Review

Emerging Perovskite Nanocrystals-Enhanced Solid-State Lighting and Liquid-Crystal Displays

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Abstract: Recent advances in perovskite nanocrystals-enhanced solid-state lighting (SSL) and liquid-crystal displays (LCDs) are reviewed. We first discuss the development, optical properties, and stability issue of materials, and then we evaluate the performance of SSL and LCDs with perovskite downconverters adopted. In SSL performance evaluation, we investigate the fitting-curve effect in calculations and optimizations where simple Gaussian fitting and precise fitting are compared in detail, and we further optimize for highly efficient, good color-rendering, and human-healthy SSL sources. For LCD performance evaluation, we study the intrinsic tradeoffs between total light efficiency and color gamut coverage. Through optimizations using real line shapes, Rec. 2020 standard coverage as large as 92.8% can be achieved through hybrid integration. Finally, we briefly discuss two future challenges: materials development and device integration. We believe the emerging perovskite nanocrystals are highly promising for next-generation SSL and LCDs.

Keywords: perovskite nanocrystals; photoluminescence; solid-state lighting; color quality scale; circadian effect; liquid-crystal displays; wide color gamut

1. Introduction

Since the invention of high-performance blue light-emitting diodes (LEDs) [1–3], phosphor-converted white LED (pc-WLED) has found widespread applications, especially in solid-state lighting (SSL) and liquid-crystal display (LCD) backlight, due to its high efficiency, long lifetime, low cost, simple optical configuration, high brightness, and fast response time [4–6]. The huge market share and still-growing needs promote the studies further. During the past decades, SSL researches have been focusing on pushing the efficiency [7–9]. However, SSL aiming at beyond energy saving, such as human healthy lighting or horticultural lighting, becomes more and more important and starts to gain attention [10,11]. Thus, the ability to tailoring spectral power distribution (SPD) of emitters according to specific requirements while keeping high efficiency is pivotal. Meanwhile, the request for large color gamut LCDs also becomes urgent. As the color gamut evaluation metric gradually upgraded from sRGB (standard Red Green Blue), via NTSC (National Television Standards Committee), and now to Rec. 2020, the traditional pc-WLED cannot fulfill the demand for highly vivid colors [12–14]. Emitters that can accomplish the requirements by next-generation SSL and LCD backlight are thus highly desirable.

In the past few years, organic-inorganic hybrid and all-inorganic halide perovskites have been explored intensively, as they are promising in applications, such as photovoltaic, LED, photodetectors, and transistors [15–22]. Moreover, their excellent photoluminescent properties make them a strong
contender for next-generation SSL and LCD backlight. As downconverters, they are not only color-tunable and narrow-band, but also easy-to-synthesize and low-cost. These properties can potentially fulfill the SSL's requirements, including high efficiency and capability of tailoring the SPD. Also, the narrow-band emission ensures vivid colors, which are essential for large color gamut LCDs.

In this review, we summarize recent advances of perovskite downconverter-enabled high-performance SSL and LCD backlight. In Section 2, we begin with a brief description of the materials development and characterization. In Section 3, we evaluate the adoption of perovskite downconverters for efficient, good color-rendering, healthy, tunable SSL, with first discussing the fitting-curve effect in SSL. In Section 4, we discuss the systems performance of LCDs that apply perovskite downconverters for large color gamut and high efficiency. Finally, in Section 5, two future challenges are emphasized: materials development and device integration.

2. Materials Development and Characterization

Metal halide perovskites (MHPs) have a most general chemical formula of $ABX_3$, where $A$ represents cations, such as $\text{Cs}^+$, $\text{CH}_3\text{NH}_3^+$, or $\text{CH}(\text{NH}_2)_2^+$, $B$ relates to metal cations usually as $\text{Pb}^{2+}$, and $X$ is halide anion like $\text{Cl}^-$, $\text{Br}^-$, or $\text{I}^-$ [23,24]. In their crystalline structures, B cation coordinates with six halide anions to form a corner-shared $[\text{BX}_6]$ octahedral configuration with $A$ cation located in each large void between the octahedra, so that to form cubic or orthorhombic structures [25,26].

Currently, lead halide perovskite nanocrystals (PNCs) are the most promising candidates that can replace phosphors or quantum-dots (QDs) in SSL and LCD backlight [27–31]. These PNCs exhibit large freedom of tailoring emission peaks. Their emission peak wavelength can be easily tuned through halide composition variations. For example, $\text{CsPbBr}_3$ NCs with size larger than 11 nm shows a photoluminescence (PL) peak at around 520 nm [32]. Adjusting the chemical composition to $\text{CsPbCl}_x\text{Br}_{3-x}$ and $\text{CsPbBr}_x\text{I}_{3-x}$ will shift the emission peak to shorter and longer wavelengths, respectively, and the entire visible band can be covered. Another intriguing optical property is their excellent color purity. The emission line widths in visible band are narrow, and the full widths at half maximum (FWHM) of PNCs are usually in the range of 12–40 nm. When integrated in SSL or LCD backlight, a blue LED is often applied as the pumping source. Figure 1 depicts the 450-nm blue LED-excited PL spectra of representative lead halide PNC series with varying halide compositions. A typical trend is that shorter emission peak wavelength exhibits a narrower FWHM. Besides these two properties, PNCs can also achieve a high PL quantum yield, even higher than 90% [33].

Generally, there are two kinds of methods to synthesize PNCs. In 2015, Kovenlenko et al. reported a strategy to synthesize all-inorganic (CsPbX$_3$) PNCs by mixing Cs-oleate and PbX$_2$ precursors in octadecene with ligands, and precipitate PNCs at high temperature. This strategy is very similar to the traditional hot-injection method for QD synthesis [33]. In the same year, Zhong et al. introduced another method, termed the ligand-assisted reprecipitation (LARP) technique, where the perovskite precursors were simply dropped into poor solvent to form PNCs [34]. By changing the composition of the cations or halide anions X, both methods can help to produce PNCs with great color tunability, excellent luminescent efficiency, and ultrahigh color purity [35–40].

However, PNCs that were fabricated through above-mentioned methods suffer from poor stability. PNCs that are easy to be formed are easy to be decomposed as well because of the low formation energy [41–43]. Water, heat, light, oxygen, or combing effects in the ambient air will all accelerate the decomposition of the perovskite nanoparticles and further lead to the luminescent quenching [44,45]. Therefore, strategies, such as using zwitterionic ligand, encapsulating PNCs into inert shells, and in-situ synthesis of perovskite nanoparticles in or on a polymer or inorganic matrix have been developed [26,46–50]. Among them, in-situ fabrication becomes more and more predominant, since it holds great promise on the stabilization of the embedded PNCs in target device structures [51–53]. For instance, a controlled drying in-situ method has already been used by Zhijing Nanotech and Lucky Cooperation in the fabrication of the first perovskite QD-embedded composite film (PQDCF)-based wide color gamut LCD prototype [51].
Beside the stability issue of PNCs, the presence of lead remains to be a concern for these materials to be widely used in consumer electronics. Efforts have been devoted to finding the environmentally friendly elements in the perovskite structure to replace lead, such as Sn$^{2+}$ and Ge$^{2+}$ [54–56]. However, at the current stage, the as-synthesized particles are either highly unstable and are sacrificed from degradation after only a few hours [57], or of relatively poor color purity not comparable with lead halide perovskites [56,58].

3. Solid-State Lighting Applications

The past decades have witnessed the thriving of SSL. It outperforms incandescent and fluorescent light bulbs in many aspects, such as power consumption, lifetime, size, brightness, and response time. The discovery and synthesis of new downconverters, such as phosphors [59–61] and QDs [62,63], keep promoting the performance of SSL so that SSL starts to aim at beyond energy saving. Previously, some studies have been focusing on perovskite-enabled high-performance SSL [64–67]. Here, we discuss the adoption of these new downconverters into RG$_{p}$B (Red, blue LED chips plus green perovskite downconverters) and RY$_{p}$G$_{p}$B (Red, blue LED chips plus yellow, green perovskite downconverters) type SSL for achieving highly efficient, excellent color-rendering, healthy, tunable lighting. These combinations allow independent intensity tuning of each color and avoid the green gap of LEDs [68].

At very early stages, numerous researches have been devoted to optimizing SSL’s energy efficiency and color rendering performance [69–74]. However, as the biological impacts of light have been studied extensively [75–79], researches started to take human-health effect into SSL design [80–83]. Under ambient light, the intrinsically photosensitive retinal ganglion cells (iPGRGs) innervating the suprachiasmatic nucleus (SCN) can influence the melatonin secretion, and thus affect the circadian rhythm [84]. In reference to the experiments on light-induced melatonin suppression, the action spectrum of the circadian effect with a peak at blue wavelength was proposed [85,86]. Lately, studies, optimizations, and designs of SSL that take circadian effect into consideration were emerging rapidly. Meanwhile, the color quality metrics of SSL are also advancing [87]. To overcome the deficits of outdated color rendering index (CRI), many metrics are proposed, such as color quality scale (CQS), color fidelity index (CFI), color gamut index (CGI), etc. For example, CQS is calculated using 15 Munsell test color samples and it is more suitable for artificial light sources that enhance the object chroma. 

![Photoluminescence (PL) spectra of a series of perovskite nanocrystals (PNCs) with different halide compositions under a 450-nm blue light-emitting diodes (LED) excitation.](image)
Recently, plethora of studies started to apply different rendering quality metrics instead of CRI. In this review, we follow their steps and take one step further to investigate the intrinsic tradeoffs among luminous efficacy of radiation (LER), CQS, and circadian action factor (CAF) for these two types of SSL. LER is a measure of light spectral efficiency, defined as:

\[
LER = \frac{K_m \int S(\lambda)V(\lambda)d\lambda}{\int S(\lambda)d\lambda},
\]

(1)

where \(K_m = 683 \text{ lm/W}\) is the LER of ideal monochromatic 555-nm source, \(S(\lambda)\) the SPD of the white light, and \(V(\lambda)\) the human eye sensitivity function. CQS, as the measure of color rendering quality, is calculated following [88]. CAF characterizes the circadian effect of light, which can be quantified by:

\[
CAF = \frac{K_c \int S(\lambda)C(\lambda)d\lambda}{\int S(\lambda)V(\lambda)d\lambda},
\]

(2)

where \(C(\lambda)\) is the circadian action function [85] and \(K_c\) is a normalization constant that ensures \(CAF = 1\) for the International Commission on Illumination (CIE) standard daylight illuminant D65.

In our optimization, five correlated color temperatures (CCTs), including 2700K, 3500K, 4500K, 5500 K, and 6500K are taken into consideration for tunable lighting sources. The objectives are:

\[
aLER = \frac{1}{5} \sum_{i=1}^{5} LER_i,
\]

(3)

\[
aCQS = \sqrt{\frac{1}{5} \sum_{i=1}^{5} CQS_i^2},
\]

(4)

\[
vCAF = \frac{CAF_5}{CAF_1},
\]

(5)

where \(i (i = 1 \sim 5)\) refers to each CCT (from 2700K to 6500K) and the root mean square value of \(aCQS\) is employed to avoid large discrepancies between different CCTs. Besides defining the objectives, it is also necessary to specify that the central wavelengths of emitters are limited in variant ranges according to their colors and the bandwidths of red and blue LEDs are set to 20 nm, while the bandwidths of green and yellow perovskite downconverters can be varied from 17 to 25 nm.

During the optimization, four optimization algorithms (genetic algorithm, particle swarm optimization, differential evolution, and adaptive simulated annealing) are utilized interchangeably to obtain global optimal solutions. For multi-objective optimizations, the intrinsic tradeoffs among objectives will create a unique geometry, termed Pareto Front [89], where each individual on the geometry demonstrate an optimal solution that has at least one objective outperforming that of others.

3.1. Fitting-Curve Effect

Before evaluating device performance, the effect of using fitting curves for replacing real SPDs in optimizations is worth discussing. Many fitting models have been proposed and applied in optimizations [90–93]. Among them, the Gaussian fitting in wavelength scale is the simplest. When compared with it, real SPDs are usually not symmetric and decrease more slowly when deviating from the emission peak wavelength. The utilization of fitting functions can simplify the data acquisition and lead to more general results. However, a natural question, how accurate the optimization results are when fitting curves are employed, needs to be addressed. To analyze this question, we evaluate the performance of optimized SSL for both RGpB and RYGpB types at a fixed CCT (2700 K), where LER, CQS, and CAF are the three objectives. Typically, low CCT SSL sources are suitable for evening lighting, where high LER and CQS with low CAF are preferred. To make a comparison, we chose Gaussian
function (Equation (6)) and Split-Pearson VII function (SP7, Equation (7)) \[93\] for simple fitting and precise fitting, respectively:

\[
S_G(\lambda, \lambda_0, \Delta\lambda) = e^{-\frac{4\ln2}{\Delta\lambda^2}(\lambda - \lambda_0)}, \quad (6)
\]

\[
S_{SP7}(\lambda, \lambda_0, \Delta\lambda) = \begin{cases} 
\frac{1}{1 + \left(\frac{\lambda - \lambda_0}{\Delta\lambda} - 1\right)^2} & (\lambda < \lambda_0); \\
\frac{1}{1 + \left(\frac{\lambda - \lambda_0}{\Delta\lambda} - 1\right)^2} & (\lambda \geq \lambda_0),
\end{cases} \quad (7)
\]

where \(\lambda_0\) is the emission peak wavelength, \(\Delta\lambda\) the FWHM, and \(a, b, c\) the fitting parameters. SPDs of blue LED, green perovskite, and red LED using these two models are presented in Figure 2 and the fitting parameters \(a, b,\) and \(c\) are listed in Table 1. In comparison with ideal Gaussian functions, the realistic SPDs are not symmetric on both sides of the emission peak wavelength and show longer “tails”.

![Figure 2. Spectral power distribution (SPDs) of blue LED, green perovskite-polymer downconverter, and red LED. The solid lines denote Gaussian fitting model and the dashed lines are based on precise fitting (SP7) model.](image-url)

| Table 1. Fitting parameters in SP7 model of all variable SPDs. |
|-----------------|---|---|---|---|
|                | \(a\) (nm) | \(b\) | \(c\) | \(\Delta\lambda\) (nm) |
| Blue LED       | 8.7579 | 1.8468 | 1.3060 | 18.3 |
| Green Perovskite | 8.1711 | 2.3090 | 1.5763 | 18.4 |
| Red LED        | 11.0988 | 1.8285 | 1.8049 | 17.3 |
| Red QD         | 11.1176 | 1.9608 | 2.2252 | 22.8 |

The Pareto Fronts of optimized SSL for RG\(_P\)B and RYG\(_P\)G\(_P\)B types at a fixed CCT (2700K) is plotted in Figure 3a–c and 3d–f as three-view diagrams, respectively. When compared with the SP7 model, the Gaussian model can achieve lower minimum CAF and larger maximum LER when CQS is low, but the highest-achievable CQS is sacrificed. However, if we focus on the moderate CQS range for RG\(_P\)B type and the relatively high CQS range for RYG\(_P\)G\(_P\)B type, the performance of the optimized SSL is comparable. Nevertheless, when comparing the Pareto Fronts obtained by applying these two fitting models is not enough. If they exhibit similar performance but dramatically different emission peak wavelengths, the simplified model still cannot present the practical cases and provide useful information. To clarify, the correlations between the emission peak wavelengths and the objectives of
these two types SSL are illustrated in Figures 4 and 5, respectively. Both models show very similar emission peak preference and trend. By the above analysis, optimizations using the simplified model indeed provide useful information, so that we can adopt Gaussian model into our simulation in the next sub-section.

![Figure 3. Pareto Fronts in three-view diagrams of optimized (a-c) RGPB- and (d-f) RYPGPB-type solid-state lighting (SSL) at a fixed correlated color temperature (CCT) (2700 K). Both Gaussian and SP7 model are calculated for comparison.](image)

**Figure 3.** Pareto Fronts in three-view diagrams of optimized (a-c) RGPB- and (d-f) RYPGPB-type solid-state lighting (SSL) at a fixed correlated color temperature (CCT) (2700 K). Both Gaussian and SP7 model are calculated for comparison.

![Figure 4. Correlations between the emission peak wavelengths and the objectives for optimized RGPB-type SSL, where (a–c) Gaussian model and (d–f) SP7 model are applied in the optimization.](image)

**Figure 4.** Correlations between the emission peak wavelengths and the objectives for optimized RGPB-type SSL, where (a–c) Gaussian model and (d–f) SP7 model are applied in the optimization.
vCAF (38.2%) is large when compared to the RG and RY adding one more emitter, the RY mutual exclusive on the upper limit. This differs from the RY constrained by the other two objectives on both upper and lower limits, while aCQS and aLER are 
p and 7, respectively. The geometries for these two types are distinct. For the RG type, vCAF is 
around 80 aCQS and 3.4 vCAF. The improvement of aCQS (17.5%) 
RGpB type can merely accomplish around 80 aCQS and 3.4 vCAF. The improvement of aCQS (17.5%) 

3.2. Device Performance

The three-view diagrams of Pareto Front for RGpB and RYPGPB-type SSL, where (a–c) Gaussian model and (d–f) SP7 model are applied in the optimization.

**Figure 5.** Correlations between the emission peak wavelengths and the objectives for optimized RYPGPB-type SSL, where (a–c) Gaussian model and (d–f) SP7 model are applied in the optimization.

**Figure 6.** Pareto Fronts in three-view diagrams of optimized (a–c) RGpB-type SSL where CCT varies from 2700K to 6500K.

**Figure 7.** Pareto Fronts in three-view diagrams of optimized (a–c) RYPGPB-type SSL where CCT varies from 2700K to 6500K.

One optimal solution per each type is chosen for further detailed studies. The SPDs of RGpB- and RYPGPB-type optimal solutions are illustrated in Figure 8a,b, respectively. RGpB type offers
333.8 lm/W aLER, 65.6 aCQS, and 3.22 vCAF, while RY<sub>p</sub>G<sub>p</sub>B type provides 333.0 lm/W aLER, 87.1 aCQS, and 3.88 vCAF. With similar aLER, RY<sub>p</sub>G<sub>p</sub>B shows 32.8% higher aCQS and 20.5% higher vCAF than RG<sub>p</sub>B. Their LER, CQS, and CAF values as a function of CCT are demonstrated in Figure 8c, where those values of reference white (blackbody radiator at CCT< 5000K and CIE standard illuminant at CCT ≥ 5000K) are also presented. The two optimal solutions have similar luminance efficacy, while the color rendering quality of RY<sub>p</sub>G<sub>p</sub>B type outperforms the RG<sub>p</sub>B type, especially at higher CCTs. Moreover, RY<sub>p</sub>G<sub>p</sub>B type can follow the circadian phase of reference white better and provide much wider tuning at both high and low CCTs. Through the analysis, we see that the RY<sub>p</sub>G<sub>p</sub>B-type optimal solution is indeed a highly efficient, good color-rendering, and human-healthy SSL source.

Noticed in Figure 8a, the gaps between different bands are so large that RG<sub>p</sub>B type is hard to achieve good color rendition (CQS metric). Under this circumstance, narrow-band emitters may not be a good choice. However, adding another emitter (RY<sub>p</sub>G<sub>p</sub>B) improves the overall performance significantly. Further increasing the number of emitters (e.g. RY<sub>p</sub>G<sub>p</sub>C<sub>p</sub>B) should achieve even better performance. Yet, in practice, the number of independently tunable emitters will tradeoff with the complexities of driving circuits and color-mixing optics design. Therefore, the four emitters-type SSL sources should be a good choice with both moderate design complexities and high overall system performance.

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**Figure 8.** SPDs of individual optimal solution at different CCTs for (a) RGP<sub>B</sub> (peak wavelengths: 477.9 nm, 555.1 nm and 617.3 nm) and (b) RY<sub>p</sub>G<sub>p</sub>B (peak wavelengths: 444.2 nm, 493.3 nm, 553.3 nm, and 619.1 nm) type SSL. (c) The detailed performance as a function of CCT.
4. LCD Backlight Applications

Another important application of perovskite downconverters is LCD backlight. As an essential part of LCDs, designs of backlight influence the color gamut, optical efficiency, viewing angle, and so on [94–96]. Currently, phosphor-converted white LEDs are the mainstream of LCD backlight [97,98]. They show relatively high efficiency, long lifetime, low cost, and simple optical configuration. However, as the color-gamut evaluation metrics keep advancing, the development of novel narrow-band emitters becomes increasingly crucial. The recently developed stable, narrow-band (18 nm), low cost, easy-to-synthesize green perovskite-polymer films have proven to be a promising candidate for wide color gamut LCDs [99]. However, stable and narrow-band red downconverters are still missing. Thus, hybrid backlight systems are preferred. Figure 9 depicts the schematic diagrams for three hybrid backlight systems. Detailed operation mechanisms will be discussed, as follows.

Figure 9a utilizes on-surface green perovskite-polymer and red QD films. Currently, the emission spectra of QD enhancement film (QDEF) still have around 30-nm FWHM at green color and the on-surface approach needs a large amount of QDs [100]. This approach results in a moderate highest-achievable Rec. 2020 standard coverage of around 82% and the QDEF itself is still expensive [101]. The hybrid on-surface configuration can enlarge the color gamut, lower the cost, and ensure that the working temperature is around room temperature, which helps to enhance the reliability and long-term stability of both QDs and perovskite nanocrystals significantly. However, since a large amount of red QDs are still needed, this approach is only suitable for high-end LCDs at this stage. Figure 9b shows another configuration where red phosphor (KSF or others) on-chip is applied instead of the on-surface red QD films, due to phosphors’ high quantum efficiency and good high-temperature stability. Compared to the two phosphor-converted WLED (2pc-WLED) approach, this hybrid method can greatly enlarge the color gamut, since the green phosphors with ideal emission peak wavelength are still quite broadband (FWHM ~ 50 nm), such that the color crosstalk of the color filters (CFs) will deteriorate the ultimate performance [102,103]. Figure 9c demonstrates another possibility that employs color-mixed LED chips. When comparing to RGB-LED backlight [104–106], this approach utilizes high-performance LEDs and avoids the green gap. Moreover, it saves the down-converting photon energies that are otherwise costed by red phosphors. However, the adoption...
of this approach needs to overcome some potential technical challenges such as light guide plate design, color-mixing issue, and thermal effects on LED chips, etc.

Previously, device performance of some hybrid systems has been investigated in a discrete sense, i.e., with fixed peak emission wavelengths. In their calculation, 91.6% of Rec. 2020 standard coverage can be achieved by hybridizing green perovskite-polymer downconverters with red QDs whose emission peak wavelength is at 650 nm [99]. Here, by assuming that the line shapes of tunable emitters keep unchanged within a small range of peak emission wavelengths, a more thorough study can be accomplished and the ultimate tradeoffs between color gamut coverage (CGC) and total light efficiency (TLE) can be evaluated.

For a typical LCD panel, the backlight will pass through three channels: red (R), green (G), and blue (B). Each channel will be sequentially modulated by the polarizer, LC, analyzer, and corresponding CF. The final output light from these three sub-pixels is then mixed to form a color pixel. Following the steps in [107,108] and assuming that the pixel displays reference white (CIE standard illuminant D65), we calculate the Pareto Front of the two-objective (CGC and TLE) optimization. Here, CGC is defined as the intersection between display color gamut area and standard color gamut area, which in our case is Rec. 2020:

\[
\text{CGC} = \frac{A_{\text{display}} \cap A_{\text{standard}}}{A_{\text{standard}}}. \quad (8)
\]

TLE is calculated, as follows:

\[
\text{TLE} = \frac{K_m \int S_{\text{out}}(\lambda)V(\lambda)d\lambda}{\int S_{\text{in}}(\lambda)V(\lambda)d\lambda}, \quad (9)
\]

where \(S_{\text{in}}\) is the SPD of backlight and \(S_{\text{out}}\) the SPD of final output light from the pixel. Note that CGC in different color spaces is not the same. A previous discussion suggested that CGC in CIE 1931 color space is more correlated to the three-dimensional (3D) color perspective model [109]. Under this consideration, we calculate CGC in CIE 1931. Meanwhile, different LC modes exhibit almost the same Pareto Front geometry and highest achievable CGC but only differ in TLE [109]. Therefore, here we use in-plane switching (IPS) mode as an example. Two sets of commercial CFs are considered: one with higher transmittance but larger crosstalk and the other with the opposite, as depicted in Figure 10a.

Because Gaussian fitting introduces a relatively large deviation on the results [101], we employ SP7 as a more precise fitting model. To specify, four combinations are investigated: RGPB (red, blue LEDs plus green perovskite), RQGPB (blue LED, green perovskite, and red QD), RKSFGPB (blue LED, green perovskite, and red KSF phosphor), and RSLAGPB (blue LED, green perovskite, and red SLA phosphor). With the two choices of CFs, there will be eight cases in total. The parameters that are
allowed to change are the emission peak wavelengths of blue LED, green perovskite, red LED, and red QD. The fitting parameters of blue and red LEDs are from [110], the SPDs of green perovskite and red QDs are from [99], the SPD of KSF phosphor is from [111], and that of SLA phosphor is from [112]. All of the SPDs are plotted in Figure 10b and the fitting parameters (including $\Delta \lambda$) used in the SP7 model are listed in Table 1.

Implementing the same optimization method described in Section 3.1, Pareto Fronts of all cases are demonstrated in Figure 11a. The solid lines represent the calculated results using CF1, whereas the dashed lines refer to the results with CF2. Due to the intrinsic optical properties of these two CFs, CF2 always provides a wider CGC at the cost of TLE. Interestingly, although the red LED has narrower FWHM than red QD, red QD offers even larger highest-possible CGC. This is because the SPD of red QD is more similar to Gaussian and shows narrower "tails". The "tails" gives rise to larger color crosstalk and ultimately sacrifices CGC. It is worth mentioning that, since the down-converting photon energy is not included in TLE, red LED should be more energy-efficient than red QD in the ideal case. KSF phosphor, on the other hand, presents lower highest-possible CGC, since its SPD is fixed. However, SLA phosphor can compete with red QD and red LED in highest-possible CGC even with fixed SPD. This can be ascribed to its deep-red emission peak wavelength, which accommodates the CFs well. Nevertheless, the broader band of SLA phosphor lowers its TLE noticeably. Details of the optimized results can be found in Table 2.

![Figure 11.](image1) (a) Pareto Fronts of hybrid-backlight in-plane switching liquid-crystal display (IPS LCDs) with different red emitters and color filters. (b) Simulated color gamut for optimized QD- and KSF phosphor-based hybrid LCDs with different color filters. Optimized emission spectra of (c) QD- and (d) KSF phosphor-based hybrid backlight without any modulation for the two different color filters.
Table 2. Optimized values of wide color-gamut IPS LCDs using different red emitters.

<table>
<thead>
<tr>
<th></th>
<th>CF1 CGC (%)</th>
<th>CF1 TLE (lm/W)</th>
<th>CF2 CGC (%)</th>
<th>CF2 TLE (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red LED</td>
<td>89.0%</td>
<td>16.2</td>
<td>92.7%</td>
<td>13.0</td>
</tr>
<tr>
<td>Red QD</td>
<td>89.1%</td>
<td>16.1</td>
<td>92.8%</td>
<td>12.6</td>
</tr>
<tr>
<td>KSF</td>
<td>86.0%</td>
<td>18.8</td>
<td>89.9%</td>
<td>15.6</td>
</tr>
<tr>
<td>SLA</td>
<td>88.8%</td>
<td>11.1</td>
<td>92.6%</td>
<td>9.7</td>
</tr>
</tbody>
</table>

Examples of using emission-tunable red emitter (QD) and fixed phosphor (KSF) are further investigated. Figure 11b depicts the color gamut area of some cases that are summarized in Table 2. The red primary color for QD using both CFs is closer to the primary colors of Rec. 2020 standard compared to the other two primary colors (i.e. green and blue). This is due to the more severe color crosstalk between green and blue CFs. In comparison with QD, KSF phosphor with fixed emission peak wavelength should sacrifice all the primaries more. This can also be sensed from Figure 11c,d, which presents the white backlight without any modulations (by LC, CF, etc.) for the two emitters. To achieve wide color gamut, the emission peak wavelengths of these three colors should be separated far enough according to CFs. For example, for both red emitters, the emission peak wavelengths of green and blue are separated further away using CF1 due to its more severe color crosstalk when comparing to CF2. To accomplish a larger CGC in the future, tailoring the SPD of emitters (especially narrowing the “tails”) and redesigning the CFs [109,113–115] will be meaningful.

5. Future Challenges

5.1. Materials Development

So far, very few studies have reported PNCs with relatively good stability against external stresses. Yet, the long-term stability still needs to be tested. Moreover, the current strategy of integrating PNCs into LCD backlight is through on-surface integration. To achieve on-chip configuration, further improvement of thermo- and photo-stability, increased optical density, and tailoring of the form factors are needed. Meanwhile, the state-of-the-art red PNCs still show a wider FWHM than Cd-based QDs. The development of stable and possibly narrower-band red PNCs is highly demanding for non-hybrid configurations. Another intriguing candidate that can boost the efficiency of LCD backlight is the perovskite nanorods (PNRs) [116,117]. By preferentially emitting partially linearly polarized light to pass through the first polarizer, the down-converted light can be less absorbed. However, macroscopic alignment of the PNRs remains challenging [118]. On the other hand, PNCs for SSL applications also confront thermo-stability issue. Unlike LCD backlight, the pumping source in SSL often provides a much higher brightness. Under this circumstance, the photo-stability against intense excitation needs to be investigated.

5.2. Device Integration

For LCD backlight, PNC-embedded films have already been used in consumer products. An example is the PQDCF integrated with blue LED and on-chip KSF phosphor. Very recently, mini-LED LCDs are growing [119]. Although the direct-lit configuration is different from edge-lit, the integration of color conversion materials/films is similar. Another possibility to incorporate PNCs is by introducing patterned PNC-CFs on the top of LCs. However, this method is quite hard, as it requires stable PNCs (especially for red ones), patterning ability, and high optical densities. Besides, future research can also be oriented toward integrating multiple functions in one component. In general, LCD backlight consists of many components (films), such as diffuser sheet, BEF, DBEF, etc. If the on-surface PQDCF offers both down-conversion and good light-diffusing capabilities, the loading of the PNCs, and thus the cost will be decreased [49]. Meanwhile, for SSL, current studies
are still limited in lab. Apart from the instability issue, integration strategy is also an important aspect. For example, to avoid thermo-stability issue of PNCs and glare of blue LED, a remote-downconverter configuration is preferred. However, this configuration will inevitably increase the bulkiness and cost. Thus, this aspect needs to be investigated for further practical SSL applications.

6. Conclusions

We have briefly reviewed the recent advances in perovskite nanocrystals-enhanced SSL and LCDs. The PNCs are favored by both SSL and LCDs, in that they are narrowband and color-tunable. However, to be adopted into these applications, the stability issue still needs further investigation. Besides, lead-free PNCs are also emerging. However, their optical performance and stability are still inferior to those of lead halide PNCs. To evaluate the system performance of SSL enabled by PNCs, we first investigate the fitting-curve effect in optimizations. Through our calculation, the performances of using simple Gaussian fitting and precise fitting are comparable, and the correlations between emission peak wavelengths and objectives for both fitting models are very similar. By further optimizations, we prove that the RYGP type can fulfill the request for highly efficient, good color-rendering, and human-healthy SSL sources. On the other hand, three configurations of LCD using PNCs as downconverters are evaluated. The LCDs using hybrid PNC-QD or PNC-red LED or PNC-SLA phosphor can achieve larger than 92.5% Rec. 2020 color gamut coverage. Finally, we highlight that better configuration or system performance can be realized through further materials development, and device or function integration remains challenging especially for SSL. As the researches on PNCs are still ongoing and they will attract more attention in the future, we believe that the emerging PNCs hold great promise for promoting the development of next-generation SSL and LCDs.

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