

Cite this: *Chem. Sci.*, 2025, 16, 15796

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 25th March 2025  
Accepted 11th August 2025

DOI: 10.1039/d5sc02236c

rsc.li/chemical-science

# Emission-tunable manganese(II) halides: structure–property relationships and functional applications

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Luminescent Mn(II) complexes have attracted extensive attention owing to their properties of color tunability, high PLQYs, large Stokes shifts and thermal stability. Luminescent Mn(II) complexes can exhibit orange, green, and red emissions depending on the environment of Mn<sup>2+</sup>. These various properties made Mn(II) complexes attractive candidates for different fields of applications such as LEDs and radiation detection. In this perspective, we connect the emissions of Mn(II) complexes with the corresponding crystal structure and the environment of Mn<sup>2+</sup>. Then, we summarize the recent progress of luminescent Mn(II) complexes in LEDs and radiation detection. Finally, we present the challenges and outlook for future research on luminescent Mn(II) complexes.

## 1 Introduction

In the past few years, lead halide perovskites have become promising materials for optoelectronic devices due to their excellent optoelectronic properties.<sup>1,2</sup> However, their toxicity and poor stability have hindered further application in many fields.<sup>3</sup> One of the most effective solutions is to find nontoxic and reliable alternatives beyond lead halide perovskite.<sup>4–6</sup> Mn(II) halides have emerged as sustainable alternatives to lead perovskites, achieving near-unity photoluminescence quantum yield (PLQY) and enabling emission tunability to green and red luminescence through structural control. These earth-abundant systems combine luminescence efficiency with environmental compatibility, addressing demands for eco-friendly photoelectric applications.

The intrinsic luminescence of manganese halides originates from d–d electronic transitions of the manganese center, where the crystal field splitting determines emission characteristics through ligand field modulation. Manganese first emerged as a strategic luminescent dopant for host materials with a low PLQY, where its distinct electronic configuration enables efficient energy transfer pathways for photoluminescence enhancement. The Mn-doped ZnS nanocrystals (NCs) synthesized by Bhargava in 1994 are the earliest semiconductor NCs, exhibiting quantum yields of less than 20%.<sup>7</sup> Mn<sup>2+</sup> dopants in II–VI semiconductors (*e.g.*, ZnS and CdSe) achieve tetrahedral coordination through isovalent substitution, activating spin-forbidden d–d photoluminescence *via* crystal field engineering.<sup>8</sup> Since then, a great diversity of Mn-doped II–VI semiconductor NCs have been explored and applied to biomedical imaging,<sup>9</sup>

white light emitting diodes,<sup>10</sup> solar cells,<sup>11</sup> radiation detection<sup>12</sup> and luminescent solar concentrators.<sup>13</sup> Given the great potential for various light emission applications of Mn-doped semiconductor NCs, metal halide perovskite NCs have also been developed as the latest semiconductor hosts of Mn(II) dopant. In 2016, Mn-doped CsPbX<sub>3</sub> perovskite NCs were almost simultaneously synthesized by Parobek *et al.*<sup>14</sup> and Liu *et al.*<sup>15</sup> *via* a modified hot injection process.

Besides being a dopant, Mn can also serve as an independent luminescent center without doping. Luminescent Mn(II) halide complexes, as some of the emerging lead free materials, have been intensively investigated over the past decades owing to their properties of tunable emission, high PLQYs, large Stokes shifts, good thermal stability and low toxic nature compared to lead halide perovskites. In recent years, various luminescent Mn(II) halide complexes have been designed and synthesized. According to the coordination environment of the Mn<sup>2+</sup> center Mn(II) halides can be classified into four-fold-coordinated, [MnX<sub>4</sub>]<sup>2–</sup>, and six-fold-coordinated, [MnX<sub>6</sub>]<sup>4–</sup>, manganese halide complexes. Based on the emission wavelength, Mn(II) halides can be classified into green and red Mn(II) phosphors. By their crystal structure, Mn(II) complexes are further classified into zero-, one- and two-dimensional structures. The diversity of Mn(II) halide complexes leads to their different photoelectric properties, which can be applied in different fields. For example, Ju *et al.* fabricated a white LED (WLED) exhibiting a luminous efficacy of up to 96 lm W<sup>–1</sup> using green (C<sub>5</sub>H<sub>6</sub>N)<sub>2</sub>MnBr<sub>4</sub> and red C<sub>5</sub>H<sub>6</sub>NMnCl<sub>3</sub> phosphors on a blue chip, reflecting the high PLQY and good thermal stability of these manganese(II) complexes.<sup>16</sup> Wang *et al.* prepared a pure red LED with (ABI)<sub>4</sub>MnBr<sub>6</sub> showing the maximum recording brightness of 4700 cd m<sup>–2</sup> and an EQE of 9.8%, suggesting the excellent electroluminescence (EL) performance of this complex.<sup>17</sup> Besides their use in LEDs, Mn(II) complexes can also be applied

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in radiation detection. A Mn-doped  $(C_{18}H_{37}NH_3)_2PbBr_4$  scintillator was finally made into imaging plates for fast neutron radiography with  $0.5 \text{ lp mm}^{-1}$  spatial resolution.<sup>18</sup> Ma *et al.* synthesized an X-ray scintillator  $(C_{38}H_{34}P_2)MnBr_4$  with a high light yield of 80 000 photon per MeV, and a low detection limit of  $72.8 \text{ nGy s}^{-1}$ , indicating the potential of manganese(II) complexes in X-ray imaging.<sup>19</sup>

According to previous research, the emission of Mn from both the dopant and Mn(II) halide complexes was due to the  ${}^4T_1(G) \rightarrow {}^6A_1(S)$  transition of  $Mn^{2+}$ . The environment of  $Mn^{2+}$  in different structures leads to differences in the luminescent properties. In this perspective, we have summarized recent progress in luminescent Mn(II) complexes. We relate the luminescent properties of Mn(II) complexes to their corresponding environment and crystal structures. Then, we discuss their applications in LEDs and X-ray imaging. Finally, we present an outlook for the future development for Mn(II) halides.

## 2 Structures and properties of Mn halides

### 2.1 Emission of Mn-doped perovskite NCs

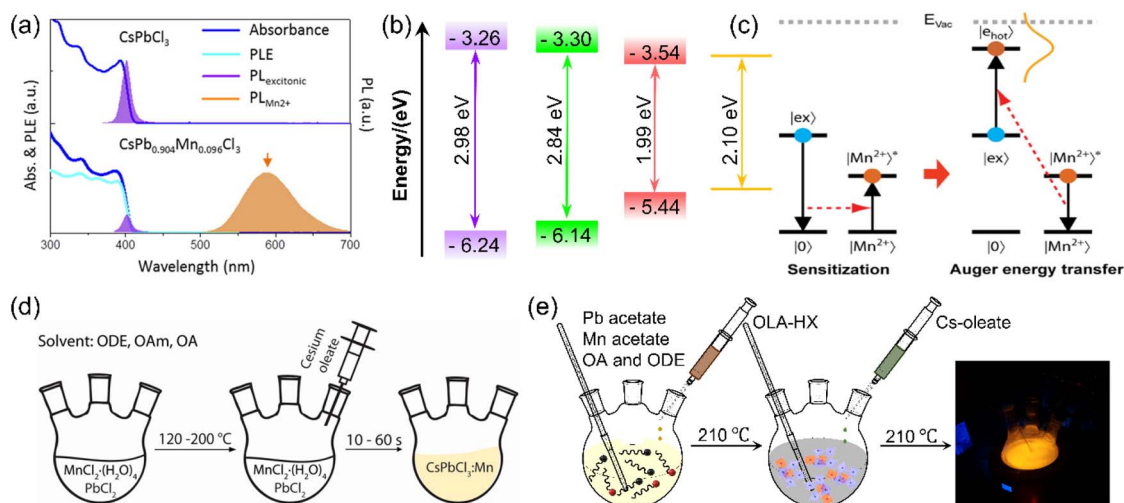
The electronic structure of  $Mn^{2+}$  in crystalline environments was analyzed through Tanabe–Sugano theory, incorporating electron correlations and crystal field (CF) effects.<sup>20</sup> Cubic CF splitting partially lifts degeneracies of the  ${}^4G$ ,  ${}^4P$ , and  ${}^4D$  terms, generating distinct  ${}^4T_1(G)$ ,  ${}^4T_2(G)$ ,  ${}^4A_1(G)$ ,  ${}^4E(G)$ ,  ${}^4T_2(D)$ ,  ${}^4E(D)$ , and  ${}^4T_1(P)$  states, which will be discussed in Sections 2.3 and 2.2 in detail.  $Mn^{2+}$  photoluminescence originates from the  ${}^4T_1(G) \rightarrow {}^6A_1(S)$  transition within visible wavelengths.<sup>21–23</sup> The emission energy depends on the CF strength, enabling chromatic tuning across host matrices *via* ligand field engineering.

For Mn as the dopant, manganese(II) ions are incorporated into metal halide hosts through substitutional doping strategies, where their luminescent activation emerges from coordination-tuned crystal field splitting. The emission characteristics are governed by the ligand-field symmetry coordination environment of the host. For instance,  $Mn^{2+}$  substitution in tetrahedral  $[ZnX_4]^{2-}$  units yields green emission under  $T_d$ -symmetry crystal field splitting,<sup>24,25</sup> while octahedral coordination in  $[CdCl_6]^{4-}$  environments generates distinct red luminescence through  $O_h$ -symmetry crystal field effects.<sup>26</sup>

Recently,  $Mn^{2+}$  doped  $CsPbCl_3$  perovskites exhibit tunable dual-band emission through structural confinement-mediated energy transfer, enabling applications in white-light-emitting diodes (WLEDs),<sup>27</sup> luminescent solar concentrators (LSCs),<sup>28</sup> and anti-counterfeiting<sup>29</sup> technologies. Fig. 1a shows that Mn-doped  $CsPbCl_3$  NCs have a distinct dual emission behavior consisting of a narrow PL band at  $\sim 400 \text{ nm}$  (blue–violet) and a broad PL band at  $\sim 600 \text{ nm}$  (yellow–orange emission). The former is generally attributed to host band edge exciton recombination and the latter to ligand field transition ( ${}^4T_1(G) \rightarrow {}^6A_1(S)$ ) of  $Mn^{2+}$  ions. Since the transition is spin-forbidden, the Mn dopant luminescence in perovskite NCs is accompanied by a microsecond or millisecond lifetime, consistent with Mn-doped II–VI semiconductor NCs.<sup>30</sup>

#### 2.1.1 Bandgap-dependent PL of Mn-doped perovskite NCs.

The emission of Mn-doped  $CsPbX_3$  perovskite NCs is host bandgap-dependent. Fig. 1b depicts the energy level alignment of  $CsPbX_3$  perovskite and  $Mn^{2+}$  ion d-state. In the case of Mn-doped  $CsPbCl_3$  NCs, the photo-generated exciton has the highest band gap energy and favours the forward energy transfer from band edge to the  $Mn^{2+}$  excited state, which ultimately contributes to the introduction of  $Mn^{2+}$  ion radiative pathway.<sup>15</sup> However, the band gap energy of Br-based or I-based



**Fig. 1** (a) The optical properties of undoped (top) and Mn-doped (bottom)  $CsPbCl_3$  NCs. (b) Band gap structure of  $CsPbX_3$  and Mn d-states. (c) Photophysical pathways of hot electron up-conversion.  $|0\rangle$  and  $|ex\rangle$  are ground and exciton states of the host NCs, respectively.  $|Mn^{2+}\rangle$  and  $|Mn^{2+}\rangle^*$  are ground and excited states of dopants, respectively.  $|e_{hot}\rangle$  represents the state generating hot electrons.  $E_{vac}$  is the vacuum level. Schematic diagram of the synthesis of Mn-doped  $CsPbX_3$  NCs *via* (d) one-step hot injection and (e) two-step hot-injection processes. (a) Reproduced with permission from ref. 15. Copyright 2016, American Chemistry Society. (c) Reproduced with permission from ref. 34. Copyright 2021, American Chemistry Society. (d) Reproduced with permission from ref. 14. Copyright 2016, American Chemistry Society.



perovskite NCs is close to that of the  $\text{Mn}^{2+}$  excited state and hinders the energy transfer process, resulting in inefficient dopant emission, as observed in Mn-doped  $\text{CsPbBr}_3$  and  $\text{CsPbI}_3$  NCs.<sup>31,32</sup> Fortunately, the quantum confinement effect provides a new chance for obtaining Mn emission in non-Cl-based perovskite NCs. For example, Parobek *et al.* directly synthesized dual-emitting  $\text{CsPbBr}_3$  nanocubes (6.5 nm) and nanoplatelets (NPLs, thickness: 2 nm) with confined size (7 nm) *via* the preformation of  $\text{A}_2[\text{Pb}_{1-x}\text{Mn}_x]\text{Br}_4$  (A = alkylammonium).<sup>31</sup> The interesting thing is that dopant emission dominates in Mn-doped  $\text{CsPbBr}_3$  NPLs, in contrast to stronger host emission in Mn-doped  $\text{CsPbBr}_3$  nanocubes, indicating more stable exciton-dopant exchange interaction due to the enhanced confinement effect in NPLs. Furthermore, Wang *et al.* first reported the hot electron up-conversion process in quantum confined Br-based perovskite NCs and NPLs.<sup>33</sup> As shown in Fig. 1c, hot electrons are generated by the Auger energy transfer from excited  $\text{Mn}^{2+}$  ions to another exciton. When the energy exceeds the threshold, hot electrons can undergo long-range transfer and improve the catalytic efficiency.<sup>34</sup>

**2.1.2 Concentration-dependent PL of Mn-doped perovskite NCs.**  $\text{Mn}^{2+}$  ion doping concentration is also capable of tailoring the emission of Mn-doped  $\text{CsPbX}_3$  perovskite NCs. Liu *et al.* synthesized  $\text{CsPb}_x\text{Mn}_{1-x}\text{Cl}_3$  perovskite NCs through adding excess  $\text{MnCl}_2$  dopant into the solution and elevating the temperature, where Mn dopant emission was tuned from 569 nm to 587 nm with the increase of doping concentration from 3% to 46%.<sup>35</sup> The red shift of Mn dopant emission was attributed to enhanced  $\text{Mn}^{2+}$ - $\text{Mn}^{2+}$  interaction, which come under observation in most Mn-doped systems.<sup>36-40</sup> In addition, as the doping concentration increases, the PLQYs of Mn-doped  $\text{CsPbCl}_3$  perovskite NCs first increases then decreases. A plausible explanation is that there is an optimal Mn doping concentration in  $\text{CsPbCl}_3$  perovskite NCs, which not only can

ensure enough  $\text{Mn}^{2+}$  ions to compete with the exciton recombination and yield intense Mn emission but also fail to cause serious PL quenching by forming  $\text{Mn}^{2+}$ - $\text{Mn}^{2+}$  pairs and causing nonradiative defects and deformation of the crystal structure at high Mn doping concentrations.<sup>41</sup> Therefore, numerous efforts have been focused on controlling the doping concentration and improving the PLQYs of Mn-doped  $\text{CsPbCl}_3$  perovskite NCs.<sup>35,40-45</sup>

**2.1.3 Improved doping and emission efficiency.** At present, the majority of Mn-doped  $\text{CsPbX}_3$  perovskite NCs are synthesized *via* a modified hot injection approach proposed by Protesescu *et al.*<sup>46</sup> Fig. 1d presents a typical synthesis process; Mn-doped perovskite NCs are formed after injecting Cs oleate into a solution containing metal halide salts ( $\text{PbCl}_2$  and  $\text{MnCl}_2$ ). However, metal halide salts are of low solubility in nonpolar solvents,<sup>47</sup> thus resulting in low doping efficiency (Table 1). Moreover, since the ratio of cations to anions is fixed at the stoichiometric ratio of metal halide salts, it is not possible to precisely tune the composition of Mn-doped perovskite NCs. In particular, it is difficult to create an environment with rich halide ions, which has been proved to favour the formation of Mn-doped  $\text{CsPbX}_3$  perovskite NCs with high stability and improved PLQY.<sup>48-51</sup> To promote doping and emission efficiency of Mn-doped  $\text{CsPbX}_3$  perovskite NCs, the authors recently proposed a novel “two step hot injection approach”.<sup>52</sup> As shown in Fig. 1e, metal acetate salts (Pb acetate and Mn acetate) with good solubility in a solution containing oleic acid are chosen as the Pb source and Mn source, respectively. The first step is to inject an excessive amount of alkylamine halide salts and induce the formation of  $[\text{PbX}_6]^{4-}$  clusters and  $[\text{MnX}_6]^{4-}$  clusters with a high coordination number. The second step is to inject Cs oleate, which can make clusters grow into Mn-doped perovskite NCs. In our method, all sources are independent of each other, so the composition of the final NCs is completely

Table 1 Synthesis information on Mn-doped perovskite nanocrystals

| Materials                               | Precursors   | Mn : Pb                                 | Temp/°C  | Method          | Doping/% | QY/% | References |
|---|--|---|----------|-----------------|----------|------|------------|
| CsPbCl <sub>3</sub> : Mn NCs            | MnCl <sub>2</sub> , PbCl <sub>2</sub> , and TOP                      | 2.5 : 1                                 | 185      | Hot injection   | 9.6      | 27   | 15         |
|   | MnCl <sub>2</sub> , PbCl <sub>2</sub> , and TOP                      | 0.4 : 1                                 | 185      | Hot injection   | 12       | 27   | 40         |
|   | MnCl <sub>2</sub> , PbCl <sub>2</sub> , and TOP                      | 2 : 1                                   | 150      | Hot injection   | 3.1      | 58.8 | 130        |
|   | MnCl <sub>2</sub> , PbCl <sub>2</sub> , TOP, and RNH <sub>3</sub> Cl | 0.05 : 1                                | 180      | Hot injection   | 1.3      | 27   | 131        |
|   | MnCl <sub>2</sub> , PbCl <sub>2</sub> , TOP, and RNH <sub>3</sub> Cl | 1 : 1                                   | 190      | Microwave       | 6.5      | 65   | 132        |
|   | MnOAc <sub>2</sub> , PbOAc <sub>2</sub> , and RNH <sub>3</sub> Cl    | 0.4 : 1                                 | 210      | Hot injection   | 17.3     | 84.4 | 133        |
|   | MnCl <sub>2</sub> , PbCl <sub>2</sub> , TOP, and CuCl <sub>2</sub>   | 0.2 : 1                                 | 260      | Hot injection   | 2        | 68   | 50         |
|   | MnCl <sub>2</sub> , PbCl <sub>2</sub> , TOP, and NiCl <sub>2</sub>   | 1 : 1                                   | 190      | Hot injection   | 1.97     | 70   | 134        |
|   | MnCl <sub>2</sub> and PbCl <sub>2</sub>                              | 1.4 : 1                                 | 200      | Hot injection   | 0.2      | 60   | 14         |
|   | MnCl <sub>2</sub> and PbCl <sub>2</sub>                              | 10 : 1                                  | 170      | Hot injection   | 27       | 54   | 35         |
|   | MnCl <sub>2</sub> and PbCl <sub>2</sub>                              | 0.6 : 1                                 | 150      | Hot injection   | 5.8      | 12.7 | 42         |
|   | MnCl <sub>2</sub> and PbCl <sub>2</sub>                              | 5 : 1                                   | RT       | LARP            | 28       | 41   | 135        |
|   | MnCl <sub>2</sub> and PbCl <sub>2</sub>                              | 0.6 : 1                                 | 200      | Solvothermal    | 1        | 64.2 | 136        |
|   | MnCl <sub>2</sub> and PbCl <sub>2</sub>                              | 3 : 1                                   | RT       | Ultrasonication | 3        | 26   | 44         |
|   | MnCl <sub>2</sub> and PbCl <sub>2</sub>                              | 2 : 1                                   | RT       | Ultrasonication | 11.8     | 41.1 | 41         |
|   | MnOAc <sub>2</sub> , PbCl <sub>2</sub> , and TMS-Cl                  | 1 : 1                                   | 170      | Hot injection   | 10.3     | 35   | 49         |
|   | MnOAc <sub>2</sub> , PbOAc <sub>2</sub> , and HCl                    | 0.1 : 1                                 | RT       | LARP            | 1.0      | 40   | 137        |
|   | CsPbCl <sub>3</sub> : Mn NPLs  | MnCl <sub>2</sub> and PbCl <sub>2</sub> | 0.05 : 1 | RT              | LARP     | 0.8  | 20         |
| MnCl <sub>2</sub> and PbCl <sub>2</sub> |  | 1 : 1                                   | 230      | Hot injection   | 50.4     | 36   | 38         |
| MnCl <sub>2</sub> and PbCl <sub>2</sub> |  | 0.8 : 1                                 | 200      | Solvothermal    | 8.8      | 20.8 | 139        |



controllable. More importantly, we used Mn : Pb in a 3 : 7 molar ratio to get 17.3% doping in cubic CsPbCl<sub>3</sub> nanocubes. In fact, metal acetate salts have been reported as unsuitable dopants, but Mn-doped CsPbCl<sub>3</sub> perovskite NCs achieved the highest 48.5% doping efficiency and 84.4% quantum efficiency at the same time *via* the two-step hot injection.

In luminescent Mn-doped NCs, surface states serve as critical determinants of emission behavior.<sup>53</sup> At low Mn-doping conditions, CsPbCl<sub>3</sub> NCs demonstrate enhanced PL intensity with increasing Mn concentrations, a behavior directly correlated with MnCl<sub>2</sub>-mediated chloride vacancy passivation during colloidal synthesis.<sup>14</sup> However, excessive dopant incorporation induces deterioration of PLQY in Mn-doped CsPbCl<sub>3</sub>, which is due to the dominant Mn–Mn exchange interactions that supersede exciton-to-dopant energy transfer process.<sup>40</sup> This fundamental competition between defect passivation and dopant–dopant coupling establishes a concentration threshold for maximizing the luminescent performance.

## 2.2 Tetrahedral units for green emission

The green emission of Mn(II) halide complexes originates from the tetrahedrally coordinated Mn(II) units, which is mostly [MnX<sub>4</sub>]<sup>2-</sup> (X = Cl, Br, I) for Mn(II) halide complexes. Tetrahedrally coordinated Mn(II) exhibits green emission, and the emission of Mn(II) tetrahedral (*T<sub>d</sub>*) crystal fields has been studied for decades.<sup>54</sup> In a Mn(II) *T<sub>d</sub>* field with oxide as ligands, green emission is obtained with a narrow FWHM.<sup>55,56</sup> However, the main drawbacks of the oxide ligand *T<sub>d</sub>* field for Mn(II) are slow emission decay and the high reaction temperature.

In 2019, Kovalenko *et al.* synthesized a series of *T<sub>d</sub>* [MnX<sub>4</sub>]<sup>2-</sup> complexes with green emission. They found that the crystal field effects and spin–orbit coupling of Mn<sup>2+</sup> determine the optical properties of manganese(II) complexes such as PL peak positions, FWHM and emission decay.<sup>57</sup>

**2.2.1 Structure of Mn(II) halide complexes consisting of tetrahedral units.** The formula of [MnX<sub>4</sub>]<sup>2-</sup> halide complexes is usually A<sub>2</sub>MnX<sub>4</sub> or AMnX<sub>4</sub>. A can be an inorganic cation like Cs<sup>+</sup> (ref. 58) or organic cations such as organic ammonium<sup>59–65</sup> and phosphorus-containing<sup>19,66,67</sup> groups. To charge balance the Mn halide system, it should require two +1 cations<sup>68</sup> or one +2 cation<sup>19</sup> to push the [MnX<sub>4</sub>]<sup>2-</sup> tetrahedron further apart.<sup>62</sup> AMnX<sub>4</sub> containing a divalent A-site typically incorporates phosphonium cations (*e.g.*, (C<sub>40</sub>H<sub>38</sub>P<sub>2</sub>)MnBr<sub>4</sub>,<sup>69</sup> (C<sub>38</sub>H<sub>34</sub>P<sub>2</sub>)MnBr<sub>4</sub>,<sup>19</sup> [DMAEMP]MnCl<sub>4</sub> and [PDMIm]<sub>2</sub>MnCl<sub>4</sub> (ref. 63)), crystallizing in triclinic or monoclinic systems. A<sub>2</sub>MnX<sub>4</sub> derivatives with monovalent A-site cations primarily utilize ammonium cations (*e.g.*, (C<sub>10</sub>H<sub>16</sub>N)<sub>2</sub>MnX<sub>4</sub> (ref. 23 and 70) and (C<sub>8</sub>H<sub>20</sub>N)<sub>2</sub>MnBr<sub>4</sub> (ref. 16)) or phosphonium cations (*e.g.*, (BzTPP)<sub>2</sub>MnBr<sub>4</sub> (ref. 71) and (BuTPP)<sub>2</sub>MnBr<sub>4</sub> (ref. 72)), typically adopting monoclinic symmetry. Both AMnX<sub>4</sub> and A<sub>2</sub>MnX<sub>4</sub> are green-emissive Mn(II) halides that exhibit zero-dimensional (0D) architectures characterized by isolated [MnX<sub>4</sub>]<sup>2-</sup> tetrahedral units (Fig. 2b and c).

**2.2.2 Optical properties of green Mn(II) halide complexes.** Optical properties of Mn(II) halide complexes, including PL, PLE and Abs, are derived from the d orbital of Mn(II) in different crystal fields. As for green [MnX<sub>4</sub>]<sup>2-</sup> complexes, the splitting of the d orbital is affected by the tetrahedral field, as shown in Fig. 2d.<sup>57,73</sup> Excitation of green *T<sub>d</sub>* Mn(II) halide complexes

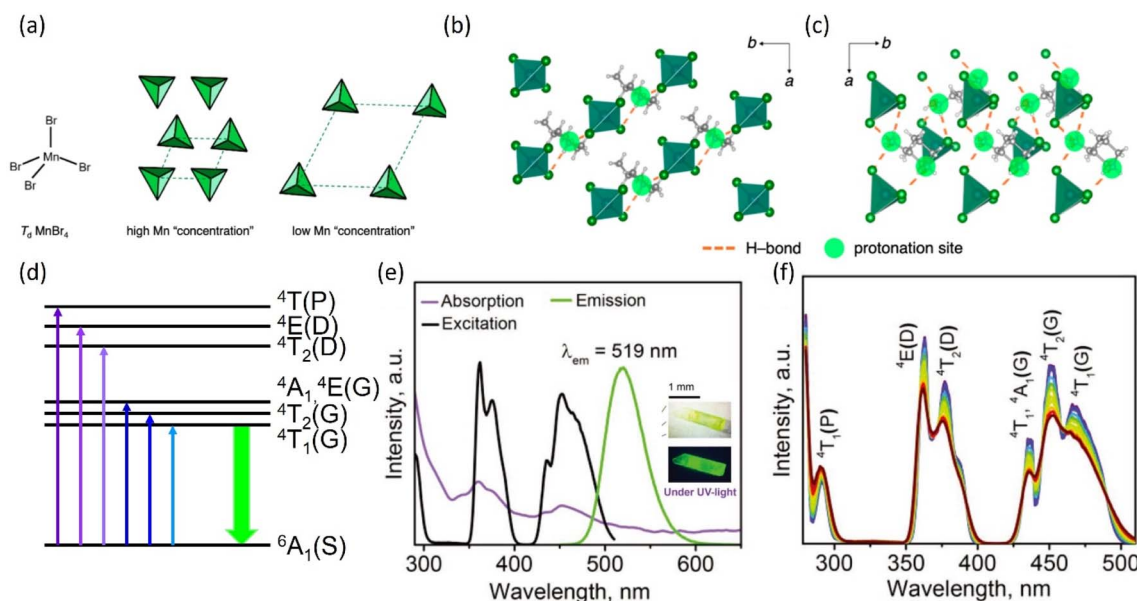


Fig. 2 Structure and luminescent properties of four-fold-coordinated [MnX<sub>4</sub>]<sup>2-</sup> complexes. (a) Illustration of manganese bromide in a tetrahedral environment with short Mn–Mn distances (high Mn “concentration”) and long Mn–Mn distances (low Mn “concentration”). (b) Crystal structure of A<sub>2</sub>MnX<sub>4</sub> with +1 cation. (c) Crystal structure of AMnX<sub>4</sub> with +2 cation. (d) Schematic diagram showing the emission mechanism of green emissive Mn(II) halide complexes. (e) Absorption, steady-state PLE and PL spectra at 298 K and (f) temperature-dependent PLE spectra of 1R/1S Mn(II) halide complexes. (a)–(c) Reproduced with permission from ref. 62. Copyright 2020, American Chemistry Society. (e and f) Reproduced with permission from ref. 65. Copyright 2023, Wiley-VCH.



mainly comes from two transitions: group one of lower energy of  ${}^6A_1$  to  ${}^4T_1(G)$ ,  ${}^4T_2(G)$ ,  ${}^4A_1$ , and  ${}^4E(G)$  transitions and group two of higher energy of  ${}^6A_1(S)$  to  ${}^4T_2(D)$ ,  ${}^4E(D)$ , and  ${}^4T(P)$  transitions. The group of higher energy sometimes also contains  ${}^6A_1$  to  ${}^4T(P)$  transition. PL emission originates from the radiative recombination from  ${}^4T_1(G) \rightarrow {}^6A_1(S)$  transition.

For example, Seshadri *et al.* synthesized  $(TMPTA)_2MnBr_4$  exhibiting green emission at 520 nm with a PLQY of 98%.<sup>62</sup> The excitation spectrum features two primary transitions:  ${}^6A_1$  to  ${}^4T_1(G)$ ,  ${}^4T_2(G)$ ,  ${}^4A_1$ , and  ${}^4E(G)$  (430–490 nm) and  ${}^6A_1(S)$  to  ${}^4T_2(D)$ ,  ${}^4E(D)$ , and  ${}^4T(P)$  (350–390 nm). Artem'ev *et al.* reported R/S-[MBA-Me<sub>3</sub>]MnBr<sub>4</sub> with emission at 519 nm (PLQY = 98%),<sup>65</sup> where excitation corresponds to  ${}^6A_1$  to  ${}^4T_1(G)$ ,  ${}^4T_2(G)$ ,  ${}^4A_1$ , and  ${}^4E(G)$  and  ${}^6A_1(S)$  to  ${}^4T_2(D)$ ,  ${}^4E(D)$ , and  ${}^4T(P)$  transitions (Fig. 2e and f).<sup>65,73</sup> Similarly, Ma *et al.* synthesized  $(C_{38}H_{34}P_2)MnBr_4$  single crystals expressing green emission (517 nm, 95%) with identical excitation characteristics.<sup>19</sup> The excitation spectrum has the same features as the absorption spectrum corresponding to two group transitions of blue and UV regions.

The photoluminescent properties of Mn(II) halides are governed by ligand-field splitting and spin-orbit coupling effects, which dictate emission energies and bandwidths.<sup>57</sup> The electron interaction between neighbouring Mn<sup>2+</sup> plays an important role in the PL performance. A tendency similar to concentration quenching in Mn-doped NCs is observed in Mn(II) halides.<sup>62</sup> The PLQY of green  $[MnX_4]^{2-}$  halide complexes is related to Mn “concentration” (Fig. 2a), which can be evaluated from the Mn–Mn distance (Fig. 3),<sup>59,60,62,63,66,68,74,75</sup> which is interpreted as analogous to the “concentration quenching effect” in Mn<sup>2+</sup>-doped inorganic phosphors.<sup>76</sup> As for 0D Mn(II) complexes, the longer Mn–Mn distances weakened the nonradiative energy transfer between neighbouring Mn<sup>2+</sup> centers in  $[MnX_4]^{2-}$  and promoted the radiative recombination of  ${}^4T_1(G) \rightarrow {}^6A_1(S)$  transition, achieving a higher PLQY.<sup>63</sup> In organic–inorganic hybrid manganese halides, photoluminescence quenching

originates from nonradiative decay pathways driven by multiphonon relaxation processes mediated through interaction between  $[MnCl_4]^{2-}$  and A-cation<sup>77</sup> and between the Mn center and X ligands.<sup>23</sup>

Beyond the PLQY, the Stokes shift critically governs luminescent behavior in Mn(II) halides. Recent studies demonstrate that controlled tetrahedral distortion enables systematic emission tuning: Zhang *et al.*<sup>78</sup> and Qi *et al.*<sup>79</sup> achieved spectral shifts from green through yellow to red by modifying  $[MnX_4]^{2-}$  distortions. This tunability arises from distortion-induced modulation of both crystal field splitting and electron–phonon coupling. Pronounced angular distortions reduce the  ${}^4T_1(G)$ – ${}^6A_1(S)$  energy gap. During triclinic-to-orthorhombic phase transitions, Br–Mn–Br angle alterations redshift emission to 555 nm with increasing Dq/B ratio.<sup>79</sup>

This reflects enhanced ligand field strength and decreased  ${}^4T_1(G)$ – ${}^6A_1(S)$  energy separation. Distorted tetrahedra intensify lattice vibrations, broadening emission linewidths from 51 nm to 68 nm *via* strengthened electron–phonon coupling.<sup>80</sup> Crucially, bond-angle distortions dominate these spectral modifications, while bond-length variations prove negligible.<sup>79</sup> The pseudohalide series further confirms this mechanism: progressive tetrahedral distortion elevates dipole moments, enhancing crystal field strength and inducing correlated emission redshifts and strengthened electron–phonon coupling, inducing bandwidth broadening.<sup>78</sup> Thus, angular distortion constitutes a rational design strategy for tailoring Mn(II) halide emission profiles.

In summary, the photoluminescence quantum yield (PLQY) of Mn(II) halides is primarily governed by Mn–Mn interatomic distances, which control concentration quenching effects. Concurrently, the Stokes shift is modulated by angular distortion within the crystal structure, which also dictates emission peak positions. Furthermore, bond-angle distortions and bond-length variations from organic A-site cations<sup>23,26,81,82</sup> influence electron–phonon coupling, determined the FWHM of luminescence.

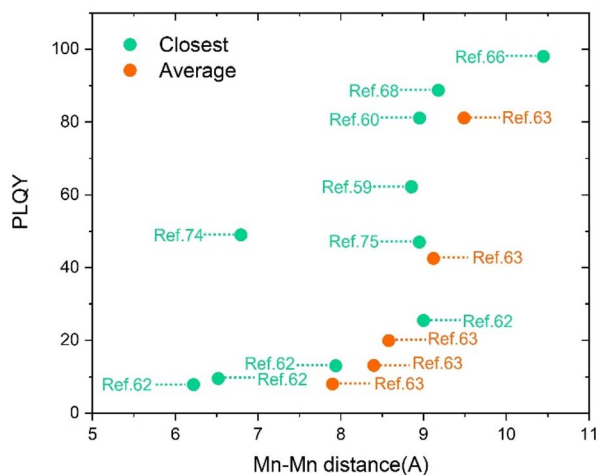


Fig. 3 Correlation between the shortest Mn–Mn distances and the PLQY. Red scatters represent samples evaluated *via* the average Mn–Mn distance and black scatters represent samples evaluated *via* the closest Mn–Mn distance.

### 2.3 Octahedral units for red emission

The red emission of Mn(II) complexes is derived from the six coordinated Mn(II) octahedral units, which are mostly  $[MnX_6]^{4-}$  ( $X = Cl, Br, I$ ) for Mn(II) halide complexes. The red emission of Mn(II) in the octahedral ( $O_h$ ) crystal field mainly arises from a stronger ligand field compared to the green emission of Mn(II) in the  $T_d$  environment.<sup>57</sup>

**2.3.1 Structure of Mn(II) halide complexes consisting of octahedral units.** For red emissive Mn(II) halide complexes, the emission comes from  $O_h$   $[MnX_6]^{4-}$  units, as shown in Fig. 4a. However, different from isolated  $[MnX_4]^{2-}$  units of green emissive Mn(II) halide complexes, a  $[MnX_6]^{4-}$  unit can be isolated or connect to another  $[MnX_6]^{4-}$  unit. According to the connection between the  $O_h$   $[MnX_6]^{4-}$  units, the structure of red emissive Mn(II) halides is crystallized to 0D, 1D and 2D structures, and the 0D structure can be further divided into an isolated structure and a partially connected structure.



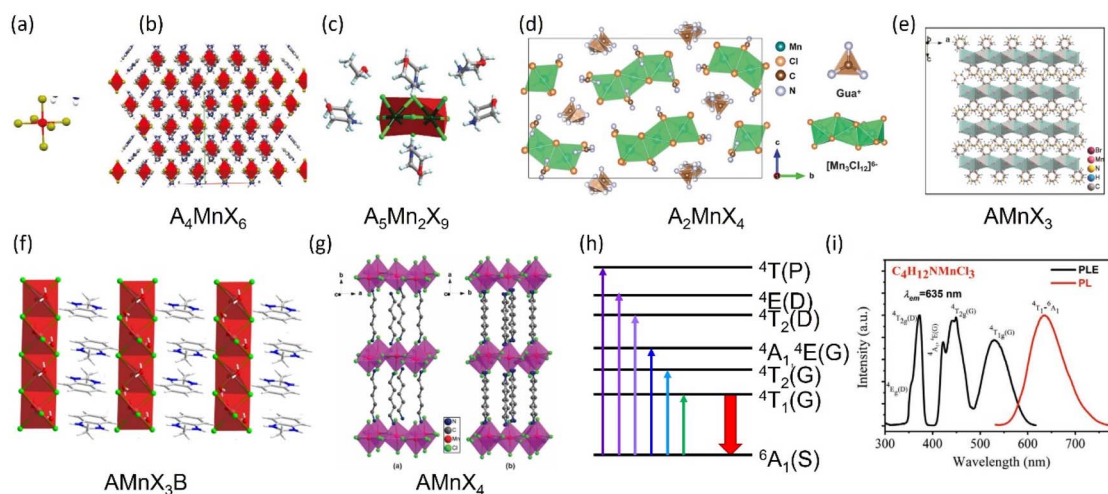


Fig. 4 Structural configurations of octahedral  $[\text{MnX}_6]^{4-}$  complexes in  $\text{Mn}(\text{II})$  halides. (a) Schematic representation of the fundamental  $[\text{MnX}_6]^{4-}$  coordination unit. (b) Zero-dimensional (0D) structure featuring isolated  $[\text{MnX}_6]^{4-}$  octahedra (exemplified by  $\text{A}_4\text{MnX}_6$ ). (c) 0D structure containing face-sharing  $[\text{Mn}_2\text{X}_9]^{5-}$  units (represented by  $\text{A}_5\text{Mn}_2\text{X}_9$ ). (d) 0D structure with face-sharing  $[\text{Mn}_3\text{X}_{12}]^{5-}$  units ( $\text{A}_2\text{MnX}_4$ ). (e) One-dimensional (1D) chain structure composed of face-sharing octahedra ( $\text{AMnX}_3$ ). (f) 1D chain structure with edge-sharing octahedra ( $\text{AMnX}_3\text{B}$ ). (g) Two-dimensional (2D) layered structure ( $\text{AMnX}_4$ ). (h) Schematic diagram showing the emission mechanism of red emissive  $\text{Mn}(\text{II})$  halide complexes. (i) PLE and PL spectra of  $\text{C}_4\text{H}_{12}\text{NMnX}_3$   $\text{Mn}(\text{II})$  halide complexes. (a and b) Reproduced with permission from ref. 17. Copyright 2021, Wiley-VCH. (c) Reproduced with permission from ref. 61. Copyright 2019, Royal Society of Chemistry. (d) Reproduced with permission from ref. 83. Copyright 2021, Wiley-VCH. (e) Reproduced with permission from ref. 84. Copyright 2018, Royal Society of Chemistry. (f) Reproduced with permission from ref. 21. Copyright 2024, American Chemical Society. (g) Reproduced with permission from ref. 92. Copyright 2016, American Chemical Society. (i) Reproduced with permission from ref. 16. Copyright 2021, Wiley-VCH.

Here, we use the formula  $\text{A}_n\text{MnX}_n$  to illustrate  $O_h$   $[\text{MnX}_6]^{4-}$  red halide complexes. A is mainly +1 or +2 cation for red  $[\text{MnX}_6]^{4-}$  halide complexes. For the isolated 0D structure, the  $\text{Mn}^{2+}$  ion is surrounded by six halide ions to form a unique  $[\text{MnX}_6]^{4-}$  octahedron with the formula  $\text{A}_4\text{MnX}_6$ , as shown in Fig. 4b.<sup>17</sup> For the partially connected 0D structure, the  $\text{Mn}^{2+}$  ion is encircled by six halide ions to form  $[\text{MnX}_6]^{4-}$  octahedral units, then two or three  $[\text{MnX}_6]^{4-}$  units further form a unique  $[\text{Mn}_2\text{X}_9]^{5-}$  or  $[\text{Mn}_3\text{X}_{12}]^{6-}$  unit by face-sharing (Fig. 4c and d).<sup>61,83</sup> The unit is separated by +1 cation A to form a 0D structure with the formula  $\text{A}_{(n+3)}\text{Mn}_n\text{X}_{(3n+3)}$ , where  $n$  stands for the number of  $[\text{MnX}_6]^{4-}$  octahedra in face-sharing to form a unique  $[\text{Mn}_n\text{X}_{3n+3}]^{(n+3)-}$  unit.

1D  $\text{Mn}(\text{II})$  halide structures feature  $[\text{MnX}_6]^{4-}$  octahedral units where the  $\text{Mn}^{2+}$  ions coordinate with six ligands. These octahedra form linear chains through face-sharing along specific crystallographic directions (Fig. 4e)<sup>16,84–88</sup> or via edge-sharing connection (Fig. 4f).<sup>21,89</sup> Face-shared 1D assemblies adopt the general formula  $\text{AMnX}_3$ ,<sup>85,90</sup> while the edge-shared counterparts conform to  $\text{AMnX}_3\text{B}$  (B = neutral ligands, e.g.,  $\text{H}_2\text{O}$ ).<sup>21,91</sup> For the 2D structure, each  $\text{Mn}^{2+}$  is also surrounded by six  $\text{X}^-$ . The  $[\text{MnX}_6]^{4-}$  octahedra share corners to form a two-dimensional network with +2 cation A occupying the space enclosed by the  $[\text{MnX}_6]^{4-}$  octahedron (Fig. 4g). In the inorganic layers, each Mn atom is surrounded by six Cl atoms, in which four equatorial Cl atoms bridge four different Mn atoms to form two-dimensional  $[\text{MnCl}_4]_n^{2-}$  inorganic layers, as shown in Fig. 4f.<sup>92</sup> Thus, the formula of 2D  $\text{Mn}(\text{II})$  halide complexes is  $\text{AMnX}_4$  with +2 A cation.

The d–d transition of  $\text{Mn}^{2+}$  in the centrosymmetric octahedral crystal field ( $O_h$ ) is forbidden by the Laporte selection rule, leading to a low PLQY.<sup>57</sup> Thus, distortion of  $[\text{MnX}_6]^{4-}$  octahedra in the structure is necessary for red emissive  $\text{Mn}(\text{II})$  halide complexes to achieve superior luminescence performance. Due to the diverse crystal structures, luminescent properties of red manganese halides are more complex than those of green manganese halides.

**2.3.2 Optical properties of red  $\text{Mn}(\text{II})$  halide complexes.** Similar to tetrahedral  $[\text{MnX}_4]^{2-}$  complexes, the optical properties of octahedral  $[\text{MnX}_6]^{4-}$  systems arise from d-orbital splitting in  $O_h$  symmetry (Fig. 4h).<sup>73</sup> Excitation involves three characteristic energy regions: the lowest-energy  ${}^6\text{A}_1(\text{S})$  to  ${}^4\text{T}_1(\text{G})$  transition in the green region, intermediate  ${}^6\text{A}_1(\text{S})$  to  ${}^4\text{T}_2(\text{G})$ ,  ${}^4\text{A}_1$ , and  ${}^4\text{E}(\text{G})$  transitions, transitions in blue, and higher-energy  ${}^6\text{A}_1(\text{S})$  to  ${}^4\text{T}_2(\text{D})$ ,  ${}^4\text{E}(\text{D})$ , and  ${}^4\text{T}(\text{P})$  transitions. The emission consistently originates from the  ${}^4\text{T}_1(\text{G})$  to  ${}^6\text{A}_1(\text{S})$  radiative transition (Fig. 4h and i).

This excitation–emission scheme persists across diverse structures: Wang *et al.* synthesized isolated 0D  $(\text{ABI})_4\text{MnBr}_6$  (629 nm, 80%),<sup>17</sup> with excitations from  ${}^6\text{A}_1(\text{S})$  to  ${}^4\text{T}_1(\text{G})$ ,  ${}^4\text{T}_2(\text{G})$ ,  ${}^4\text{A}_1$ , and  ${}^4\text{E}(\text{G})$  (525 nm, 374 nm and 440 nm) and  ${}^6\text{A}_1(\text{S})$  to  ${}^4\text{T}_2(\text{D})$  and  ${}^4\text{E}(\text{D})$  (340 nm and 365 nm). Wu *et al.* reported partially connected 0D  $(\text{Gua})_2\text{MnCl}_4$  (650 nm, 76%) with similar excitations.<sup>83</sup> Ju *et al.* demonstrated equivalent transitions in 1D  $\text{C}_4\text{-H}_{12}\text{NMnCl}_3$  (635 nm, 91.8%).<sup>16</sup>

The distinct photoluminescent properties of green- and red-emissive  $\text{Mn}(\text{II})$  halide complexes fundamentally arise from differences in crystal field splitting within tetrahedral  $T_d$   $[\text{MnX}_4]^{2-}$  and octahedral  $O_h$   $[\text{MnX}_6]^{4-}$  coordination



Table 2 Comparisons of red Mn(II) complexes in structure and luminescent properties

| Sample   | Dimension | Peak/nm | PLQY/% | Stokes shift/nm | Closest Mn–Mn distance/Å | $\Delta d/\text{Å}$ | $\Delta\theta/^\circ$ | Ref.      |
|--|-----------|---------|--------|-----------------|--------------------------|---------------------|-----------------------|-----------|
| $(\text{CH}_6\text{N}_3)_2\text{MnCl}_4$   | 0D        | 642     | 69, 76 | 125             | 3.323                    | 0.0057              | 4.65                  | 83 and 85 |
| $(\text{ABI})_4\text{MnBr}_6$  | 0D        | 629     | 80     | 289             | 8.642                    | 0.0086              | —                     | 17        |
| $(\text{ABI})_4\text{MnCl}_6$  | 0D        | 630     | 99     | 370             | —                        | 0.0413              | 3.50                  | 82        |
| $(\text{MBI})\text{MnCl}_4 \cdot \text{H}_2\text{O}$   | 1D        | 650     | 50     | 300             | —                        | 0.0260              | 3.93                  |           |
| $(\text{MBZI})(\text{MnCl}_3\text{H}_2\text{O}) \cdot \text{H}_2\text{O}$                              | 1D        | 632     | 71     | 181             | —                        | 0.0253              | 4.09                  | 21        |
| $(\text{C}_8\text{H}_9\text{N}_2)_n\{(\text{MnCl}_3(\text{H}_2\text{O}) \cdot \text{H}_2\text{O})\}_n$ | 1D        | 645     | 13     | 200             | 3.645                    | 0.0251              | 3.95                  | 89        |
| $(\text{TMSO})\text{MnCl}_3$   | 1D        | 629     | 86     | ~179            | 3.243                    | 0.0069              | 6.00                  | 90        |
| $(\text{TMSO})\text{MnBr}_3$   | 1D        | 626     | 58     | ~176            | 3.377                    | 0.0075              | 4.93                  |           |
| $\text{D}-(\text{C}_6\text{H}_{17}\text{NO}_2)[\text{MnCl}_3]$   | 1D        | 646     | 67     | —               | 3.213                    | 0.0081              | 5.69                  | 86        |
| $\text{L}-(\text{C}_9\text{H}_{17}\text{NO}_2)[\text{MnCl}_3]$   | 1D        | 656     | 57     | —               | 3.210                    | 0.0079              | 5.65                  |           |
| $\text{CsMnCl}_3$  | 1D        | 644–665 | 42     | —               | 4.1                      | 0.0074              | 4.23                  | 94        |

environments, governing both excitation and emission characteristics.<sup>16,73,77</sup> The associated Stokes shift between  ${}^6\text{A}_1(\text{S})$  to  ${}^4\text{T}_1(\text{G})$  excitation and  ${}^4\text{T}_1(\text{G})$  to  ${}^6\text{A}_1(\text{S})$  emission further correlates with these distinct geometries.<sup>77</sup> While Mn–Mn interatomic distances influence the photoluminescence quantum yield (PLQY) of six-coordinated Mn(II) halides by mitigating concentration quenching,<sup>93</sup> the luminescence efficiency in red-emitting systems is more critically governed by octahedral distortion, as mandated by the Laporte selection rule.

For instance, comparing 0D red manganese halides:  $(\text{ABI})_4\text{MnBr}_6$  achieves 80% PLQY (Mn–Mn > 8.74 Å),<sup>17</sup> compared to  $(\text{Gua})_2\text{MnCl}_4$  (76%, 8.551 Å)<sup>83</sup> and  $\text{CsMnCl}_3$  (42%, 4.1 Å).<sup>94</sup> However, due to the divisive crystal structure of red manganese halides, the “concentration” of Mn is not a reliable parameter.<sup>76</sup> Different from green manganese halides, the Mn–Mn distance in red manganese halides is not the main influencing parameter. Paradoxically, 1D  $\text{CsMnCl}_3$  exhibits a longer nearest Mn–Mn distance (4.1 Å) yet a lower PLQY (42%)<sup>94</sup> than  $(\text{TMSO})\text{MnCl}_3$  (3.24 Å, 86%)<sup>90</sup> and  $(\text{C}_9\text{H}_{17}\text{NO}_2)[\text{MnCl}_3]$  (3.213 Å, 67%)<sup>86</sup> (Table 2), demonstrating that the Mn–Mn distance exerts

a comparatively minor influence on the PLQY in red-emitting systems due to the Laporte selection rule. Furthermore, the significant PLQY difference between  $(\text{CH}_3)_4\text{NMnCl}_3$  (94%) and  $(\text{CH}_6\text{N}_3)_2\text{MnCl}_4$  (69%)<sup>85</sup> underscores the dominant role of distortion. As displayed in Table 2 and Fig. 5, the high-PLQY of red Mn halides consistently exhibit elevated bond-length ( $\Delta d$ ) or bond-angle ( $\Delta\theta$ ) distortion parameters (defined below), contrasting with green emitters where the Mn–Mn distance is paramount. This highlights the critical constraint of the Laporte rule on six-coordinated Mn(II) luminescence, necessitating significant focus on structural distortion.

$$\Delta d^2 = \frac{1}{6} \sum_{i=2}^6 [(d_i - d_{\text{ave}})/d_{\text{ave}}]^2 \quad (1)$$

$$\Delta\theta^2 = \frac{1}{12} \sum_{i=1}^{12} [(\theta_i - 90^\circ)/90^\circ]^2 \quad (2)$$

where  $d_{\text{ave}}$  is the average Mn–Br bond lengths,  $d_i$  is the individual Mn–X (X = Cl, Br or O) bond length, and  $\theta_i$  is a single Br–Mn–Br bond angle.

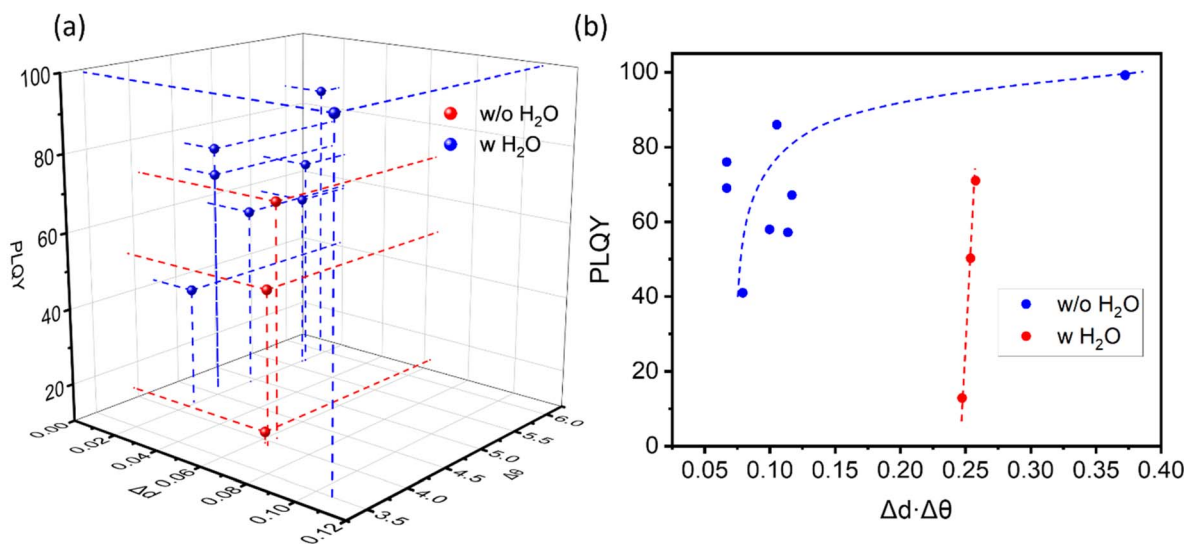


Fig. 5 PLQY and structure. (a) PLQY with Mn–X distance distortion ( $\Delta d$ ) and X–Mn–X angle distortion ( $\Delta\theta$ ). (b) PLQY with the composite parameter  $\Delta d \cdot \Delta\theta$ .



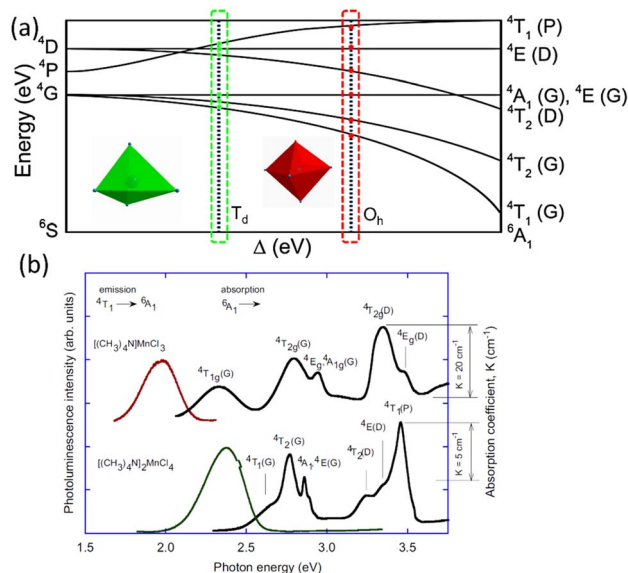


Fig. 6 (a) Tanabe–Sugano diagrams for  $\text{Mn}^{2+}$  ( $3d^5$ ). (b) PL and PLE of green  $[(\text{CH}_3)_4\text{N}]_2\text{MnCl}_4$  and red  $[(\text{CH}_3)_4\text{N}]\text{MnCl}_3$ . (a) Reproduced with permission from ref. 58. Copyright 2021, Wiley-VCH. (b) Reproduced with permission from ref. 73. Copyright 2009, Elsevier.

Compounds incorporating Mn–O bonds from  $\text{H}_2\text{O}$  ligands exhibit markedly higher  $\Delta d$  and  $\Delta\theta$  values yet significantly reduced PLQY, warranting separate analysis of hydrated and anhydrous systems. To assess octahedral distortion, we introduce the composite parameter  $\Delta d \cdot \Delta\theta$ . The PLQY exhibits no monotonic dependence on  $\Delta d$  or  $\Delta\theta$  alone (Table 2 and Fig. 5a). For example,  $(\text{TMSO})\text{MnCl}_3$  showed a higher PLQY (86%)<sup>90</sup> despite the lower  $\Delta d$  (0.0069 Å) than  $\text{CsMnCl}_3$  (42%, 0.0074 Å).<sup>94</sup> Similarly,  $(\text{ABI})_4\text{MnCl}_6$  exhibited a higher PLQY (99%)<sup>82</sup> despite

but a lower  $\Delta\theta$  ( $3.5^\circ$ ) than  $(\text{C}_9\text{H}_{17}\text{NO}_2)\text{MnCl}_3$ .<sup>86</sup> The PLQY for red Mn halides demonstrates a monotonic increase with the composite distortion parameter  $\Delta d \cdot \Delta\theta$  (Fig. 5b). Although hydrated compounds exhibit greater distortion, their PLQY is consistently lower, attributed to detrimental perturbations of the crystal field by O ligands. Furthermore, water-mediated structure regulation can introduce potential emission instability, causing luminescence fluctuations.

Therefore, achieving stable, high-efficiency red emission necessitates the use of anhydrous, halide-coordinated  $\text{Mn}(\text{II})$  systems, where optimized octahedral distortion maximizes radiative efficiency within the constraints of the Laporte rule.

#### 2.4 Structure regulation between red and green emissions

Emission mainly depends on the  $T_d$  and  $O_h$  ligand fields of  $\text{Mn}^{2+}$ , and thus changing the coordination environment of  $\text{Mn}^{2+}$  can influence the optical properties of  $\text{Mn}(\text{II})$  halide complexes. For  $\text{Mn}(\text{II})$  halide complexes with same components, changing the coordination geometry around  $\text{Mn}^{2+}$  from four-fold-coordinated  $[\text{MnX}_4]^{2-}$  to six-fold-coordinated  $[\text{MnX}_6]^{4-}$  changes the emission from green to red.<sup>73,91</sup> Furthermore, besides halides, O also participates in the crystal field according to Mn–O bonding and change the coordination number of  $\text{Mn}^{2+}$ , making  $\text{Mn}(\text{II})$  complexes sensitive to environment.<sup>64</sup> The structure regulation between four  $\text{Mn}(\text{II})$  complexes in  $T_d$  and  $O_h$  ligand fields expands potential applications for low-dimensional  $\text{Mn}(\text{II})$  halide complexes.

The emission characteristics of  $\text{Mn}(\text{II})$  halides are fundamentally governed by ligand field symmetry, where tetrahedral ( $[\text{MnX}_4]^{2-}$ ) and octahedral ( $[\text{MnX}_6]^{4-}$  or  $[\text{MnX}_4\text{L}_2]^{2-}$ ) coordination geometries yield distinct green and red luminescence, respectively.<sup>73,91</sup> Phase transitions between these configurations

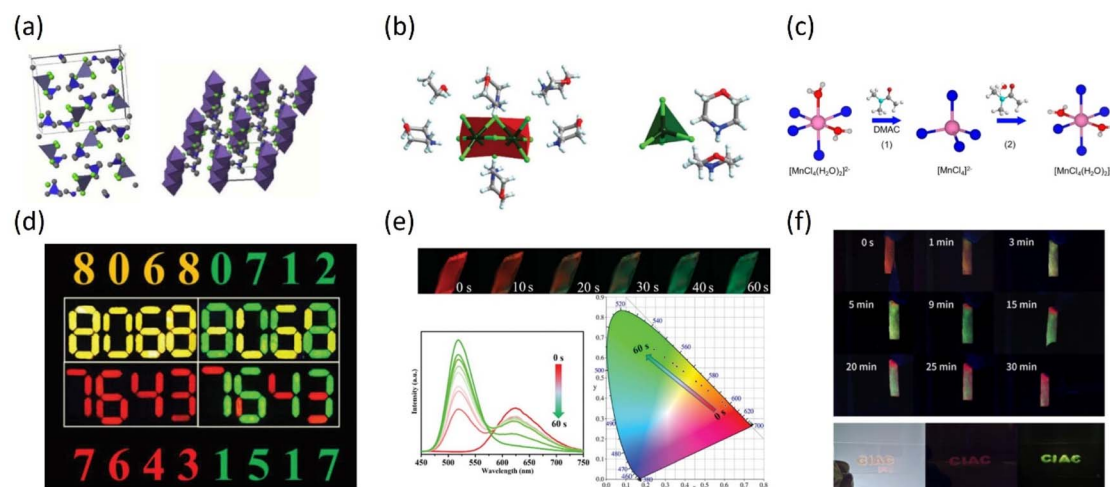


Fig. 7 Structure and luminescent properties of  $\text{Mn}(\text{II})$  halide complexes with phase regulation between red and green emissions. (a) Crystal structure of green  $(\text{C}_5\text{H}_6\text{N})_2\text{MnBr}_4$  and red  $\text{C}_5\text{H}_6\text{NMnBr}_3$ . (b) Crystal structure of  $(\text{C}_4\text{NOH}_{10})_5\text{Mn}_2\text{Cl}_9 \cdot \text{C}_2\text{H}_5\text{OH}$  and  $(\text{C}_4\text{NOH}_{10})_2\text{MnCl}_4$ . (c) Phase regulation between  $\text{Cs}_2[\text{MnX}_4(\text{H}_2\text{O})_2]$  and  $\text{Cs}_2\text{MnX}_4$ . (d) Photographs of the water-induced phase transformation process of  $\text{CsMnBr}_3 \cdot \text{Pb}^{2+}$  NCs under 365 nm UV light. (e) Thermo-chromic luminescence of  $(\text{C}_4\text{NOH}_{10})_5\text{Mn}_2\text{Cl}_9 \cdot \text{C}_2\text{H}_5\text{OH}$  and  $(\text{C}_4\text{NOH}_{10})_2\text{MnCl}_4$  under thermal treatment. (f) Photographs of test strips loaded with  $\text{Cs}_2[\text{MnX}_4(\text{H}_2\text{O})_2]$  powder after adding DMAC. (a) Reproduced with permission from ref. 73. Copyright 2009, Elsevier. (b and e) Reproduced with permission from ref. 61. Copyright 2019, Royal Society of Chemistry. (d) Reproduced with permission from ref. 96. Copyright 2024, Wiley-VCH. (c and f) Reproduced with permission from ref. 58. Copyright 2020, Wiley-VCH.



enable dynamic emission switching through three structural mechanisms, with optical responses quantifiable *via* crystal field parameters using Tanabe–Sugano diagrams (Fig. 6a).<sup>57,73,77</sup> This framework establishes that Racah parameters ( $B$ ,  $C$ ) describe the electron–electron repulsion, while crystal field splitting ( $\Delta$ ) determines the  ${}^4T_1(G)$  excited-state energy. Crucially,  $\Delta O_h > \Delta T_d$  positions  ${}^4T_1(G)$  ( $T_d$ ) energetically above  ${}^4T_1(G)$  ( $O_h$ ), explaining that the green-to-red emission shift is compositional in systems like  $[(CH_3)_4N]_2MnCl_4$  (green) and  $(CH_3)_4NMnCl_3$  (red),<sup>77</sup> with Stokes shifts scaling proportionally to  $\Delta$  magnitude (Fig. 6b).

Structural transitions occur through: (1) solvent mediation, where molecules like ethanol in red-emitting  $(C_4NOH_{10})_5Mn_2Cl_9 \cdot C_2H_5OH$  template  $[Mn_2Cl_9]^{5-}$  connectivity without direct  $Mn^{2+}$  coordination, with thermal removal yielding green-emitting  $[MnCl_4]^{2-}$  (Fig. 7c and e).<sup>61</sup> (2) Direct ligand coordination, where  $H_2O$  converts  $[MnX_4]^{2-}$  to distorted  $[MnX_4(H_2O)_2]^{2-}$ ,<sup>58,64,95</sup> as demonstrated in hydration-driven transitions from red  $CsMnBr_3 : Pb^{2+}$  to green  $Cs_3MnBr_5 : Pb^{2+}$  nanocrystals (Fig. 7d).<sup>22</sup> While hydrated complexes typically exhibit red emission,<sup>58</sup> centrosymmetry-induced Laporte forbidden transition quenches luminescence, as evidenced by the PLQY reduction from 82% to 0% in hydrated  $C_6N_2H_{16}MnBr_4$ .<sup>64</sup> However, structural distortion enables anomalous blue emission<sup>95</sup> characterized by accelerated PL decay originating from sub-bandgap states, facilitating non-radiative recombination pathways, and enhanced electron–phonon coupling mediated by O–H vibrational modes in coordinated  $H_2O$  molecules. Dehydration restores original luminescence, confirming reversibility.<sup>64</sup>

These structure regulations enabled Mn(II) halides achieve predictable emission switching through well-defined structural mechanisms. Future research may: (1) quantify relationships between lattice strain, ligand covalency, and distortion metrics to enable rational material design; (2) explore distortion-engineered emission beyond conventional spectral ranges; (3) optimize switching cyclability for robust anti-counterfeiting and optical encryption technologies leveraging environmental sensitivity.<sup>22,64,96</sup>

### 3 Applications of Mn(II) halide complexes

Lead halide perovskites have become a new class of promising materials in optoelectronic devices due to their excellent optoelectronic properties.<sup>1,2</sup> Perovskites with the advantages of high luminescence performance, tunable emission and facile synthesis can achieve light-emitting diodes (LEDs) with high brightness, low cost, and wide color gamut for applications.<sup>97–99</sup> Along with the superior optoelectronic performance, the ability to form large, high-quality crystals and polycrystalline layers<sup>100</sup> makes lead halide perovskites some of the most promising materials for X-ray imaging technologies.<sup>101</sup> However, the toxicity and poor stability of lead perovskites have hindered their further application.

To overcome these obstacles, a series of lead-free luminescent metal halide complexes have been developed, featuring diverse coordination geometries centered on  $Bi^{3+}$ ,  $Sb^{3+}$ ,  $Cu^+$ ,  $Sn^{2+}$ , and  $Zr^{4+}$  ions coordinated with halide ligands.<sup>102–110</sup> Some lead-free metal halide complexes exhibit high luminescence performance with PLQY above 90%, such as  $(TEBA)_2SbCl_5$  (ref. 106) and  $(C_9NH_{20})_2SbCl_5$ ,<sup>105</sup> which have been applied to white LEDs as phosphors. In addition to high PLQY, the large Stokes shift makes the lead-free metal halide complexes promising materials for radiation detection such as neutron<sup>111</sup> and X-ray imaging.<sup>112–114</sup>

However, the lead-free metal halide-based WLEDs can only be effectively pumped by a UV light-emitting diode chip with lower efficiency than the blue LED chip, leading to luminous efficacy loss of the LED.<sup>16</sup> Mn(II) halide complexes exhibit tunable green and red emissions by the crystal field and can be effectively pumped by the blue chip, making it suitable for LED applications.

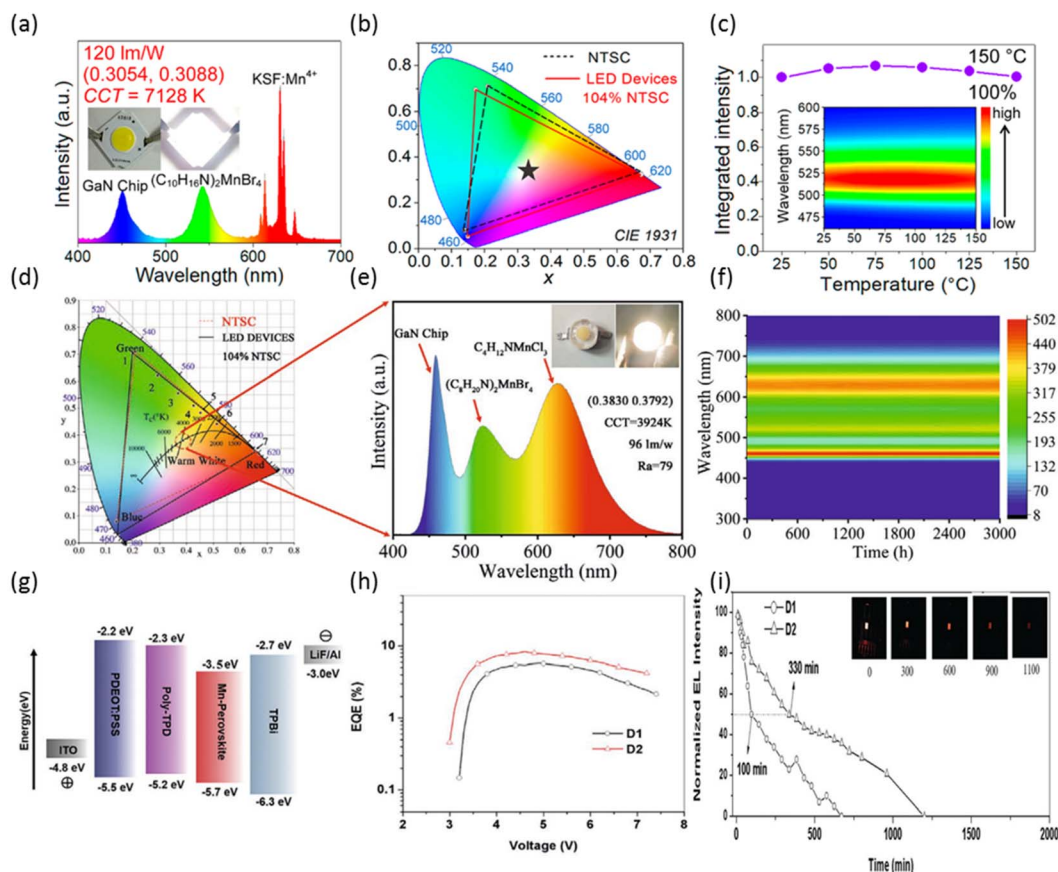
#### 3.1 Light emitting diodes

**3.1.1 Mn(II) halide complexes as color conversion materials.** According to the above description, Mn(II) halide complexes achieve high PLQYs in both green and red emissive regions and can be excited by blue light (400–500 nm) through the  ${}^6A_1$  to  ${}^4G$  transition. The superior luminescent properties and thermal stability make Mn(II) complexes promising materials for blue chip pumped white LED (WLED) applications.

As for green 0D Mn(II) halide complexes, the longer Mn–Mn distances in  $[MnX_4]^{2-}$  lead to a high PLQY of near unity.<sup>60,66</sup> Thus, the four coordinated Mn(II) complexes are applied as green phosphor in the color conversion layer. A WLED can be fabricated by mixing the green-emitting Mn(II) phosphor and red-emitting  $K_2SiF_6:Mn^{4+}$  (KSF) on a blue chip,<sup>68,87</sup> as shown in Fig. 8a. By mixing  $(C_5H_6N)_2MnBr_4$  complexes with KSF, Deng *et al.* fabricated a WLED with an initial luminous efficacy of  $93.90 \text{ lm W}^{-1}$  on a blue InGaN chip (460 nm). The corresponding WLED displayed zero attenuation in emission intensity to  $92.87 \text{ lm W}^{-1}$  after continuous work for 410 minutes.<sup>87</sup> Xia *et al.* fabricated a WLED device by the  $(C_{10}H_{16}N)_2MnBr_4$  and KSF phosphors on a blue InGaN chip (450 nm).<sup>68</sup> The WLED displayed a correlated color temperature (CCT) of 7218 K and a high luminous efficacy of up to  $120 \text{ lm W}^{-1}$  with the CIE chromaticity coordinates of (0.3054, 0.3088) located on the white region. The WLED covers a wide color gamut of 104% NTSC in CIE 1931 (Fig. 8b). The green  $(C_{10}H_{16}N)_2MnBr_4$  phosphor showed no temperature quenching behaviour below  $150 \text{ }^\circ\text{C}$  (Fig. 8c), which is attractive for use in the backlights of LCD devices.

The other way to achieve an LED from a conversion layer with a blue chip is by combining the green and red Mn(II) halide complexes in one layer. Different from the lead halide perovskites that fast anion exchange take place within 5 minutes in one layer,<sup>87</sup> emissions of Mn(II) halide complexes depend on  $T_d$  and  $O_h$  crystal fields and are stable in media with different compositions. Deng *et al.* fabricated LED devices through depositing a polystyrene (PS) film containing green emissive





**Fig. 8** Luminescent and stability properties of LEDs with Mn(II) halide complexes. (a) Emission spectrum of the white LED fabricated with  $(C_{10}H_{16}N)_2MnBr_4$  and the  $K_2SiF_6 : Mn^{4+}$  phosphors on the InGaN chip ( $\lambda_{em} = 450$  nm) at a 20 mA. The insets show the photographs of the device. (b) Color gamut of NTSC standard (black dotted line) and the fabricated white LED (red line, 104%) in the CIE 1931 system. (c) Integrated PL intensity of  $(C_{10}H_{16}N)_2MnBr_4$  as a function of temperature. (d) Color gamut of NTSC standard (red dotted line) and the fabricated white LED (black line, 104%) in the CIE 1931 system. (e) Emission spectrum of the white LED using a blend of  $C_4H_{12}NMnCl_3$  and  $(C_8H_{20}N)_2MnBr_4$  on the InGaN chip ( $\lambda_{em} = 460$  nm). The inset shows the photograph of the LED device with power off and on. (f) Integrated emission spectrum intensity of a white LED under operation as a function of time. (g) Bandgaps of the  $(AB)_4MnBr_6$  EL-LED. (h) EQEs of  $(AB)_4MnBr_6$  EL-LEDs at different voltages. (i) Stability of the  $(AB)_4MnBr_6$  EL-LED with a voltage of 5.0 V. (a–c) Reproduced with permission from ref. 68. Copyright 2020, American Chemical Society. (d–f) Reproduced with permission from ref. 16. Copyright 2021, Wiley-VCH. (g–i) Reproduced with permission from ref. 17. Copyright 2021, Wiley-VCH.

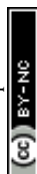
$(C_5H_6N)_2MnBr_4$  and red emissive  $C_5H_6NMnCl_3$  phosphors on a blue chip.<sup>87</sup> The CRI and CCT can be further adjusted by changing the ratio between green and red Mn(II) halide phosphors. Similarly, Ju *et al.* fabricated a WLED based on a conversion layer consisting of  $C_4H_{12}NMnCl_3$  and  $(C_8H_{20}N)_2MnBr_4$ .<sup>16</sup> The WLED exhibited an outstanding luminous efficacy of  $96 \text{ lm W}^{-1}$  and a wide color gamut of 104% NTSC in CIE 1931 (Fig. 8d and e). The corresponding PL peak positions and photoluminescence intensity showed no obvious decrease after 3000 hours under continuous operation (Fig. 8f).

**3.1.2 Mn(II) halide complexes as emitting materials.** Beyond serving as photoluminescent down-conversion phosphors, Mn(II) halide complexes can function directly as emissive layers in electroluminescent LEDs (hereafter termed EL-LEDs).<sup>17,66</sup> As shown in Fig. 8g, Mn(II) based EL-LEDs exhibit a layer structure. Chen *et al.* applied  $(Ph_4P)_2MnBr_4$  doped with host materials TCTA and 26DCZPPY as an emitting layer, achieving a green EL-LED with a turn-on voltage of 4.8 V and

a peak luminance of  $2339 \text{ cd m}^{-2}$  with an external quantum efficiency (EQE) of 9.6%.<sup>66</sup> Wang *et al.* fabricated a red EL-LED with EL emission at 627 nm with CIE color coordinates (0.69, 0.31) through OD  $(AB)_4MnBr_6$ .<sup>17</sup> The corresponding red EL-LED exhibited the maximum recording brightness of  $4700 \text{ cd m}^{-2}$  and EQE of 9.8%, as shown in Fig. 8h. The half-life of the device reached 5.5 h at 5 V (Fig. 8i), which showed superior performance among the lead free red EL-LEDs.<sup>115</sup>

Owing to the luminescent properties and stability, Mn(II) halide complexes are promising lead-free materials for both WLEDs and monochrome EL-LEDs.

**3.1.3 Mn(II) halide complexes with circularly polarized luminescence.** Beyond their conventional luminescent properties, manganese halides exhibit significant promise for applications in circularly polarized luminescent (CPL) materials.<sup>116</sup> CPL materials hold immense potential for advancing next-generation optoelectronic technologies, including circularly polarized light-emitting diodes (CP-LEDs),<sup>65</sup> three-dimensional



(3D) displays, CPL switches, and CPL detectors.<sup>117,118</sup> Manganese-based halides are particularly attractive candidates for high-performance CPL materials due to their exceptional photochemical stability, high photoluminescence quantum yields (PLQYs), low toxicity, and potential for incorporating additional functionalities such as ferroelectricity and magneto-chiroptical coupling.

Recent research has actively explored manganese halides as CPL emitters. Chen *et al.* synthesized chiral complexes (D)- and (L)-(*tert*-butyl prolinato)MnCl<sub>3</sub>, achieving dissymmetry factors *g* of  $6.1 \times 10^{-3}$  and  $-6.3 \times 10^{-3}$ , respectively.<sup>86</sup> Subsequently, Artem'ev *et al.* reported R/S-[MBA-Me<sub>3</sub>]MnBr<sub>4</sub> with a *g* of  $4.5 \times 10^{-3}$ .<sup>65</sup> Chen *et al.* further demonstrated significantly enhanced performance in R/S-DACAMnBr<sub>3</sub>,<sup>119</sup> achieving larger *g* values of 0.292 and 0.231. Notably, many CPL-active manganese halides, including 0D green emitters, exhibit one-dimensional long-range order in crystal structures.<sup>67,120–122</sup> This structural predisposition appears favorable for CPL generation. Given that red-emitting manganese halides also frequently adopt 1D structural motifs (Table 2), they demonstrate considerable potential for future CPL material development. Manganese halides emerge as highly promising platforms for circularly polarized luminescence, leveraging their inherent material advantages and structural versatility. The observed propensity for 1D crystal structures, common in both green- and red-emitting variants, coupled with recent demonstration of significant dissymmetry factors, underscores their strong potential for realizing efficient and functional CPL materials.

### 3.2 Radiation detection

**3.2.1 Neutron imaging.** Due to large Stokes shifts and high PLQYs, Mn-doped perovskite NCs have huge potential for fast neutron imaging. Fast neutrons are uncharged elementary particles with the kinetic elementary energy exceeding 1 MeV, which have low interaction cross sections and high penetration depths for both high- and low-*Z* elements. In contrast, other types of radiation sources, such as X-rays,  $\gamma$ -rays, and thermal neutrons, only respond to heavy or light elements. Therefore, fast neutron imaging is increasingly a nondestructive detection technology for large-scale samples of dense, mixed-*Z* compositions. However, the resolution of fast neutron imaging is still limited by conventional scintillator materials. In 2020, McCall *et al.* first reported a recoil proton detector based on colloidal semiconductor NCs in solvents with high hydrogen density.<sup>111</sup> It is noteworthy that Mn-doped CsPbClBr<sub>2</sub> perovskite NCs offer the best spatial resolution with 27 pixels because of the highest Stokes shift among a variety of semiconductor NCs tested. Subsequently, the same research group synthesized ultra-high concentration ( $>100 \text{ mg mL}^{-1}$ ) Mn-doped CsPbClBr<sub>2</sub> NCs through using 3-(*N,N*-dimethyloctadecylammonio)propane-sulfonate (ACS18) as the zwitterionic ligand, promoting 8 times brighter light yield than oleyl-capped NCs under fast neutron irradiation.<sup>43</sup> Although Mn-doped CsPbClBr<sub>2</sub> NCs as a fast neutron scintillator have exhibited improved resolution and light yield, the liquid suspension is inconvenient to use for realistic imaging purposes. Another feasible strategy is that

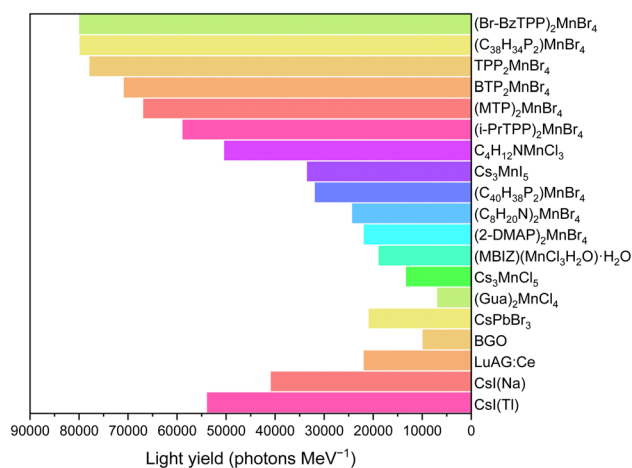


Fig. 9 Comparison of scintillator light yields of various Mn(II) complexes and previously reported and commercially available scintillators.

Zheng *et al.* proposed a single-component 2D Mn-doped (C<sub>18</sub>-H<sub>37</sub>NH<sub>3</sub>)<sub>2</sub>PbBr<sub>4</sub> perovskite scintillator, in which hydrogen-rich organic components absorb fast neutrons and the dopant Mn<sup>2+</sup> acts as luminescent centers in the perovskite that could offer a high Stokes shift and avoid self-absorption.<sup>18</sup> The Mn-doped (C<sub>18</sub>H<sub>37</sub>NH<sub>3</sub>)<sub>2</sub>PbBr<sub>4</sub> scintillator was finally made into imaging plates for fast neutron radiography with 0.5 lp mm<sup>-1</sup> spatial resolution, but its light yield still falls behind the commercial ZnS(Ag):PP scintillator screen. In the future, effective methods should be explored to enhance the interaction between Mn-doped perovskite and fast neutrons and improve its light yield.

**3.2.2 X-ray imaging.** As for X-ray imaging, a large Stokes shift is essential in order to avoid self-absorption within the relatively thick scintillating layer.<sup>101</sup> Mn(II) complexes exhibit a large Stokes shift for <sup>6</sup>A<sub>1</sub>(S) to <sup>4</sup>T<sub>1</sub>(G) excitation and the corresponding <sup>4</sup>T<sub>1</sub>(G) to <sup>6</sup>A<sub>1</sub>(S) emission, indicating a lower degree of self-absorption under X-ray excitation. The superior luminescent properties and large Stokes shift make Mn(II) complexes efficient X-ray scintillators for X-ray imaging.

As a group of low toxic candidate for X-ray scintillators, many Mn(II) complexes exhibit superior steady-state X-ray light yields than commercial BGO (10 000 photons per MeV), CsI: Tl (54 000 photons per MeV), CsI: Na (41 000 photons per MeV), LuAG: Ce (22 000 photons per MeV) and toxic CsPbBr<sub>3</sub> (21 000 photons per MeV),<sup>123</sup> as displayed in Fig. 9.<sup>16,19,65,69,83,94,124</sup> Among them, the green emissive (C<sub>38</sub>H<sub>34</sub>P<sub>2</sub>)MnBr<sub>4</sub>,<sup>19</sup> TPP<sub>2</sub>MnBr<sub>4</sub>,<sup>125</sup> (Br-BzTPP)<sub>2</sub>MnBr<sub>4</sub> (ref. 71) and red emissive C<sub>4</sub>H<sub>12</sub>NMnCl<sub>3</sub> (ref. 16) Mn(II) complex X-ray scintillations have reached high light yields of 80 000 photons per MeV, 78 000 ± 2000 photons per MeV, 80 100 photons per MeV and 50 500 photons per MeV, respectively.

Another important parameter for scintillators is the evaluation of afterglow. A high afterglow can reduce the signal-to-noise ratio of X-ray imaging. Thus, it is always desirable to reduce the afterglow to obtain X-ray imaging with high contrast, especially for CT imaging. Compared with the commercial CsI: Tl (1.5% @ 3 ms), the Mn(II) complex X-ray scintillators exhibit a lower residual afterglow signal, as shown in Table 3.



Table 3 Comparisons of Mn(II) complex scintillators in light yield, detection limit, spatial resolution and afterglow

| Material   | Light yield/photons per MeV | Detection limit             | Spatial resolution/lp mm <sup>-1</sup> | Afterglow  | References |
|--|-----------------------------|-----------------------------|--|--|------------|
| S-[MBA-Me <sub>3</sub> ]MnBr <sub>4</sub>                          | —                           | 320 μGy s <sup>-1</sup>     | —                                      | —  | 65         |
| (Gua) <sub>2</sub> MnCl <sub>4</sub>                               | 7000                        | 145.3 nGy s <sup>-1</sup>   | 8                                      | BGO < (Gua) <sub>2</sub> MnCl <sub>4</sub> < CsI(Tl) | 83         |
| Cs <sub>3</sub> MnCl <sub>5</sub>                                  | 13 400                      | 470 μGy s <sup>-1</sup>     | 4.0                                    | —  | 94         |
| (MBIZ)(MnCl <sub>3</sub> H <sub>2</sub> O)·H <sub>2</sub> O        | 19 000                      | 204 nGy s <sup>-1</sup>     | 11.1                                   | 30 ms(1%)  | 21         |
| (2-DMAP) <sub>2</sub> MnBr <sub>4</sub>                            | 22 000                      | 9.5 nGy s <sup>-1</sup>     | 20–25                                  | —  | 140        |
| (C <sub>8</sub> H <sub>20</sub> N) <sub>2</sub> MnBr <sub>4</sub>  | 24 400                      | 24.2 nGyair s <sup>-1</sup> | 5                                      | 2.06 ms(1%)  | 16         |
| (C <sub>40</sub> H <sub>38</sub> P <sub>2</sub> )MnBr <sub>4</sub> | 32 000                      | 288 nGy s <sup>-1</sup>     | —                                      | ~BGO   | 69         |
| Cs <sub>3</sub> MnI <sub>5</sub>                                   | 33 600                      | 400 nGy s <sup>-1</sup>     | 7.45                                   | —  | 124        |
| C <sub>4</sub> H <sub>12</sub> NMnCl <sub>3</sub>                  | 50 500                      | 36.9 nGyair s <sup>-1</sup> | —                                      | 3.14 ms (1%)   | 16         |
| (i-PrTPP) <sub>2</sub> MnBr <sub>4</sub>                           | 59 000                      | 42.3 nGyair s <sup>-1</sup> | 46.6                                   | —  | 72         |
| (MTP) <sub>2</sub> MnBr <sub>4</sub>                               | 67 000                      | 28.1 nGyair s <sup>-1</sup> | 6.2                                    | —  | 141        |
| BTP <sub>2</sub> MnBr <sub>4</sub>                                 | 71 000                      | 86.2 nGyair s <sup>-1</sup> | 23.8                                   | —  | 142        |
| TPP <sub>2</sub> MnBr <sub>4</sub>                                 | 78 000 ± 2000               | 8.8 nGy s <sup>-1</sup>     | 15.7                                   | 3 ms (0.5%)  | 125        |
| (C <sub>38</sub> H <sub>34</sub> P <sub>2</sub> )MnBr <sub>4</sub> | 80 000                      | 72.8 nGy s <sup>-1</sup>    | ~3                                     | 10 ms (to the background)                            | 19         |
| (Br-BzTPP) <sub>2</sub> MnBr <sub>4</sub>                          | 80 100                      | 30 nGy s <sup>-1</sup>      | 14.06                                  | 0.3 ms to baseline                                   | 71         |

The detection limit of X-ray dose rate required for X-ray medical diagnostics is 5.5 μGy S<sup>-1</sup>.<sup>126</sup> For Mn(II) complex X-ray scintillators, the detection limit can reach as low as 8.8 nGy s<sup>-1</sup>,<sup>125</sup> which is about 625 times lower than the requirement. A high spatial resolution of 15.7 lp mm<sup>-1</sup> was achieved in TPP<sub>2</sub>MnBr<sub>4</sub> X-ray scintillation imaging, superior to the Eu<sup>3+</sup> doped CsPbBr<sub>3</sub> glass-ceramic (10 000 photons per MeV and 15.0 lp mm<sup>-1</sup>)<sup>127</sup> and providing a higher light yield (Table 3). Furthermore, the Mn(II) complex can be imbedded in a flexible matrix such as PDMS to build a flexible scintillator with good resolution and expanding the corresponding application.<sup>19</sup>

Manganese(II) halide complexes have emerged as promising lead-free alternatives in optoelectronics, addressing the toxicity and stability limitations of lead halide perovskites despite their superior photophysical properties. While diverse lead-free metal halides (*e.g.*, based on Bi<sup>3+</sup>, Sb<sup>3+</sup>, and Cu<sup>+</sup>) exhibit high PLQY and potential in radiation detection, their reliance on UV excitation limits the white light-emitting diode (WLED) efficiency. Mn(II) halides overcome this constraint through blue-light-excitable green/red emission tunable *via* crystal field engineering. For WLEDs, tetrahedral [MnX<sub>4</sub>]<sup>2-</sup> complexes achieve near-unity PLQYs and serve as efficient color converters when blended with red phosphors on blue chips, delivering high luminous efficacy and thermal stability up to 150 °C. Alternatively, hybrid green/red Mn(II) phosphor layers in polymer matrices enable stable, tunable WLEDs with negligible efficiency decreasing after 3000 hours. Beyond photoluminescence, Mn(II) complexes function as electroluminescent emitters in LEDs, achieving green emission and red luminescence.

In radiation detection, the large Stokes shift of Mn halides minimizes self-absorption, enabling efficient X-ray scintillators with light yields (50 500–80 100 photons per MeV exceeding commercial scintillators, ultralow detection limits and high spatial resolution (Table 3). For neutron imaging, Mn-doped CsPbClBr<sub>2</sub> provides high spatial resolution *via* recoil proton detection,<sup>43</sup> while 2D Mn-doped lead halides offer solid-state alternatives despite the lower light yield.<sup>18</sup> Furthermore, chiral Mn(II) halides demonstrate significant circularly polarized

luminescence (CPL) with dissymmetry factors up to 0.292,<sup>81,127</sup> attributed to their prevalent 1D structures and enabling applications in CP-LEDs, 3D displays, and optical switches.

Therefore, Mn(II) halides constitute a versatile, environmentally benign platform for advanced optoelectronics, excelling in blue-pumped WLEDs, high-resolution radiation detection, and chiroptical devices. This multifunctionality stems directly from their tunable emission, exceptional stability, and structurally adaptive coordination chemistry, positioning them as a cornerstone for sustainable photonic material innovation.

## 4 Conclusions and outlook

In this perspective, we have summarized the recent progress in Mn(II) complexes through their structures and luminescent properties. The properties of color tunability, high PLQYs, large Stokes shifts and thermal stability make Mn(II) complexes a class of promising materials for LEDs and radiation detection such as neutron and X-ray imaging.

Luminescent properties are mainly determined by the environment of the Mn<sup>2+</sup> centre. The dopant Mn<sup>2+</sup> exhibits orange emission in the lead halide perovskite host. The luminescent performances depend on the bandgap of the perovskite host and Mn<sup>2+</sup> ion doping concentration. As for the green emissive Mn(II) halide phosphors, the emission and excitation are affected by the four-fold-coordinated [MnX<sub>4</sub>]<sup>2-</sup> tetrahedron in a 0D structure. The PLQY of Mn(II) halides is primarily governed by Mn–Mn interatomic distances, the Stokes shift is modulated by angular distortion within the crystal structure and FWHM is determined by electron–phonon coupling influenced by structural distortions and organic A-site cations.<sup>23,26,81,82</sup> The red emission of Mn(II) complexes is derived from [MnX<sub>6</sub>]<sup>4-</sup> octahedra through six-fold-coordinated [MnX<sub>6</sub>]<sup>4-</sup> octahedra. The [MnX<sub>6</sub>]<sup>4-</sup> octahedral units can connect through face-sharing and further crystallize into 0D and 1D structures. However, d–d transition of Mn<sup>2+</sup> in the centrosymmetric octahedral crystal field is forbidden, leading to a low PLQY for red emissive Mn(II) complexes. Thus, distortion of [MnX<sub>6</sub>]<sup>4-</sup> octahedra from both



the Mn–X length and X–Mn–X angle in the structure is necessary to achieve superior luminescence performance. Green emissive Mn(II) complexes with a PLQY near unity and red emissive Mn(II) complexes with a PLQY over 90% have already been achieved in previous research studies.

The luminescent properties, stability and low toxic nature of Mn(II) complexes make them suitable for LED and X-ray imaging applications. Mn(II) complexes are applied as color conversion materials on blue chips. The luminous efficacy of LEDs based on Mn(II) complexes and KSF phosphors reached up to 120 lm W<sup>-1</sup>. The luminous efficacy of the LED fabricated by Mn(II) complexes as both green and red phosphors reached up to 96 lm W<sup>-1</sup>. Besides, Mn(II) complexes can also be used as emitting materials in EL-LEDs. A red EL-LED with the maximum recording brightness of 4700 cd m<sup>-2</sup> and EQE of 9.8% was achieved by (ABI)<sub>4</sub>MnBr<sub>6</sub>, which showed superior performance among the lead free red EL-LEDs. Manganese halides also exhibit promise for application in CPL materials,<sup>116</sup> which hold immense potential for advancing next-generation optoelectronic technologies, including circularly polarized light-emitting diodes (CP-LEDs),<sup>65</sup> three-dimensional (3D) displays, CPL switches, and CPL detectors.<sup>117,118</sup> Because of the large Stokes shift, Mn(II) complexes are thought to be promising materials for efficient radiation detection such as neutron and X-ray imaging. The spatial resolution for neutron scintillators reached 27 pixels by Mn-doped CsPbClBr<sub>2</sub> perovskite NCs. The currently prepared Mn(II) complex X-ray scintillators displayed the highest light yield of 80 000 photons per MeV, a spatial resolution of 25 lp mm<sup>-1</sup> and the lowest detection limit of 8.8 nGy s<sup>-1</sup>.

Although these results are encouraging, further improvements in Mn(II) complexes are still needed for both theoretical research and practical applications. (i) Material balancing efficiency and stability: the future development of Mn-based halides hinges on resolving the inherent trade-off between the PLQY and thermal and environmental stability. For both tetrahedrally coordinated green emitters and octahedrally coordinated red emitters, achieving a high PLQY requires sufficient Mn–Mn separation distances. Small inorganic cations may therefore not be suitable due to their tendency to decreasing Mn–Mn distance. Two strategies can address this challenge: Mn doping within octahedral/tetrahedral host frameworks<sup>25</sup> or incorporation of bulky rigid organic A-site cations,<sup>81</sup> enabling adequate Mn–Mn spacing while simultaneously enhancing material stability. (ii) Theoretically quantifying structure–property relationships: recently, Zhu *et al.*<sup>85</sup> has quantitatively correlated Mn octahedral distance mismatch with red emission efficiency in Mn-based halides. However, a quantitative or semi-quantitative understanding of how lattice distortions in high-symmetry octahedra govern excitonic behavior remains critical. For octahedrally coordinated red emitters, establishing correlations between crystallographic parameters (*e.g.*, bond length mismatch<sup>85</sup> and bond angle distortion<sup>128</sup>) and PLQYs will provide essential guidelines for designing efficient Mn-halide phosphors. Machine learning models that map crystallographic descriptors to optical outputs could further accelerate the discovery of high-performance red-emitting Mn halides. (iii)

Application-driven innovations: colloidal Mn-based nanocrystals with narrow emission linewidths are essential for red and green color conversion layers in next-generation micro-LEDs.<sup>129</sup> A key advantage of Mn halides lies in their compatibility with high-temperature hot-injection methods, similar to lead halide perovskites, for synthesizing small-sized colloidal NCs. Advancing pixel-level patterning techniques for these nanomaterials could enable environmentally friendly color-conversion micro-LED technologies. Furthermore, Mn(II) halides have a high halogen content, showing promising prospects as scintillators. Developing highly luminescent Mn bromides/iodides with elevated atomic numbers (*Z*) may enable achieving efficient X-ray scintillators through enhanced photon attenuation and radiative recombination.

Manganese halides constitute a versatile, lead-free platform with tunable emission, large Stokes shifts, and exceptional stability. Future progress hinges on elucidating structure–distortion–property relationships, advancing synthetic control for environmental resilience, and pioneering device paradigms that leverage their unique photo-physics. Cross-disciplinary efforts integrating crystallography, spectroscopy, and device engineering will accelerate their deployment in next-generation optoelectronics and radiation detection.

## Author contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Data availability

No primary research results, software or code has been included, and no new data were generated or analysed as part of this perspective.

## Acknowledgements

This work was supported by National Natural Science Foundation of China (22075129).

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