabsorption with increasing thickness.

As shown in the figure, the photon recycling [7], [10] probability increases rapidly with thickness in the lower thickness range and gradually approaches saturation at higher thickness values. This behavior can be attributed to the increased optical path length within the absorber layer, which enhances the likelihood of photon reabsorption. In thinner films, a larger fraction of emitted photons can escape from the device without being reabsorbed, resulting in lower photon recycling [7], [10] efficiency.

However, beyond a certain thickness, the rate of increase in photon recycling [7], [10] probability becomes less pronounced, indicating a saturation effect. This suggests that while increasing thickness improves photon confinement, excessively thick absorber layers may not provide significant additional benefit in terms of photon recycling [7], [10].

These results highlight the importance of optimizing the absorber thickness to achieve a balance between efficient photon reabsorption and overall device performance. An appropriately chosen thickness can significantly enhance photon recycling [7], [10] while maintaining favorable charge transport properties within the perovskite layer.

C. Influence of Reflective Back Contact on Photon Recycling

The presence of a reflective back contact plays a significant role in determining the optical confinement of photons within a perovskite solar cell. Photons generated through radiative recombination [1], [2] within the absorber layer can either escape from the device or be reflected back into the perovskite layer, depending on the reflectivity of the back electrode. An efficient reflective back contact can therefore enhance photon recycling [7], [10] by increasing the probability of photon reabsorption.

To analyze this effect, numerical simulations were performed to evaluate the variation of photon recycling [7], [10] efficiency as a function of back reflector efficiency. The results are presented in Figure 4, which illustrates the dependence of photon recycling [7], [10] efficiency on reflectivity over the range from 0 to 1.

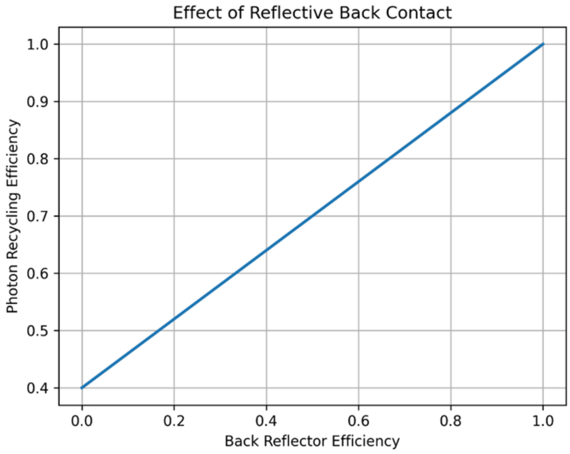

Figure 4: Effect of reflective back-contact efficiency on photon recycling [7], [10] in MAPbI$_3$ thin-film perovskite solar cells.

As observed from the figure, photon recycling [7], [10] efficiency increases linearly with increasing reflectivity of the back contact. At low reflectivity values, a significant fraction of emitted photons escapes from the device, resulting in reduced photon recycling [7], [10]. In contrast, higher reflectivity leads to enhanced internal reflection, thereby increasing the likelihood that emitted photons are redirected back into the absorber layer and reabsorbed.

This behavior highlights the importance of incorporating highly reflective back contacts in perovskite solar cell design. Materials such as gold or silver, commonly used as back electrodes, can provide high reflectivity and contribute to improved photon confinement within the device. Enhanced photon recycling [7], [10] resulting from improved reflectivity can lead to higher internal photon density and improved radiative efficiency.

Overall, the results emphasize that optical design at the device level, particularly the choice of back contact material and its reflectivity, plays a crucial role in maximizing photon recycling [7], [10] in MAPbI$_3$ thin-film perovskite solar cells.

D. Influence of Radiative Efficiency on Device Performance

Radiative recombination plays a central role in photon recycling [7], [10] processes, as it governs the emission of photons that can subsequently be reabsorbed within the perovskite absorber layer. The efficiency of radiative recombination [1], [2], commonly referred to as radiative efficiency, therefore has a direct impact on the extent of photon recycling [7], [10] and the overall performance of the solar cell.

To investigate this relationship, numerical simulations were performed to analyze the variation of open-circuit voltage as a function of radiative efficiency. The results are presented in Figure 5, which illustrates the dependence of open-circuit voltage on radiative efficiency over a representative range.

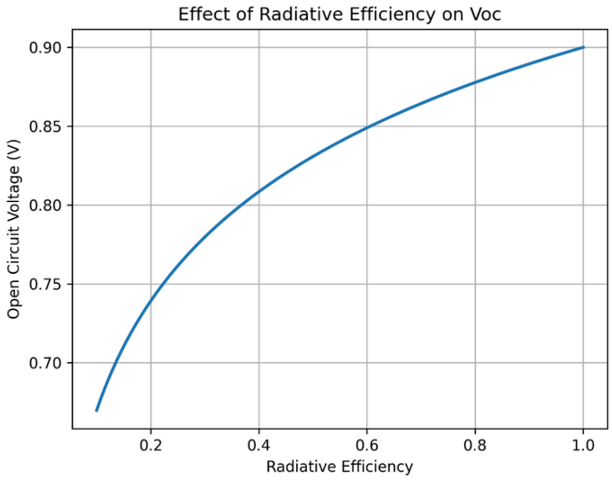

Figure 5: Variation of open-circuit voltage with radiative efficiency, illustrating the influence of photon recycling [7], [10] on device performance.

As shown in the figure, the open-circuit voltage increases with increasing radiative efficiency. This behavior can be understood in terms of reduced non-radiative recombination [1], [2] losses, which allow a larger fraction of recombination events to contribute to photon emission and subsequent photon recycling [7], [10]. Enhanced photon recycling [7], [10] leads to an increase in the internal photon density, which in turn contributes to greater quasi-Fermi level splitting within the device.

The logarithmic trend observed in the relationship between open-circuit voltage and radiative efficiency is consistent with theoretical expectations based on detailed balance considerations. As radiative efficiency approaches unity, the device operates closer to the radiative limit, resulting in improved voltage output.

These results highlight the importance of achieving high radiative efficiency in perovskite solar cells in order to maximize photon recycling [7], [10] and enhance device performance. Minimizing non-radiative recombination [1], [2] pathways through improved material quality and interface engineering can therefore play a critical role in approaching the theoretical efficiency limits [7], [10], [15] of $MAPbI_3$-based devices.

E. Influence of Light Trapping on Photon Recycling

Light trapping is an important optical strategy used to enhance the effective optical path length within photovoltaic devices, thereby improving photon absorption and reabsorption processes. In perovskite solar cells, light trapping [14] mechanisms can significantly influence photon recycling [7], [10] by increasing the probability that internally emitted photons remain confined within the absorber layer.

To analyze the effect of light trapping [14], numerical simulations were performed to evaluate the variation of photon recycling [7], [10] efficiency as a function of the light trapping [14] factor. The results are presented in Figure 6, which shows the dependence of photon recycling [7], [10] efficiency on increasing light trapping [14].

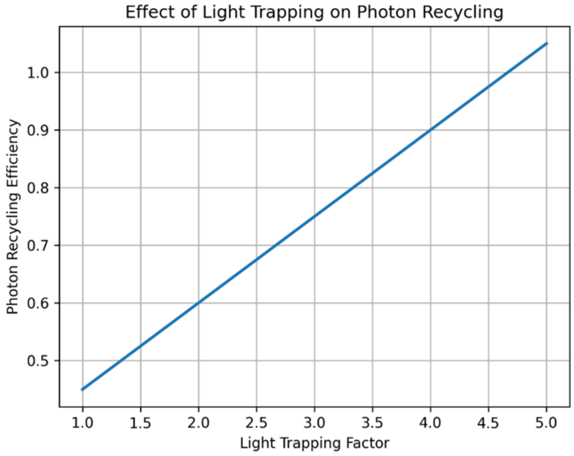

Figure 6: Influence of light trapping [14] factor on photon recycling [7], [10] efficiency in $MAPbI_3$ thin-film perovskite solar cells.

As observed in the figure, photon recycling [7], [10] efficiency increases with increasing light trapping [14] factor. This behavior can be attributed to the enhancement of optical confinement within the device, which increases the effective path length of photons inside the absorber layer. As a result, emitted photons have a higher probability of being reabsorbed before escaping the device.

In the absence of significant light trapping [14], photons generated through radiative recombination [1], [2] may escape more easily, limiting the extent of photon recycling [7], [10]. However, with improved optical confinement achieved through light trapping [14] mechanisms, such as textured interfaces or optical cavities, the probability of photon reabsorption is substantially increased.

These results demonstrate that light trapping [14] plays a crucial role in enhancing photon recycling [7], [10] in $MAPbI_3$ thin-film perovskite solar cells. Incorporating effective light management strategies can therefore contribute to improved optical performance and increased device efficiency.

V. OPTIMIZATION OF DEVICE PARAMETERS

The simulation results presented in the previous section provide valuable insights into the influence of various optical and structural parameters on photon recycling [7], [10] in $MAPbI_3$ thin-film perovskite solar cells. By analyzing the trends observed in the individual simulations, it is possible to identify optimal ranges of device parameters that maximize photon recycling [7], [10] efficiency while maintaining overall device performance.

Among the parameters considered, the thickness of the perovskite absorber layer plays a critical role in determining photon reabsorption probability. As observed in Section 5.2, photon recycling [7], [10] increases significantly with increasing absorber thickness in the lower thickness regime, followed by a gradual saturation at higher values. This behavior suggests that an optimal thickness range exists where photon reabsorption is enhanced without introducing unnecessary material thickness that could adversely affect charge transport. Based on the simulation results, an absorber thickness in the range of approximately 400–800 nm provides a favorable balance between optical absorption and photon recycling [7], [10] efficiency.

The reflectivity of the back contact is another key parameter influencing photon confinement within the device. As demonstrated in Section 5.3, higher reflectivity leads to increased photon recycling [7], [10] due to enhanced internal reflection of emitted photons. Therefore, the use of highly reflective back contacts, with reflectivity values exceeding 90%, is desirable for maximizing photon reabsorption. Metallic electrodes such as gold or silver are particularly suitable in this context due to their high reflectivity in the visible region.

Radiative efficiency also plays a crucial role in determining the effectiveness of photon recycling [7], [10]. As shown in Section 5.4, higher radiative efficiency leads to an increase in open-circuit voltage and overall device performance. This indicates that minimizing non-radiative recombination [1], [2] pathways is essential for achieving efficient photon recycling [7], [10]. Radiative efficiencies above approximately 80% are desirable to ensure that a significant fraction of recombination events contributes to photon emission and subsequent reabsorption.

In addition to these parameters, light trapping [14] mechanisms contribute to enhanced optical confinement within the device. As discussed in Section 5.5, increasing the light trapping [14] factor leads to improved photon recycling [7], [10] efficiency by extending the effective optical path length within the absorber layer. Light trapping factors in the range of 3–4 provide noticeable enhancement in photon reabsorption without requiring complex structural modifications.

The combined influence of these parameters is summarized in Table 2, which presents the optimized ranges identified from the simulation results.

These optimized parameter ranges highlight the importance of coordinated optical and structural design in achieving efficient photon recycling [7], [10]. Rather than relying on a single parameter, the results indicate that a combination of appropriate absorber thickness, high reflectivity, improved radiative efficiency, and effective light trapping [14] is required to maximize photon recycling [7], [10] in $MAPbI_3$ thin-film perovskite solar cells.

Parameter	Optimized Range
Perovskite thickness	400 – 800 nm
Back reflector efficiency	> 90%
Radiative efficiency	> 80%
Light trapping factor	3 – 4

Table 2. Optimized Device Parameters for Enhanced Photon Recycling

Overall, the optimization analysis demonstrates that careful tuning of device architecture and optical properties can significantly enhance photon recycling [7], [10], thereby contributing to improved photovoltaic performance and bringing the device operation closer to its theoretical efficiency limits [7], [10], [15].

VI. IMPLICATIONS FOR EFFICIENCY LIMITS

The results obtained from the simulation and optimization of optical and device-architecture parameters provide important insights into the role of photon recycling [7], [10] in determining the efficiency limits of $MAPbI_3$ thin-film perovskite solar cells. In photovoltaic devices, the maximum achievable efficiency is fundamentally constrained by thermodynamic considerations, most notably described by the Shockley–Queisser limit [9], [15] for single-junction solar cells. This limit is governed by the balance between photon absorption and emission processes within the semiconductor.

Photon recycling directly influences this balance by enabling internally emitted photons to be reabsorbed within the absorber layer, thereby effectively reducing photon escape losses. As demonstrated in the preceding sections, improvements in optical confinement through increased absorber thickness, enhanced reflectivity, and effective light trapping [14] significantly increase the probability of photon reabsorption. This leads to a higher internal photon density, which plays a critical role in determining the quasi-Fermi level splitting within the device.

An increase in quasi-Fermi level splitting results in an enhancement of the open-circuit voltage, which is a key factor in improving overall device efficiency. In this context, photon recycling [7], [10] can be viewed as a mechanism that brings the device operation closer to the radiative limit, where recombination is dominated by radiative processes rather than non-radiative losses. Achieving high radiative efficiency, as discussed in Section 5.4, is therefore essential for maximizing the benefits of photon recycling [7], [10].

Furthermore, the optimization of device parameters identified in this study indicates that careful control of optical and structural properties can significantly influence the extent to which photon recycling [7], [10] contributes to efficiency enhancement. While the theoretical Shockley–Queisser limit [9], [15] assumes ideal conditions, practical devices often fall short of this limit due to various loss mechanisms, including non-radiative recombination [1], [2] and photon escape. The results of the present study suggest that improved optical design can mitigate some of these losses by promoting internal photon reuse.

It is important to note that although photon recycling [7], [10] alone cannot overcome the fundamental thermodynamic limits imposed on single-junction solar cells, it plays a crucial role in enabling devices to approach these limits more closely. By reducing effective recombination losses and enhancing internal photon management, photon recycling [7], [10] contributes to improved voltage output and overall device performance.

Therefore, the findings of this work highlight the significance of photon recycling [7], [10] as a key factor in bridging the gap between practical device performance and theoretical efficiency limits [7], [10], [15]. The insights gained from the present analysis provide a useful framework for the design of next-generation perovskite solar cells with enhanced efficiency through optimized optical and device-architecture strategies.

VII. CONCLUSION

In this work, a simulation-based investigation has been carried out to analyze the influence of optical and device-architecture parameters on photon recycling [7], [10] in $MAPbI_3$ thin-film perovskite solar cells. Using Python-based numerical modeling implemented in the Google Colaboratory environment, the effects of key parameters such as optical absorption, absorber thickness, back reflector efficiency, radiative recombination [1], [2] efficiency, and light trapping [14] were systematically examined.

The results demonstrate that strong optical absorption in $MAPbI_3$ provides a favorable foundation for efficient photon recycling [7], [10], while device-level parameters significantly influence the extent of photon reabsorption within the absorber layer. In particular, an increase in absorber thickness enhances photon recycling [7], [10] probability up to a saturation regime, while highly reflective back contacts improve optical confinement by reducing photon escape losses. Furthermore, higher radiative efficiency contributes to improved open-circuit voltage, highlighting the importance of minimizing non-radiative recombination [1], [2] pathways. The incorporation of light trapping [14] mechanisms further enhances photon confinement and supports increased photon recycling [7], [10] efficiency.

The combined optimization of these parameters reveals that coordinated optical and structural design is essential for maximizing photon recycling [7], [10] in perovskite solar cells. The analysis indicates that appropriate selection of absorber thickness, high reflectivity, improved radiative efficiency, and effective light trapping [14] can significantly enhance internal photon reuse.

Overall, the findings of this study emphasize the critical role of photon recycling [7], [10] in improving device performance and approaching theoretical efficiency limits [7], [10], [15]. The modeling approach adopted in this work provides a useful framework for understanding the interplay between optical processes and device architecture, and offers practical insights for the design and optimization of high-efficiency $MAPbI_3$-based perovskite solar cells.

REFERENCES

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