1. Introduction

Perovskite photovoltaic solar cells (PPSC) have reached efficiencies comparable to those of the best crystalline silicon (c-Si) devices within only a few years, owing to the tremendous electrical and optical properties of the metal-halide hybrid perovskite materials. For single junction PPSC, the best performance demonstrated so far reaches or even surpasses the short-circuit current density $J_{sc}$ of 25.8 mA cm$^{-2}$, open circuit voltage $V_{oc}$ of 1.179 V, and fill factor FF of 0.846, leading to power conversion efficiency PCE of 25.7%. These achievements are already quite close to the theoretically expected maximum values, especially for $J_{sc}$, which is typically 2783 mA cm$^{-2}$ under AM1.5G illumination, given that the band gap energy in these studies is estimated to be 1.53 eV. Furthermore, tandem PPSC constructed from at least two different perovskite materials appears promising but also more challenging and less mature. In the case of the most common two terminal (2T) configuration, a net performance increase was recently demonstrated compared to single junction PPSC.[6]

As for any optoelectronic device, light management in PPSC is of primary importance in attaining the best performance. As schematized in Figure 1, LM is expected to impact three key performance parameters: i) impinging sunlight can be efficiently collected and then absorbed leading to high $J_{sc}$, ii) $V_{oc}$ can be enhanced as a result of the so-called photon recycling (PR), provided there is strong external luminescence, and the semiconductor exhibits weak non-radiative recombinations, iii) the energy yield (EY) that tends to replace the two previous criteria usually considered under standard test conditions (STC). However, for the latter, requested studies remain complex because they couple illumination models and angular-dependent optical, thermal, and electrical models of the cell for one year.[9,10] Nonetheless, simply considering the incidence angle in the evaluation of absorption and thus $J_{sc}$ is a first step toward EY improvement.

As illustrated in Figure 1, the LM in PPSC results from three interdependent considerations: the photonic engineering (PE) at the wavelength scale, the material choices, and the nanofabrication processes. In practice, the last two directly define the PPSC architecture.

In brief, regardless of the envisaged semiconductor, the LM can invoke several kinds of PE. Most frequently, the LM results in anti-reflection (AR) over the whole absorbed spectral range, leading to a larger $J_{sc}$ as well as possibly larger EY if the AR effect also occurs over a wide angular domain. Moreover, beyond the AR effects, light trapping (LT) mechanisms can be involved at the band edge of the perovskite material, also leading to a larger $J_{sc}$ whereas enhanced PR can enhance $V_{oc}$ because of the absorption suppression just above the band gap under the previously mentioned conditions. This well-established PE is reviewed in more detail in Section 4.2. The LM could even be extended to the infrared domain to possibly limit the parasitic sub-band gap absorption and enhance the thermal radiation, to decrease the operating temperature.[14] Finally, for the specific case of 2T tandem PPSC, the LM is required to ensure concurrent absorption optimization and current matching between the two cells.

In the specific case of metal-halide perovskites, intrinsic properties make these materials particularly relevant for LT, compared to the standard case of c-Si solar cells. First, metal-halide perovskites are direct band gap semiconductors,
whereby the light is more easily absorbed in a submicron thick layer, in which LT and possibly PR can occur at the band edge, as detailed later. Second, their refractive indices are lower than that of c-Si, thus, the AR effect is easier to obtain over the spectral range of interest. Finally, the ability to recycle photons has been shown in the specific case of lead iodide perovskite.[15]

Other key properties of metal-halide perovskites, mainly electrical and aging related, have direct consequences on the typical architecture of the PPSC. The diffusion lengths of the carriers in the perovskites imply that both contacts should be in the vicinity of the photocarrier generation, thereby covering both sides of the cell.[16] In addition, one of these contacts should obviously be transparent to sunlight. The double heterojunction architecture is widespread, leading to the use of additional intermediate layers, namely, the electron/hole transport layers (ETL/HTL). Then, the back metallic contact, ideally made of noble metal, can act as a back mirror. In any case, a careful optical design is required to keep low parasitic absorption in the surrounding layers. Moreover, an effective encapsulation should be added to prevent the perovskite from degradation. Therefore, the perovskite should be carefully selected considering the impact of its optical properties.

Let us finally envisage the wide panel of low-cost elaboration techniques and strategies enabling the structuring of the perovskite thin film at various scales ranging from sub-micron to over-micron. First PPSC mainly relied on a mesoporous architecture, in which the perovskite infiltrated the scaffold. Then, the elaboration techniques of the perovskite in liquid or vapor phases result in better microcrystallization, and thus larger diffusion lengths. Simple planar architectures have therefore replaced mesoporous ones.[17–19] The far larger diffusion lengths enable the current planar PPSC to surpass the performances of the best mesoporous PPSC.

As a result of these significant modifications, LM has evolved such that if the mesoporous architecture has been optimized for efficient LM owing to the scaffold (typically made of TiO₂) to enhance the J_{sc}, most of the planar cells demonstrated in the last few years (see e.g., Supporting Information of ref. [20]) exhibit performances approaching the limit, up to about 90% of the maximum achievable J_{sc}, mostly by considering the AR.

A refined LM can still enable additional improvements in performance toward the limits. For example, reduced optical losses from LT especially at the band edge help gain the last missing mA cm⁻², as detailed in the following. In addition, V_{oc} can be improved with an accurate treatment of the photocarrier recombination mechanisms and the associated rates.

It should be noted that LM has already been widely studied in other thin-film solar cells made of various high refractive index inorganic materials, such as c-Si, GaAs, and Cu(In,Ga) (Se,S₂)[21,22] as well as organic materials[23,24] that have lower indices and diffusion lengths compared to perovskites.

A few review papers discussed various LM techniques for PPSC.[25,26] In this paper, the focus is mainly on PE for corrugated dielectric material, without any additional metallic material inside or in the vicinity of the perovskite material. Indeed, if using metal can induce LT due to plasmonics effect, other phenomena such parasitic absorption can frequently balance this effect.[27]

After a brief presentation of the main PPSC architectures and material choices that impact LM, and summarizing PE, various published structures relying on a wave optics approach are further analyzed. Thus, by unraveling the various mechanisms involved, different proposed strategies are compared to deduce guidelines for further optimization. These guidelines are subsequently illustrated through simulations of the optical properties of a few case studies.

2. Key PPSC Materials and Architectures

The LM in the PPSC directly results from the architecture, that is, a stack of layers of various materials and thus optical indices, each layer having a thickness on the order of a few tenths of wavelengths with possible structuring from small to large scales compared to the wavelength. The main properties of the perovskite materials impacting LM have already been discussed. However, the comparisons may appear difficult and need to be treated carefully because of the discrepancies between the structures investigated, as detailed hereafter.

2.1. Patterning of the PPSC

Let us present an overview of the main patterning processes and examine architectures that have been proposed in the literature. Because of the low diffusion lengths in the first fabricated metal-halide hybrid perovskites, the first PPSC used mesoporous architectures to limit recombination. The infiltration of TiO₂ scaffolds into the perovskite material, enabled a more efficient collection of carriers, and, in certain cases, LM.[28–30] However, as already mentioned in Section 1, most promising approaches nowadays rely on planar architectures.

The layers considered next are almost flat provided their roughness is at a sub-wavelength, nanometer scale, especially in the case of perovskite with good crystallinity. However, a 2D structuring can be introduced into the PPSC stack, notably for single junction PPSC. In this frame, the perovskite layer itself can be one of the patterned layers, or only surrounding layers are structured, and the perovskite can be considered flat.
The various envisaged technical solutions for each of the two strategies are sketched in Figure 2b–e. Patterning of the perovskite layer can be achieved by various approaches. Such a structuring can initially be generated by depositing the active layer on top of patterned layers, for example with ETL/HTL constituting the bottom layer ("bottom–up" like approach, Figure 2b); the pattern can be either random or periodic. Alternatively, the perovskite layer itself can be directly patterned after its deposition ("top–down" like approach, Figure 2c), again either in a random manner or periodic manner.

Another approach is to realize flat perovskite layers and to corrugate other adjacent layers (Figure 2d), such as the encapsulation layer, possibly associated with the metal back contact or only the front contacts, and finally a glass substrate covering layer.

Finally, the front substrate or the back contact layer can be patterned within a broad range of sizes, ranging from hundredths of nanometers to almost a millimeter; then the other layers of the stack are conformally deposited, leading to a fully structured cell (Figure 2e). All envisaged patterns can be either periodic or aperiodic.

2.2. Influence of the Choice of Materials

2.2.1. Perovskite Medium

The choice of the absorbing material for PPSC results from multiple constraints. First, the material should exhibit optimal band gap energy, in the range 1.1–1.4 eV as well as optimal electrical properties and stability. Then, various deposition processes can be envisaged for a given metal halide perovskite, which may lead to various grain sizes of the material during the crystallization process. For sizes on the order of the wavelength, this can affect LM.

Methylammonium lead iodide perovskite material (CH$_3$NH$_3$PbI$_3$, MAPI) has been widely considered in the early stages of PPSC development because of its rather simple chemical composition, despite $E_g$ being slightly above the optimal range. Different $E_g$ have been reported for MAPI typically in the range of 1.55–1.6 eV. This implies more than 7% uncertainty on the maximum achievable $J_{sc}$, which is already on the order of the achievable gain using LM, as discussed later. Thus, the quantitative comparison between different studies is rather delicate, even if the same material is implied with respect to chemical composition. Differences in the aging of the perovskite could also impact the comparison. Finally, various dispersion models can be used to fit the dielectric function, leading to differences that also impact the optical indices that are used for simulations.

For all of these reasons, it has to be emphasized that, only the relative impact of LM can be put into perspective, however, the various performances cannot be accurately compared. Finally, although MAPI can still be used as a typical case study, other materials have been developed in the past few years. These materials are more stable and exhibit a slightly lower $E_g$, primarily because of the substitution of MA by FA (formamidinium, (NH$_2$)$_2$CH), possibly with Cs, as discussed later.

2.2.2. Transport and Contact Layer Materials

For the transport layers, mainly polymer materials are used as well as thin layers of inorganic materials such as TiO$_2$. It is observed that materials such as those based on C$_{60}$ fullerene, acting as ETL, exhibit significant absorption at the shortest wavelengths of the solar spectrum, whereas polymers used as HTL mainly absorb at larger wavelengths, close to and above the band gap of the perovskite. Concerning the electrodes, two distinct optical properties are required. On the side of the glass substrate, transparent conductive oxides are required, with the best possible transparency, whereas the metallic material on the back contact needs to be as reflective as possible. Then, there is
often a compromise to be made between suitable band levels, high electrical conductivity, and barrier to possible migrations, and low parasitic absorption, even if the thicknesses of these transport layers remain limited.

3. Background on Photonic Engineering Mechanisms

Let us now summarize the various kinds of PE, mostly at the wavelength scale, that can be envisaged to improve LM in both single-junction and 2T multi-junction PPSC, along with their impact on geometrical requirements for PPSC. They are sketched in Figure 3. Most of the strategies derived are those already developed for other kinds of direct or even indirect band gap material used in thin film, such as those mentioned in Section 1.

It appears that LM results from various light-structure interaction mechanisms. These mechanisms occur mainly either in the vertical direction (i.e., orthogonal to the stack) or along the directions of the patterns. Depending on the scale of the structure with respect to the wavelength, three main models can be employed: an effective medium at sub-wavelength scales; then, wave optics at the wavelength scale; or geometrical optics at larger scales.

3.1. Photonic Engineering in Multilayer Unpatterned Stack

It is well known that geometrical optics is mainly suitable when the dimensions are far larger than the wavelength. Thus, it cannot accurately describe the interference effects that occur within the thickness of the numerous thin films that compose the cell. In contrast, optical indices of a medium that is textured at subwavelength scales can be homogenized in an approximated way using effective medium theory (EMT), such as the Bruggeman model. Then, descriptions involving wave optics are the most rigorous, and wave optics mechanisms might also be the most promising ones.

Let us first briefly recall the two basic mechanisms used to enhance light harvesting in a flat stack that is, without the assistance of any patterning. When using a rather high index, highly absorbing material, a properly designed stack enables drastic reduction of the impedance mismatch with the surrounding environment, whereas in a finite thickness absorbing layer, especially with low absorption, a Fabry Perot like approach is preferred, leading to highly enhanced but narrow band absorption.

Within a typical PPSC stack, having a metallic contact that can act as a back mirror, these two approaches can be invoked. Schematically, at short wavelengths, the large extinction coefficient of the perovskite enables single pass absorption in the perovskite film, but the AR effect is required. At larger wavelengths close to band gap, where the absorption drops, and multiple passes are required, the second approach is well-suited (Figure 3b).

The exact nature of the layers, and thus their optical indices and thicknesses are restricted by other constraints such as energy band levels, electrical resistance, risk of shunting, or even diffusion barriers for some species. Consequently, parasitic optical absorption has to be carefully studied. Moreover, broadband enhancement of the absorption under normal incidence is unlikely to be obtained using such simple architectures.

3.2. Photonic Engineering in Multilayer, Patterned Stack

In addition to the continuum of propagation waves, light can be confined inside the discrete set of in-plane, transverse guided modes existing in the stack. It is noticeable that the in-plane wave vector of any of these guided modes is larger than those of the free space modes. Thus, these modes cannot be simply coupled from free space to a perfectly flat stack, without any periodic or aperiodic corrugation. Then, the various kinds of in-plane structuring—with dimensions of the wavelength scaled up by two orders—all induce diffraction. Whereas the impinging light lies around the normal incidence and has thus negligible in-plane wave vector \( k_{\parallel} \), the light inside the device

![Figure 3. Main light management strategies. a) For LM without peculiarities, reflectance can be important. b. Using a flat or a patterned structure that can be considered homogeneous (e.g., given the subwavelength dimensions), LM can lead to a rather broadband AR effect as well as to Fabry Perot modes that can enhance the absorption. c) With random textures, scattering, possibly Lambertian, can result in LM, that can also enhance absorption. d) With periodic or strongly correlated patterns, in addition to AR and Fabry Perot effects, some LT can occur, drastically enhancing absorption, especially at the band edge of the perovskite.](image-url)
is diffracted. Indeed, the electromagnetic field can be expanded over a set of plane waves thanks to the in-plane spatial frequencies induced in the medium by the structuring. The reflected waves also experience diffraction accordingly. Considering various kinds of structuring and the resulting spatial frequencies, three main cases can be envisaged:

i) A random structuring tends to induce isotropic diffraction, that is, Lambertian scattering. This scattering does not depend on the wavelength within the absorbed spectral range, and it can typically lead to broadband AR effect (Figure 3c); however, the absorption enhancement remains limited. Indeed, given the already large absorption (except at the band edge) of the perovskite, and the back reflection induced by the metallic contact, the absorption enhancement can be at most on the order of 4π² with an index lower than other materials, in particular inorganic ones.

ii) A correlated disordered structuring that enhances a specific set of spatial frequencies, leads to a spectrally dependent absorption enhancement. A careful choice of the sizes of the patterns is required to enhance the absorption in the desired spectral range.

iii) A particular case among the previous cases discussed, is the periodic, so-called photonic crystal (PC) structuring. Most structures consist of a square or triangular lattice with simple patterns, such as pillars or holes with a vertical profile, smoother pyramidal, or even parabolic profiles. These mainly lead to discrete modal properties. A few complex patterns with periodic arrangement have been explored, with the larger local density of modes enabling an absorption enhancement in a targeted spectral range.

In any case, the diffraction efficiency, which is the amount of light that is effectively diffracted, and thus intended to be absorbed, strongly depends on the pattern of the structuring, including the optical index contrast as well as the diffraction order p. Whereas, when using scattering, the diffraction efficiency hardly depends on the direction, when using periodic structures, the diffraction is generally larger for the first diffraction order.

It is observed that a strong LT phenomenon occurs when the impinging light is coupled because of strongly correlated structure, or, more conveniently, periodic patterns, having respectively a correlation length, or a period Λ, within at least one guided mode of the stack (Figure 3d). According to a perturbation approach, without loss of generality, the phase matching condition for the 1D case, can be expressed as,

\[ β_m = k_{\text{eff}} + p \frac{2π}{Λ} \]  

where \( β_m \) is the in-plane wave number of the \( m^{th} \) guided mode of the stack. As a result of time reversal symmetry, the light coupled in the guided mode, if not fully absorbed, can be decoupled after a certain length. These modes are the so-called “quasi-guided mode” (QGM).

Such modes can drastically enhance the light path inside the waveguide layer. Thus, if the in-coupled QGM is mainly confined to the perovskite layer rather than the surrounding layers, the useful absorption is enhanced. More precisely, the absorption is optimized at critical coupling, that is, when an equilibrium is reached between diffraction efficiency and absorption. Consequently, the spectral bandwidth of the LT is set since the quality factor of the mode at the optimal absorption is on the order of \( n/2k \), \( n, k \), respectively for the real and imaginary parts of the complex optical index.

Such a resonant LT appears promising in enhancing the low absorption close to the band gap of the perovskite, provided it is not reduced elsewhere at shorter wavelengths. More precisely, within the width of the resonance, the absorption can be significantly larger than the previously mentioned broadband limit. Resonant LT could also be used in tandem PPSC mainly to optimize the \( J_{\text{oc}} \), provided LT occurs in a guided mode specifically confined to one of the perovskite layers. As already discussed, for the other spatial frequencies that do not lead to LT, patterning can still result in a rather broadband AR effect, in addition to the effect resulting from the design of the stack.

Further analysis of all these effects can be found elsewhere.

In addition to the first order contributions of these PE approaches in enhancing the absorption and hence \( J_{\text{oc}} \), other strategies can be used to enhance \( V_{\text{oc}} \), using a PR mechanism. To simplify, PR is supposed to induce at the \( V_{\text{oc}} \) operating point a high density of photons into the absorbing materials, giving a chance to electron–hole pairs to recombine radiatively rather than non-radiatively. Typically, this requires at first order the inhibition of the radiation, and consequently of the absorption, in the luminescence spectral domain of the semiconductor. Thus, enhancing simultaneously the \( J_{\text{oc}} \) using LT and the \( V_{\text{oc}} \) using PR is a compromise.

In any case, it has to be emphasized that all these effects should ideally target only the perovskite layer only and not enhance the parasitic absorption in other layers. To achieve, simulations of the absorption in each layer can be made using electromagnetic methods such as widespread FDTD or RCWA methods, to take into account detailed chromatic dispersion properties of each of the corresponding material.

### 3.3. Main Geometrical Requirements on Patterns for Light Trapping

As mentioned previously, 2D in-plane structuring is able to diffract the impinging sunlight under quasi-normal incidence into the numerous modes of PPSC, possibly including the guided modes. Indeed, the architectures of both single and multi-junction PPSC reviewed in the Section 2.1 can be schematized as one or several sub-micron thick high index perovskite layers lying between two lower indices ETL and HTL and possibly also lower index layers in the multi-junction case. All these layers lie on a TCO layer, having an index also lower than the one of perovskite, and are then covering a low index glass substrate. Finally, this stack is coated with a metal on top. Such structures exhibit several guided modes in both TE and TM polarization states. Let us first make the assumption of weak corrugation that does not change significantly the effective indices of the stack of active layers on the substrate. The largest effective index modes—typically 2.2—are mainly confined in the perovskite, whereas the other modes, with effective indices below 1.9, are confined to the entire stack of layers. In this frame, for normal
incident light ($k_{\text{inf}} = 0$) and for the highest efficient coupling at order $p = 1$, Equation (I) can be rewritten in the form

$$\beta_m = \frac{2\pi N_{\text{eff},m}}{\lambda} = \frac{2\pi}{\Lambda}$$

(2)

where $\Lambda$ is the period, or the characteristic length in correlated patterns. This 1D case can easily be extended to 2D patterns.

Thus, to be able to efficiently couple into the fundamental guided mode, which is mainly confined to the perovskite, at wavelengths corresponding to the band edge, for example, 750 nm, $\Lambda$ should be around 340 nm, whereas they are larger than 400 nm for higher order guided modes. This results in a QGM, as discussed at the end of Section 3.2. At shorter wavelengths, such structuring can also couple light into the various low effective index modes (including Fabry Perot like modes) of the stack that may also result in a broadband AR effect. This typically implies that at the micron scale or even larger patterns in any of the layers of the stack, it is rather unlikely that there will be coupling of the impinging light into guided modes in the low absorption domain, where such a coupling is of fundamental interest. Such patterns only induce coupling into the Fabry Perot like modes of the stack and/or diffraction at high orders with limited efficiency.

4. Reported Light Management Strategies in PPSC, Analysis of Selected Results

Some studies are reported here to illustrate concrete LM strategies. The chosen perovskite material and its thickness are of primary importance. First of all, planar PPSC as envisaged in Section 2.1 for the architecture and in Section 3.1 for the corresponding PE are discussed, attesting to the importance of the thicknesses on LM. Then, results on in-plane patterned PPSC are reviewed, with focus on the PE involved.

4.1. Impact of the Perovskite Thickness in Planar PPSC

Most studies related to thickness optimization only focus on the perovskite layer, and report mainly on the usefulness of the absorption derived, as detailed below. However, the entire stack has been considered in a few papers, to investigate parasitic absorption, as discussed later.

### Table 1. Experimental performances of planar PPSC with optimized perovskite thickness (nr: not reported).

| Material       | Thickness [nm] | $J_{sc}$ [mA cm$^{-2}$] | $V_{oc}$ [V] | FF  | PCE [%] | Ref   |
|----------------|----------------|--------------------------|--------------|-----|---------|-------|
| MAPICl         | 330            | 21.5                     | 1.07         | 0.67| 15.4    | [17]  |
| MAPI           | 300            | 20.4                     | 1.03         | 0.749| 15.7    | [18]  |
| MAPI           | 285            | 18.8                     | 1.07         | 0.63| 12.7    | [84]  |
| MAPI (solution process) | 330 | 17         | 0.94         | 0.62| 11.8    | [85]  |
| MAPI           | 303            | 21.3                     | 1.07         | 0.715| 18.4    | [86]  |
| FAMAPBrI       | 480            | 24                       | 1.14         | 0.75| 20.8    | [87]  |
| FAPI           | 600            | 26.35                    | 1.189        | 0.817| 25.59   | [5]   |
| MAPI           | 492            | 21.56                    | nr           | nr  | nr      | [88]  |
| MAPI           | 350            | 21.9                     | 1.05         | 0.72| 16.5    | [89]  |

As already mentioned, the optimal thickness of the sole perovskite layer is selected as a compromise between maximizing optical absorption and keeping low bulk recombination of the carriers. In addition to the analysis of a few seminal cases of single junction PPSC, a synthesis of several studies, mainly experimental, is presented to report on the effect of the perovskite layer thickness of planar single junction PPSC made of MAPI; then other lead-halide perovskites are also considered. The detailed performances of the representative cells are summarized in Table 1, and when available, the external quantum efficiency (EQE) is plotted as in Figure 4 in a spectral range limited from 400 to 800 nm to simplify the comparison.

**MAPI**: One of the first high efficiency planar PPSC,[17] made out of about 300 nm thick MAPICl layer, exhibited a $J_{sc}$ of 21.5 mA cm$^{-2}$. In this seminal paper, M. Liu et al. already mentioned the possibility of an optimum thickness to balance absorption and recombination. It was shown later by Y. Da et al.[83] that this cell suffered from optical losses corresponding to 11.3% of the energy losses, while realizing more than 20% of the achievable $J_{sc}$. This was mainly related to reflectance and parasitic absorption of fluorine-doped tin oxide (FTO). This thus emphasizes the importance of minimizing these effects by a careful design of the stack.

Then, the first high-efficiency PPSC solution processed at room temperature, proposed by D. Liu et al.[80] consisted of an about 300 nm thick MAPI layer, generating a $J_{sc}$ of 20.4 mA cm$^{-2}$, which is about 5 mA cm$^{-2}$ below the maximum achievable $J_{sc}$ given a typical $E_g$ of MAPI. The EQE (Figure 4) was rather flat and remained lower than 0.8. This deficit could be resulting from both optical losses (too low absorption in the perovskite) and electrical losses (too high recombination).

Momblona et al.[84] conducted an experimental study on PPSC made of MAPI deposited by thermal evaporation, increasing the thickness from 160 to 900 nm. If the $J_{sc}$ increased rather monotonously with the perovskite layer thickness, it would never exceed 20.4 mA cm$^{-2}$. The main parameter that decreased with increasing perovskite layer thickness was the filling factor. As a result, the cell exhibiting optimal performance was obtained for a perovskite layer with thickness around 300 nm. More precisely, whereas the $J_{sc}$ slightly increased, both the $V_{oc}$ and the FF significantly
Figure 4. EQE of the various PPSC reported in Table 1.\textsuperscript{[5,18,84–89]}

decreased at thicknesses larger than 300 nm. At these early ages of PPSC, the corresponding optimal PCE was 12.7%, with a $J_{sc}$ of 18.8 mA cm$^{-2}$. Then, further investigations on the $J_{sc}$ deficit using the EQE (Figure 4) revealed that optical losses for $≈$300 nm thick perovskite were important at both short wavelengths and from 600 to 700 nm, compared to the 900 nm thick fully absorbent perovskite layer. The enhanced absorption in the range of 700–750 nm is likely to be a cavity effect. Thus, even if a thickness of about 300 nm appears to be optimal from the in terms of PCE, it is too thin to prevent optical losses. In addition, even with such thin absorbing layers, the cells still suffer from electrical losses.

In a similar way, D. Liu et al.\textsuperscript{[85]} also studied PPSC consisting of a ITO/ZnO/MAPI/P3HT/Ag stack, in which MAPI was obtained using thermal evaporation or solution processing. Again, despite the larger absorption and limited short-circuit observed for thicker films, the limited diffusion length led to an optimum thickness layer of about 330 nm for the MAPI layer of the solution processed PPSC. It is observed that the corresponding EQE (Figure 4) is rather low and flat. This could be related to the scattering due to sub-micron crystallinity that mitigates cavity effects at larger wavelengths.

More recently, Y. Liu et al.\textsuperscript{[86]} still using MAPI, similarly concluded that there are more power losses in PPSC when the thickness of the MAPI layer is either less or more than about 300 nm. They noticed that the grain size increased with thickness, favoring larger thickness. It was also observed that, at wavelengths larger than 650 nm, the EQE of the 303 nm thick MAPI PPSC (Figure 4) was lower than the one for the 564 nm thick MAPI PPSC. This is related to the significantly low absorption in this spectral range.

Other Lead-Halide Perovskites: As an alternative, Correa-Baena et al.\textsuperscript{[85]} used multi-cation perovskite materials; these were recently in the spotlight, especially considering their higher stability.\textsuperscript{[86]} Using FA$_0.83$ MA$_0.17$ Pb(I$_0.83$ Br$_0.17$)$_3$, together with mesoporous TiO$_2$, the thickness that maximizes the PCE was found to be at least 480 nm. The corresponding $J_{sc}$ was $≈$24.4 mA cm$^{-2}$. Considering the band gap of this material, reported to be about 1.63 eV,\textsuperscript{[89]} this is already the maximum achievable value. The EQE (Figure 4) is noticeably high (owing to an IQE of almost 100%) and flat at large wavelengths. This could be related to the mesoporous TiO$_2$ that induces some scattering effect.

Unlike previous papers, Rai et al.\textsuperscript{[92]} focused on the $V_{oc}$ deficit related to non-radiative recombination as a function of thickness, expressed in terms of molar concentration of the precursor solution. This time, the studied perovskite was Cs$_8$FA$_0.1$Pb(I$_{0.85}$ Br$_{0.15}$)$_3$, with a band gap of 1.62 eV, so close to the band gap of MAPI. They also noticed that $V_{oc}$ decreases with thickness, whereas the $J_{sc}$ increases. As for the previously mentioned paper, the grain size increased with thickness; the molar concentration of the precursor solution that maximizes PCE corresponded to a thickness of about 400 nm of the perovskite layer, 30% larger than the one usually obtained using MAPI. This may be attributed to a larger diffusion length of the photocarriers for this perovskite.

Nine et al.\textsuperscript{[93]} simulated the effect of the thickness of several FACsPbI$_2$ layers optically and electrically, leading to a larger optimal thickness of approximately 600 nm, twice the thickness usually obtained using MAPI. Indeed, better electrical properties of this perovskite material, especially carrier mobility, allow such a thicker layer.

Synthesis: It is observed that these studies tend to an optimal thickness of about 300 nm when using MAPI. This thickness could lead to the state-of-the-art PCE of Li et al.\textsuperscript{[94]} with a noticeably high $J_{sc}$ of 24.1 mA cm$^{-2}$, mainly because of the ETL including graphdiyne, which improves electrical properties. Then, the ETL is the perovskite used for the best up-to-date single junction PPSC\textsuperscript{[95]} the performance of which was mentioned in the introduction. In this case, the perovskite thickness is of about 600 nm, and, among numerous refinements of the architecture, the $≈$50 nm thick TiO$_2$ layer may help trap the light.

It appears that choosing a thickness smaller than the one maximizing the $J_{sc}$ would help keep the resistance low while FF and PCE high. Then, with such a $J_{sc}$ of $≈$90% of the maximum achievable $J_{sc}$, LM can optimize the absorption in the perovskite, especially at photon energies close to the band gap, where the absorption starts to decrease.

Understanding the reasons for obtaining large variations of the internal perovskite absorption spectrum for similar
thicknesses of the same perovskite material (MAPI) is of great interest, for example, for cases 2 to 5 of Table 1 and the corresponding EQE plots in Figure 4. The variations may be due to differences in the surrounding layers (thicknesses, indices) or the perovskite itself, like microcrystallinity that can induce scattering. These phenomena are described next, starting with the analysis of the effect of the layers surrounding the perovskite, still in an unpatterned stack.

4.1.2. Detailed Analysis of Planar Single Junction PPSC

If there is an optimal thickness for the perovskite layer, the effect of the other layers, especially on the absorption and reflectance, should also be analyzed. Here, a selected set of publications focusing on this issue is reviewed.

Ball et al. studied planar PPSC using an optical model based on the transfer-matrix formalism with experimentally determined complex refractive index data. They focused on a typical stack made of FTO/TiO₂/MAPI/Spiro-OMeTAD/Au. Under the assumption of Eq. 1.56 eV, the detailed analysis revealed that for a calculated J<sub>sc</sub> of 21.56 mA cm<sup>-2</sup>, parasitic absorption induces a decrease of about 1.72 mA cm<sup>-2</sup>, and reflection losses corresponding to J<sub>sc</sub> decrease by 1.36 mA cm<sup>-2</sup>, leading to a total loss of more than 10% of the collected current. On the other hand, the IQE losses can be estimated by another 10%. Moreover, most of the optical losses take place in the 420 nm thick FTO. This underlines the importance of taking care of all the layers of the stack.

Lin et al. investigated the properties of PPSC made of MAPI in detail. After measuring the optical indices of MAPI and the other materials, they simulated the properties of PPSC, assuming an IQE of 100%. They identified the two absorption regimes of a flat PPSC, previously discussed in Section 3.1, namely the single pass and the cavity regime. Thus, the optical cavity effects at wavelengths larger than 500 nm, leading to the losses are related to reflectance (equivalent to 4.2 mA cm<sup>-2</sup>), whereas the parasitic absorption remains limited to half despite a subwavelength roughness (typically from 10 to 50 nm RMS) at both ITO/TiO₂ and MAPI/Spiro-OMeTAD interfaces.

4.1.3. Analysis of Unpatterned, High Efficiency, All Perovskite 2T tandem PPSC

Compared to other tandem architectures, the 2T case leads to possibly limited optical losses, but such cells require an equilibrium of the current densities delivered by the two subcells. Among recent results and investigations, Xiao et al. investigated in detail the 2T tandem PPSC (Figure 6a) both numerically and experimentally. Using optical simulations, they demonstrated that the attainable J<sub>sc</sub> is indeed the smallest J<sub>sc</sub> delivered by each of the subcells, strongly depends on the thickness of each perovskite layer (Figure 6b), provided that the thicknesses of the other layers are set considering both electrical and optical properties (low parasitic absorption).

Indeed, it appears that the top perovskite has to be thick enough to absorb enough light, but that a too thick layer also absorbs too much light, and finally that the overall J<sub>sc</sub> is limited by the bottom sub cell. The thickness of the perovskite bottom sub cell has to be large enough, that is, more than 1.1 μm. When fabricated on a small surface, such a cell exhibits even a slightly lower J<sub>sc</sub> than simulated, likely due to the too pessimistically predicted absorption. Even if this result remains a record for the time of its publication, its EQE (Figure 6c) reveals some non-ideal characteristics. Indeed, in addition to the relatively
low values of the EQE plateaus, there is an overlap of the absorption domains of the two perovskite materials between 500 and 700 nm, indicating that some undesirable thermalization still occurs below 700 nm in the bottom sub cell.

4.2. In-Plane Structuring in Single Junction PPSC Impacting Short Circuit Current Density

At this stage, it appears that even the best reported cells exhibit an EQE that can still be improved using a PE at the wavelength scale, even if most cells already benefit from the roughness of the microcrystalline perovskite.

In this section, the important criteria that should be met are highlighted to ensure a fair demonstration of LM. The report on selected studies is organized as a function of the various architectures as envisaged in Section 2.1.

4.2.1. General Criteria for Fair LM Demonstration

The impact of LM on the performance of a solar cell can be demonstrated by comparing a patterned device with an unpatterned reference. In case of superficial structuring or with the addition of specific LM layers, the absorption improvement is generally obvious compared to the same unpatterned stack, or, even more favorable, unpatterned stack without the additional flat LM layer. Moreover, integrating the LM layer could lead to a better charge collection, by decreasing the carrier path; the specific LM effect would then be difficult to distinguish. Therefore, great care should be taken in defining a reference structure or device. In particular, the volume of perovskite materials should be as close as possible in both structures. In addition, the net enhancement of EQE, efficiency, or even yield value can be accurately estimated provided the unpatterned reference has been optimized first. These conditions should be met in order to discuss LM for PPSC performance optimization.

4.2.2. Periodic Patterning for Resonant LT

Superficial Structuring and Light Management Layers: Peer et al. simulated planar PPSC with a stack including a 400 nm thick MAPI layer. The cell lay on top of a 700 µm thick glass substrate. A microlens array was then added on the top face of the glass substrate, by imprinting a polymer such as polystyrene (Figure 7a). Each micro lens of the triangular lattice had a smooth profile close to the truncated pyramids. For an aspect ratio period/height close to 1 of the microlenses, and a period of 700 nm, an optimized gain of 6.3% of the $J_{sc}$ was reported compared to the flat reference, with the EQE displaying noticeable dips likely due to cavity effects in the cell (Figure 7b). Then, according to the EQE of the cell coupled to the microlens array, the overall resulting broadband enhancement of the absorption at lower wavelength is attributed to the AR effect and LT at the band edge. The optimal period of the pattern is rather large, in agreement with a low effective index of the coupled QGM. This means that LT occurs in this QGM that is hardly guided in the perovskite, but that has a non-negligible overlap with the pattern. This overlap remains limited, as revealed by the high quality factor of the resonance. Therefore, the absorption reaches almost 1, which is very close to critical coupling conditions.

Wei et al. fabricated bioinspired back electrodes by imprinting the HTL made of PCBM before the conformal deposition of the Bphen/Ag back contact. The patterns were either a periodic sinusoidal 1D grating or a uniform 2D moth-eye structure (Figure 8a), with a typical pitch of about 600 nm. It was then experimentally shown (Figure 8b) that the EQE of the 240 nm thick MAPICl PPSC increased by 10% up to 40% at the band edge, mainly because of the 2D moth eye pattern. The overall $J_{sc}$ increased by 14.3%, mainly due to absorption increase, but a lower series resistance was also measured for patterned cells, which led to a slight increase of the IQE. As shown by the FDTD simulations of periodic structures, this is because of light diffraction into the guided modes, rather than plasmonic effects. It can be confirmed by Fourier analysis of the top view of the moth eye pattern that a significant part of the...
spatial frequencies lie in the optimal range for LT (Figure S1, Supporting Information).

Kim et al.\cite{44} simulated nanosphere arrays of TiO$_2$ conformally coated with silica on a standard MAPI PPSC stack, with a MAPI thickness limited to 100 nm. Provided suitable spacing and nanosphere diameter, the $J_{sc}$ could jump from 14 to 18.7 mA cm$^{-2}$. Authors invoked the Mie scattering effect of the array to explain the enhancement, but it appears that the FEM simulation has likely been done using periodic boundary conditions, and thus the LT effect occurs at several wavelengths, such as 705 or 790 nm for those at the band edge of MAPI. This is in line with the larger EQE enhancement close to the band edge, as can be seen in Figure 9. Anyhow the overall $J_{sc}$ is limited due to the unusually low thickness.

**Figure 7.** PPSC with microlens array on air-glass side. a) Schematic of the PPSC. b) Simulated absorption spectrum for microlens array of period 700 nm and height 800 nm. The absorption of flat solar cell is overlaid for comparison. Reproduced with permission.\cite{55} Copyright 2017, Optical Society of America.

**Figure 8.** PPSC with bio inspired PCBM HTL. a) SEM (left) and AFM (right) images of the spin-coated layer (top) of grating patterned layer (middle) and moth-eye patterned layer (bottom). b) External quantum efficiency, EQE, spectra of PPSC, and relative enhancement obtained by dividing the spectra of grating and moth-eye patterned devices by that of flat one. Reproduced with permission.\cite{48} Copyright 2017, Wiley.
Structuring of the Perovskite: Schmager et al.\textsuperscript{[40]} simulated a classical MAPI PPSC (Figure 10a). Compared to the planar configuration, square lattice of holes etched in the MAPI layer, with various etching depths, and filled with Spiro-OMeTAD, were envisaged. To avoid any short circuit, an optimized partial etching of 120 nm led to a 5.6% increase of $J_{sc}$, compared to the initially flat 300 nm thick MAPI layer with an equivalent volume of perovskite. This results in a LT at the band edge, but without any sharp resonance, as observed on the spectral response of other patterns (Figure 10b).

The same group\textsuperscript{[41]} also realized nanoimprinted PPSC made of Cs$_{0.1}$(FA$_{0.83}$MA$_{0.17}$)$_{0.9}$Pb(I$_{0.83}$Br$_{0.17}$)$_3$. Their experimental results show a relative improvement of 2% of the PCE compared to the planar reference for the complete, gold coated solar cell. This was obtained from an increase of $J_{sc}$ from 19.1 to 19.4 mA cm$^{-2}$ with noticeably identical $V_{oc}$ and FF (Figure 11b). The EQE of the patterned cell was improved at wavelengths larger than 680 nm. A coupling to a quasi-guided mode is observed in the perovskite band edge (Figure 11), leading to a significant EQE enhancement (Figure 12).

Textured Substrate: Du et al.\textsuperscript{[59]} simulated a strongly corrugated MAPI layer by cones realized in ITO coated glass substrate with an intermediate conformal PEDOT layer lying on ITO (Figure 13a). With optimized period and radius, a 15–17% improvement was expected in the PCE compared to the best flat cells of equivalent volume (Figure 13b). The optimal period of about 400 nm is in agreement with the required period inducing LT into the guided modes, given the fact that the effective index of the modes is lower than those in our examples because of strong corrugation of MAPI filled with low index material. AR and resonant light trapping are thus simultaneously obtained.

4.2.3. Periodic Structures for Non Resonant LM: Anti-Reflection and Scattering

Superficial Structuring and Light Management Layers: Hossain et al.\textsuperscript{[50]} proposed to coat the MAPBI like perovskite, having a thickness from 100 to 400 nm, with zinc oxide. More precisely, first a thick, lightly doped ZnO ensured the top

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**Figure 9.** EQE of the patterned PPSC (solid line) and of the planar references (dashed line) (left) and EQE enhancement (right) of reported simulated $J_{sc}$ enhancements of Table 2, mainly resulting from light management, for MAPI single junction PPSC, for any in-plane pattern (additional layers, structuring of the perovskite or conformal perovskite) and identified photonic concept.\textsuperscript{[40,44,46,48,50,55,59]}

**Figure 10.** Various 2D in plane patterns of the MAPI layer in a PPSC. a) Layer stack of the simulated patterned PPSC along with associated layer thicknesses. Three configurations of the active layer are simulated: 1) a planar reference; 2) a cylindrical indentation into the perovskite layer of variable depth; and 3) a hole geometry which corresponds to the maximum cylindrical indentation. b) Absorption in the perovskite layer of the hole pattern and the 120 nm deep indentation compared to the corresponding planar reference and the theoretical Yablonovitch limit for two different initial perovskite layer thicknesses of (left) 200 nm and (middle) 300 nm; $J_{sc}$ for all data are compared (right). The displayed nanophotonic patterns employ a geometrical $ff = 0.4$ and a period of 380 nm. Reproduced with permission.\textsuperscript{[40]} Copyright 2019, Elsevier.
contact, which could then be covered by patterned textures in the form of pyramids or non-resonant metasurfaces. The period was set to 800 nm. According to the mechanism typically occurring using such a period, no sharp resonances enhanced the absorption at the band-edge; only an AR like effect occurred. Both kinds of patterns lead to simulated equivalent $J_{sc}$ enhancements of about 3 mA cm$^{-2}$ irrespective of the thickness of the perovskite between 100 and 400 nm, resulting in a relative enhancement roughly from 25% to 12% within the same range, but only 10% for the thickness of 300 nm. 

Tockhorn et al. [51] simulated and fabricated a 550 nm thick PPSC made of a mixed cation, mixed halide Cs$_{0.05}$(FA$_{0.83}$MA$_{0.17}$)$_{0.95}$Pb(I$_{0.83}$Br$_{0.17}$) perovskite material on various periodically patterned glass substrates, in p–i–n configuration. The top side of the glass substrates was coated with low index, NaF thin film. Compared to the planar reference, patterned structures could exhibit a $J_{sc}$ of up to 1 mA cm$^{-2}$ larger. This results from a broadband enhancement of the EQE, including at the band edge, mainly attributed to the AR effect, as verified by simulations where the volume of perovskite was kept constant. This is in line with the flat EQE enhancement, as observed in Figure 12. The resulting PCE reaches 19.7%, which is 1% above that of the planar reference.

**Structuring of the Perovskite:** Paetzold et al. [34] proposed to pattern the ITO front electrode with a square lattice of pillars. The ETL was then corrugated along with the ≈320 nm thick MAPICl layer that planarized the stack prior to the HTL and back contact deposition Al. They observed increased absorption and EQE as the lattice period decreased, up to the smallest value envisaged, that is 500 nm. This led to an increase of the $J_{sc}$ by 5%. Broadband enhancements were observed, at wavelengths shorter than the band edge of the material as well as a limited LT at the band edge in line with the EQE enhancement plotted in Figure 12. This is likely due to the lack of large enough spatial frequencies to couple the quasi-guided modes of the structure, given a period slightly above the optimal range. In addition, there might be a slight change in the volume of perovskite between the patterned cells compared to the flat reference.

**Textured Substrate:** Qarony et al. [46] calculated the EQE for three different configurations of PPSC using the same volume of perovskite and including moth eye periodical patterns with a period of about 150 nm, typically leading to scattering. The first one only had a pattern at the top air/ZnO interface (thus is

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**Figure 11.** a) External quantum efficiency and reflectance spectra of the planar and nanoimprinted perovskite solar cells. The nanoimprinted perovskite layer has a period of 480 nm. The nanoimprinted perovskite solar cell displays enhanced absorption and current generation close to the band gap. b) The current density-voltage characteristics of these both cells demonstrate an increase of the $J_{sc}$ for the nanoimprinted cell. Reproduced with permission.[41] Copyright 2019, Elsevier.

**Figure 12.** EQE of the patterned PPSC (solid line) and of the planar references (dashed line) (left) with EQE enhancement ((right) of Table 3, mainly resulting from light management, for single junction PPSC, for any kind of in-plane pattern (additional layers, structuring of the perovskite or conformal perovskite) regardless of the main identified photonic concept.[32,34,41,49,51,53,54]
more comparable to the former structures), but the two others considered a conformally patterned stack, either on a patterned Al substrate, or on a patterned NiO/ITO layer. The patterned Al substrate clearly led to a lower EQE as a result of additional parasitic absorption. Moreover, a slightly lower $J_{sc}$ was obtained with the conformal stack on the flat Al substrate compared to the top patterned stack. Even this last case exhibits a low EQE enhancement (Figure 12).

4.2.4. Aperiodic Patterning for LM

**Superficial Structuring and Light Management Layers:** Dudem et al. proposed a multifunctional inverted micro-structured pyramidal polydimethylsiloxane (PDMS) AR layer to enhance the device efficiency, through AR and self cleaning. The MAPI layer was 340 nm thick. The sizes of the pyramid were in the range of 1 to 10 μm, which is too large for efficient diffraction. Compared to flat PDMS, the $J_{sc}$ increases by 0.30 mA cm$^{-2}$ up to 21.25 mA cm$^{-2}$, corresponding to a limited AR effect, as confirmed by the flat EQE enhancement (Figure 12).

Jošt et al. similarly fabricated a so-called light management foil on the glass substrate of a planar 270 nm thick MAPI cell, which led to a limited EQE enhancement (Figure 12). At first, the thick glass substrate prevents a strong overlap between any guided mode into the perovskite and the foil. Moreover, regardless of the glass thickness, the lack of LT is also related to the far too low spatial frequencies resulting from the texturing. Indeed, on the available top view of the foil, a Fourier transform analysis reveals (Figure S2, Supporting Information) that most of the Fourier components lie below 7 μm$^{-1}$, whereas the optimum $\beta_s$ should be in the range of 18–34 μm$^{-1}$ for the first order of diffraction, and even larger for the other orders.

On the other side of the stack, Zhang et al. measured and modeled the impact of the roughness of the back mirror on the back scattering of MAPICI PPSC. The reference was made of a perovskite layer with a significant roughness after crystallization, coated with a thick Spiro-OMeTAD layer that planarizes, followed by a flat gold mirror. With a thinner HTL, the gold mirror replicated the roughness of the perovskite layer leading to back scattering of the light. The PCE increased from 19.3% to 19.8%, mainly as a result of the increase in $J_{sc}$ from 22.7 to 23.6 mA cm$^{-2}$. It is observed that the EQE enhancement obtained is the largest at the band edge. This could be related to the grain size that appears to be in the range of 200–500 nm, which includes the optimal range for efficient LT.

**Structuring of the Perovskite:** Pascoe et al. proposed textured MAPI at the scale of several hundreds of nanometers as a consequence of gas crystallization. The EQE was enhanced at wavelengths larger than 550 nm (Figure 12), because of the induced scattering. Accordingly, the averaged $J_{sc}$ increased from 21.3 mA cm$^{-2}$ for planar references with about 300 nm MAPI layer thickness to 22.1 mA cm$^{-2}$ for patterned samples of comparable volume. As previously mentioned, the noticeably large EQE enhancement close to the band edge can be related to the typical grain size of the order of 500 nm.

4.2.5. Synthesis on In-Plane Structuring in Single Junction PPSC

**Impacting Short Circuit Current Density**

In the previously described studies reporting on $J_{sc}$ enhancements attributed to LM, it can be noticed that most of the possible architectures envisaged in Section 2.1 have been considered, using all the PE described in Section 3. Tables 2 and 3 summarize the $J_{sc}$ enhancements reported in the previously described studies.

Table 2 focuses on the simulations of periodic patterning of MAPI-based single junction PPSC. It is observed that LT can indeed significantly increase the $J_{sc}$ for very thin perovskite layers. The enhancement is more limited at a thickness of about 300 nm. An accurate comparison of the $J_{sc}$ enhancements is still not possible since performance enhancement strongly depends on the choice of the unpatterned reference.
and specifically its optimization in terms of LM, as discussed previously. However, the EQE enhancements (Figure 9) can clearly reach larger values with LT than for AR.

In Table 3, focusing on experimental results, for various perovskite materials, the $J_{sc}$ enhancements are of the same order as the simulated ones, with the same aforementioned precautions. As for the simulated PPSC, the EQE enhancements (Figure 12) also reach larger values using patterns matching the scale of the wavelength in the material. Moreover, the periodic case\cite{41} leads to the largest enhancement. Then, the patterns are obtained with direct nanoimprinting of the perovskite layer, which is a scalable, low cost technique.\cite{99} It is also observed that the random wavelength scale patterns, resulting from the perovskite layer processing either within the entire thickness\cite{32} or in a more superficial way,\cite{49} appear promising.

### 4.3. LM for PR

LM for $V_{oc}$ enhancement attributed to PR in PPSC is discussed in a limited number of publications.\cite{100}

Nanz et al.\cite{101} investigated, mainly theoretically, the effect of various kinds of LM strategies on PR, for multilayer stacks that are part of PPSC, primarily without HTL and metallic contact. They were thus able to derive an upper limit $\Delta V_{oc}$ for each case, under the assumption of pure radiative recombination. According to the summarized principle reminded previously, the $\Delta V_{oc}$ resulting from PR in a patterned multilayer was in between the values obtained with the Lambertian multilayer and the rigorously planar multilayer. Indeed, the Lambertian multilayer, including a better absorber, also radiates luminescence, whereas, for targeted thicknesses, luminescence can be partly guided, leading to recycling. Then, the quasi-guided mode of the patterned multilayer leads to enhanced PR compared to the Lambertian multilayer, and also an enhanced $J_{sc}$ compared to the flat multilayer. However, Bowman et al.\cite{102} showed that using a more realistic model including recombination, PR was rather unlikely to occur at maximum peak power even if the cell only interacts with a limited solid angle. In this context, increasing the absorption and thus the extraction appears to be more promising to the detriment of recycling.

### 5. Simulations and Perspective

As shown in the previous section, a limited number of studies, mainly focused on $J_{sc}$ enhancements, demonstrate a LM effect in PPSC. This synthesis also illustrates that due to a lack of common references, different kinds of PE can hardly be compared to determine the most promising architectures for AR and light trapping. Therefore, in this study, some of the promising patterns are simulated to compare the performances using typical materials and architecture of a PPSC.

#### 5.1. Methodology

The rigorous coupled wave analysis\cite{103} is appropriate for the simulation of periodically patterned stacks under plane wave illumination. The $S^4$ code\cite{104} available in the Solcore package\cite{105} was used. The derived $J_{sc}$ are obtained using AM1.5G spectrum\cite{106} with an IQE of 1.

### Table 2. Reported simulated $J_{sc}$ enhancements mainly resulting from light management for MAPI single junction PPSC, with any kind of in-plane pattern (additional layers, structuring of the perovskite or conformal perovskite) and the main identified PE.

| Material | Perovskite thickness [nm] | $J_{sc}$ enhancement [%] | Pattern type | Photonic concept | Ref |
|----------|---------------------------|--------------------------|--------------|-----------------|-----|
| MAPI     | 400                       | 6.3                      | periodic add. patterned layer | Broadband AR and LT | [55] |
| CsFAMAPB | 120                       | 31.7                     | periodic add. patterned layer | Broadband AR and LT | [44] |
| CsFAMAPBI| 300                       | 5.6                      | periodic add. patterned layer | Broadband AR and LT | [40] |
| MAPI     | 180                       | 17                       | periodic conformal perovskite | Broadband AR and LT | [59] |
| CsFAMAPB | 300                       | 10                       | periodic add. patterned layer | Broadband AR | [50] |
| MAPICl   | 300                       | 3                        | periodic substrate corrugation | Broadband AR | [32] |

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and specifically its optimization in terms of LM, as discussed previously. However, the EQE enhancements (Figure 9) can clearly reach larger values with LT than for AR.

In Table 3, focusing on experimental results, for various perovskite materials, the $J_{sc}$ enhancements are of the same order as the simulated ones, with the same aforementioned precautions. As for the simulated PPSC, the EQE enhancements (Figure 12) also reach larger values using patterns matching the scale of the wavelength in the material. Moreover, the periodic case\cite{41} leads to the largest enhancement. Then, the patterns are obtained with direct nanoimprinting of the perovskite layer, which is a scalable, low cost technique.\cite{99} It is also observed that the random wavelength scale patterns, resulting from the perovskite layer processing either within the entire thickness\cite{32} or in a more superficial way,\cite{49} appear promising.

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### Table 3. Reported experimental $J_{sc}$ enhancements mainly resulting from light management, for single junction PPSC, with any kind of in-plane pattern, and main identified PE.

| Material | Perovskite thickness [nm] | $J_{sc}$ enhancement [%] | Pattern type | Photonic concept | Ref |
|----------|---------------------------|--------------------------|--------------|-----------------|-----|
| MAPI     | 240                       | 14.3                     | periodic add. patterned layer | Broadband AR and LT | [48] |
| CsFAMAPBI| 370                       | 2                        | periodic struct. of the perovskite | Broadband AR and LT | [41] |
| CsFAMAPBI| 550                       | 6.3                      | periodic struct. of the ETL | Broadband AR | [51] |
| MAPICl   | 320                       | 5                        | periodic struct. of the perovskite | Broadband AR | [34] |
| MAPI     | 340                       | 1.8                      | aperiodic add. patterned layer | Broadband AR | [53] |
| MAPI     | 270                       | 4.8                      | aperiodic add. patterned layer | Broadband AR | [54] |
| MAPICl   | 300                       | 4                        | aperiodic add. patterned layer | Broadband AR | [49] |
| MAPI     | 300                       | 3                        | aperiodic substrate corrugation | Broadband AR | [32] |
Optical indices used are from Manzoor et al.\textsuperscript{[107]} for MAPI, from McIntosh et al.\textsuperscript{[108]} for PMMA, and from Ball et al.\textsuperscript{[88]} for all other materials: Sodalime glass as a substrate, ITO, TiO\textsubscript{2}, doped Spiro-OMeTAD (as HTL material), and gold. Thicknesses were set to 100 nm for top contact, 20 nm for ETL, and 300 nm for Au.

The ETL is supposed to be a thin TiO\textsubscript{2} layer, dense and flat, to avoid scattering, and to limit parasitic absorption compared to other envisaged organic materials.

5.2. Optimization of the Key Layers Thicknesses in Various Planar Single-Junction PPSC

Let us first consider illumination through a planar PPSC on an infinitely thick substrate under normal incidence (Figure 14). The thicknesses of the MAPI layer \( t_{\text{MAPI}} \) and of the HTL \( t_{\text{HTL}} \) are supposed to vary in the ranges of 300–700 nm and 200–400 nm, respectively. As observed in Figure S3, Supporting Information, the \( J_{\text{sc}} \) of such a cell increases with \( t_{\text{MAPI}} \). Moreover, for a given \( t_{\text{MAPI}} \), the \( t_{\text{HTL}} \) has a non-negligible influence on \( J_{\text{sc}} \); for example for the smallest MAPI thickness of the considered range, the \( J_{\text{sc}} \) can be increased by more than 0.5 mA cm\textsuperscript{−2}, up to about 21.74 mA cm\textsuperscript{−2}.

The low \( J_{\text{sc}} \) for the thinnest considered MAPI is due to lower absorption at long wavelengths, as observed in Figure S5, Supporting Information, for a given HTL thickness of 240 nm.

Given the possible identified advantages of using a thinner MAPI layer, mainly for the electrical properties, the thickness is set to 300 nm in the following. Since an AR PMMA layer is then coated on the illuminated side of the glass substrate (Figure 14), the substrate thickness has to be set for the simulation. Realistic value of 1 mm is chosen, with a fully neglected roughness. For the selected \( t_{\text{MAPI}} \), the coupled influence of PMMA thickness, \( t_{\text{PMMA}} \), and \( t_{\text{HTL}} \) is studied. According to Figure S6, Supporting Information, a significantly increased \( J_{\text{sc}} \), up to about 21.92 mA cm\textsuperscript{−2}, can be obtained for \( t_{\text{PMMA}} = 360 \text{ nm} \) together with \( t_{\text{HTL}} = 250 \text{ nm} \). This last structure is then used as a planar but optimized reference for fair estimation of the impact of PE. The corresponding spectrum is displayed in Figure 15.

5.3. Introduction of Various 2D PC to Enhance the Current Density

As already discussed, to further increase the absorption and thus \( J_{\text{sc}} \), the most efficient strategies are to couple the impinging light into the guided modes using the properly designed patterns. In the following, several 2D square lattices of cylindrical patterns are envisaged. Each resulting 2D PC has typically three parameters that can be optimized: i) period \( P \), ii) filling fraction (\( ff \)) which is the ratio of the hole surface to the period surface, and iii) thickness \( t \). These 2D PC (Figure 14) can be located either:

1) In the MAPI layer, thus made of holes filled with HTL material for a fair comparison, the volume of the MAPI material is the same as in the planar PPSC such that the total thickness changes. Moreover, \( t < t_{\text{MAPI}} \) to prevent short circuits between HTL and ETL. A thick slab of HTL \( t_{\text{HTL}} = 250 \text{ nm} \) is...
kept for planarization;

2) In the top PMMA layer, patterned in a PC of air holes, with \( t = \theta_{\text{PMMA}} \), favoring diffraction efficiency, given the low index of the PMMA;

3) Concurrently at the two previous locations, each PC having its own set of parameters.

In the following studies, all the PC parameters are scanned over realistic ranges. The step for \( P \) and \( t \) is 5 nm, whereas only three \( ff \) have been envisaged: 0.3, 0.4, and 0.5; these appear to be the most realistic values compatible with a large patterned area at a reasonable cost.

### 5.3.1. Single Junction: 2D PC in the Perovskite Layer

Regarding the best planar PPSC coated with PMMA, an increase of almost 1 mA cm\(^{-2} \), leading to a \( J_{sc} \) of 22.88 mA cm\(^{-2} \) is obtained with a PC of MAPI (Figure S7, Supporting Information), with \( P = 400 \text{ nm} \), \( ff = 0.4 \), and \( t = 110 \text{ nm} \). It has been checked that \( ff \) of 0.3 and 0.5 lead to current densities lower than the optimal, but still larger than the reference. The corresponding spectra in Figure 15 reveal that the improvement is mainly due to a larger band edge absorption, as confirmed by the absorption enhancement in the same figure.

It is observed that other periods, smaller than 550 nm, can lead to more limited \( J_{sc} \) enhancement. However, it has been verified that using periods around 5 and 10 \( \mu \text{m} \) lead to a \( J_{sc} \) lower than 21.85 mA cm\(^{-2} \). This confirms that such periods, far larger than the sub-micron optimal one, are not conducive to efficient diffraction and thus do not lead to any \( J_{sc} \) enhancement, when compared with an optimized planar reference.

### 5.3.2. Single Junction: 2D PC in the PMMA Covering Layer

Regarding the best planar PPSC coated with PMMA, an increase of almost 0.9 mA cm\(^{-2} \), leading to a \( J_{sc} \) about 22.75 mA cm\(^{-2} \), is obtained with a PC in the PMMA layer. The 2D PC parameters are \( P = 665 \text{ nm} \), \( ff = 0.4 \), and \( t = 615 \text{ nm} \) (Figure S8, Supporting Information). It has been verified that \( ff \) of 0.3 and 0.5 lead to lower current densities. In the corresponding spectra in Figure 15, it is observed that the improvement is due to both the AR effect and limited LT at band edge absorption, implying low effective index guided modes that are only able to interact, weakly, with the pattern on top of the thick substrate. The enhancement remains lower than the one induced by the 2D PC in the perovskite layer. Again, it is verified that periods far larger than the optimal one, typically around 5 and 10 \( \mu \text{m} \pm 0.5 \) lead to a \( J_{sc} \) lower than 22 mA cm\(^{-2} \), providing limited enhancement because of reduced diffraction efficiency.

### 5.3.3. Single Junction: Combination of the two 2D PC

Given the previous enhancements, a structure that combines the two 2D PC, one in the PMMA and the second at the MAPI/HTL interface, can be envisaged. RCWA method implies that the period of such a combined architecture is a integer \( N_{\text{PMMA}} \) times the period of the 2D PC in the PMMA (\( P_{\text{PMMA}} \)), and another integer \( N_{\text{MAPI}} \) times the pitch of the 2D PC in the MAPI (\( P_{\text{MAPI}} \)); other PC parameters (\( ff_{\text{PMMA}} \), \( t_{\text{PMMA}} \); \( ff_{\text{MAPI}} \), \( t_{\text{MAPI}} \) for the other) can differ (Figure 14). To illustrate possible further \( J_{sc} \) enhancement, the parameters of the 2D PC at the MAPI/HTL interface are whose of the previously optimized PPSC with a flat PMMA layer, that is \( P_{\text{MAPI}} = 400 \text{ nm} \), \( ff_{\text{MAPI}} = 0.4 \), \( t_{\text{MAPI}} = 110 \text{ nm} \). Thus, \( ff_{\text{PMMA}} = 0.5 \) and \( t_{\text{PMMA}} = 405 \text{ nm} \) are among the thinnest most favorable values of the previously considered PPSC with 2D PC in PMMA and a planar MAPI layer. Then, \( N_{\text{PMMA}} \) is scanned from 5 to 8 and \( N_{\text{MAPI}} \) from 9 to 15, given the fact that \( P_{\text{PMMA}} \) is typically larger than \( P_{\text{MAPI}} \) based on previous studies. The simulated \( J_{sc} \) displayed in Figure S9, Supporting Information shows that a limited increase, of about 0.26 mA cm\(^{-2} \), up to
23.14 mA cm\(^{-2}\), is possible provided \(P_{PMMA} = 530\) nm. It is observed in Figure 15 that such \(J_{sc}\) enhancement results from both LT and AR effects compared to the planar reference. If the full space of various possible PC parameters has not been scanned, then the previous parameters are not fully optimized, the interest in such a combination remains yet demonstrated.

5.4. 2T Tandem

A 2T tandem PPSC generally exhibits thermalization, as previously described in Section 4.1.3. Thus, in this example, a case study is considered for possible improvement. In the following simulations, the optical indices provided for the considered materials are used. The planar stack (Figure 16), considered as a reference, is close to the one shown in Figure 6a. In contrast to our previous studies, the glass substrate is again supposed to be infinitely thick to avoid additional interference in the substrate. Within the stack, the layer thicknesses (except perovskites) have been set to realistic values such as \(t_{ITO} = 100\) nm, \(t_{SnO_2} = t_{NVPB} = 10\) nm (simplified version of a mixed material ETL), \(t_{C60} = 10\) nm for both HTL as well as \(t_{PEDOT-PSS} = 10\) nm, and \(t_{Cu} = 100\) nm. As justified later, the SnO\(_2\) layer, with \(t_{SnO_2} = 100\) nm, acts as an optical spacer (the 1 nm thick Au layer has been neglected).

Setting the thicknesses of both perovskite layers to \(t_{1.77 eV PK} = 400\) nm (also the maximum in the considered range) and \(t_{1.22 eV PK} = 880\) nm (in the range 800–1200 nm) leads to the highest \(J_{sc}\) of 16.25 mA cm\(^{-2}\), which appears to be limited by the 1.77 eV perovskite subcell. This value is slightly larger than the one obtained by Xiao et al. Moreover, because of a slight mismatch between our thicknesses of the charge transport layers and authors’ choices, it is obtained for different perovskite thicknesses. However, the absorbance spectra derived for both sub cells (Figure 17) still exhibit a thermalization effect. Simply increasing \(t_{1.77 eV PK}\) could be at the expense of collecting the charges.

In this frame, the possible enhancement of the \(J_{sc,1.77 eV PK}\) using a 2D PC at the ITO / 1.77 eV perovskite layer interface is studied. The 2D PC consists of a square lattice of ITO pillars, coated with conformal ETL. Then a 1.77 eV perovskite layer planarizes the corresponding subcell, while keeping an equivalent volume of perovskite in the planar tandem cell.

A significant enhancement of \(J_{sc,1.77 eV PK}\) up to 17.92 mA cm\(^{-2}\), was observed for \(P = 325\) nm, \(ff = 0.5\) (here defined as the ITO filling fraction), and \(t = 160\) nm (Figure S10, Supporting Information). The reason is twofold (see spectra in Figure 17): a broadband AR, and a limited LT at the band edge of the 1.77 eV perovskite material that slightly reduces the thermalization. LT specifically occurs in one of the absorbing materials, to the detriment of the other. This results from a guided mode mainly confined in the perovskite of interest, with limited overlap in the other perovskite, as a result of the rather large, 100 nm SnO\(_2\) optical spacer. Indeed, this layer can prevent evanescent coupling between quasi guided modes of the perovskites. In addition, it could protect the 1.77 eV perovskite material during fabrication, but the junction between the two subcells might then also be less efficient.

This first step leads to a strong \(J_{sc}\) disequilibrium between the two subcells, with \(J_{sc,1.22 eV PK}\) slightly decreasing to 15.7 mA cm\(^{-2}\), compared to the planar reference. In a second step, to increase \(J_{sc,1.22 eV PK}\), this low-\(E_g\) perovskite layer can
also be patterned rather than simply increasing the already large thickness.

Starting from the last structure, a second 2D PC is introduced at the 1.22 eV perovskite material/HTL interface. To target LT with larger wavelength, close to the band edge of this perovskite, its period has to be increased. However, given the constraint induced by the boundary conditions of the simulation, a supercell having a period twice that of the single PC device was selected with one pattern in the 1.22 eV perovskite material, and two patterns in the 1.77 eV perovskite material (Figure 16), while keeping \( f \) and thicknesses constant. The volume of this perovskite is kept constant, with HTL acting as a planarizer, with a minimum thickness of 10 nm (with a larger volume as in the planar alternative).

It appears that \( J_{sc,1.77\text{eV PK}} \) remains unchanged, whereas \( J_{sc,1.22\text{eV PK}} \) is increased up to 16.2 mA cm\(^{-2}\), reducing, but not eliminating the disequilibrium. As expected, this results from the LT at the band edge of the 1.22 eV perovskite material (Figure 17). This last result appears as proof of concept to integrate two PC to induce LT as well as possibly AR, in two different absorbing layers of a given stack, provided each one exhibits guided modes without overlapping. If not yet optimized, it is observed that, providing the first subcell is planarized, the two PC could practically have independent parameters, offering additional degrees of freedom to reduce disequilibrium. Given the required spacer, such a concept could also be applied to other kind of three or four terminal multijunction cells.

6. Conclusion - Perspectives

Light management for PV solar cells was mainly intended to increase the \( J_{sc} \) as a result of larger absorption. When using metal-halide perovskite materials, LM is shown to result from an interaction between the various selected materials, the patterning processes, and PE. Moreover, demonstrating LM requires some rigorous criteria to be able to distinguish between electrical, material, and photonic effects.

The studies presented in this review have demonstrated that the easiest \( J_{sc} \) enhancement is indeed the most frequently envisaged effect, especially for single junction cells, compared with the still highly challenging \( V_{oc} \) enhancement. Studies on EY are not mature because of a lack of studies at the module scale. As demonstrated by several authors, even thickness optimization within flat PPSC can enhance absorption as a result of the Fabry Perot effect with consideration given to electrical constraints. To further increase the absorption at the perovskite band edge, an in-plane pattern at various scales can be introduced into one of the layers. However, patterns at the wavelength scale appear to be the most efficient. In any case, the \( J_{sc} \) enhancement compared to already optimized flat reference was confined to a few percent. Regarding the photonic regime, the broadband AR effect was the most frequently observed, but only LT was able to significantly enhance the absorption at the band edge, as confirmed by our own simulations. In addition, it was confirmed both through analysis of the literature and through our simulations that direct patterning of the perovskite leads to more efficient LT than an additional layer on top of the substrate. Finally, in 2T tandem cells, it was demonstrated that one PC in each subcell can enhance each of the \( J_{sc} \) separately.

The strategies developed for these opaque, single junction PPSC can be adjusted for other configurations of PPSC such as emerging interdigitated back-contact structures\(^\text{[109]}\) or other applications of hybrid perovskites for sunlight harvesting. Indeed, accurately tuned spectral absorption is required in semitransparent single junction. Moreover, the same concepts can be tweaked to tailor the reflectivity spectrum for perovskite-based color printing devices\(^\text{[110–113]}\) and engineering absorption management in full-color perovskite detectors.\(^\text{[114,115]}\)

This work has a far larger context. Other ongoing studies concerning materials and processes need to be more stable. In this frame, it is observed that record cells might not share the same encapsulation strategies as more realistic, large surface cells and modules\(^\text{[116]}\) both for aging and safety reasons.\(^\text{[117,118]}\) All perovskite tandem cells are even more challenging from the point of view of fabrication,\(^\text{[119,130]}\) but are also very promising since they combine the potential of perovskite based cells and modules with high yields.

Finally, according to the reciprocity relation between absorption and emission,\(^\text{[121]}\) light extraction strategies in perovskite
LEDs\cite{10,12,13} as well as resonances of high quality factor into perovskite-based laser,\cite{99,124,125} which uses concepts similar to those derived in this work. Even LM in 2T tandem cells could be mimicked in white LEDs obtained by stacking several emit
ing materials. For LEDs, high light extraction efficiency is key to high-level efficiency.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

all-perovskite tandem cells, light trapping, single-junction perovskite cells

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