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Direct polarized luminescence from perovskite superlattices by manipulating transition dipole moment orientation

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1 Introduction

Linearly polarized light with electric field oscillations confined to a fixed plane, plays a critical role in numerous applications such as bioimaging, anti-counterfeiting technology and three-dimensional displays (Geng, 2013; Cunningham et al., 2016; Bloxham et al., 2021; Song et al., 2025). This polarization-dependent phenomenon enables selective material interactions while suppressing isotropic background signals, thereby achieving remarkable signal-to-noise ratios exceeding conventional limits. Traditional approaches relying on external polarizers, however, inevitably suffer from substantial energy losses (>50%) (Srivastava et al., 2017; Wang et al., 2021), fundamentally limiting their applicability in energy-efficient devices. Such limitations have driven intensive research into directly generating polarized emission from the emissive layer of light-emitting diodes (LEDs), which promises to circumvent these efficiency bottlenecks.

The polarization characteristics of luminescence material are fundamentally governed by the transition dipole moment (TDM) orientation. Although the LEDs based on organic molecules with aligned TDMs can perform linearly polarized electroluminescence (EL), the degree of polarization (DOP) achieved actually was limited until now (<40%) (Culligan et al., 2003; Geng et al., 2003). On the other hand, anisotropic inorganic nanocrystals (e.g., nanorods, nanoplatelets) exhibit exceptional single-particle photoluminescence polarization with DOP values exceeding 70% (Scott et al., 2017). Nevertheless, the transition from individual nanocrystals to functional films introduces critical challenges—randomized orientation distributions during solution processing dramatically degrade macroscopic polarization characteristics. This fundamental limitation highlights the urgent need for developing novel material systems capable of maintaining aligned TDM orientations in macroscopic assemblies.

Colloidal perovskite nanocrystals have recently emerged as a paradigm-shifting material platform, combining solution processability with exceptional optoelectronic properties including near-unity quantum yields and spectral tunability across the visible spectrum (Wu et al., 2018; Ko et al., 2025; Ma et al., 2025). Of particular significance is their unique excitonic fine structure, characterized by bright triplet states with enhanced oscillator strengths (Becker et al., 2018), coupled with spontaneous self-assembly capabilities into orientationally ordered superlattices (Cui et al., 2021; Blach et al., 2022; Kumar et al., 2022). From a crystallographic perspective, perovskite superlattices are macroscopic quantum state materials formed by the periodic arrangement of perovskite nanocrystals acting as “artificial atoms” in two-dimensional or three-dimensional space (Boles et al., 2016). The synthesis techniques for perovskite superlattices

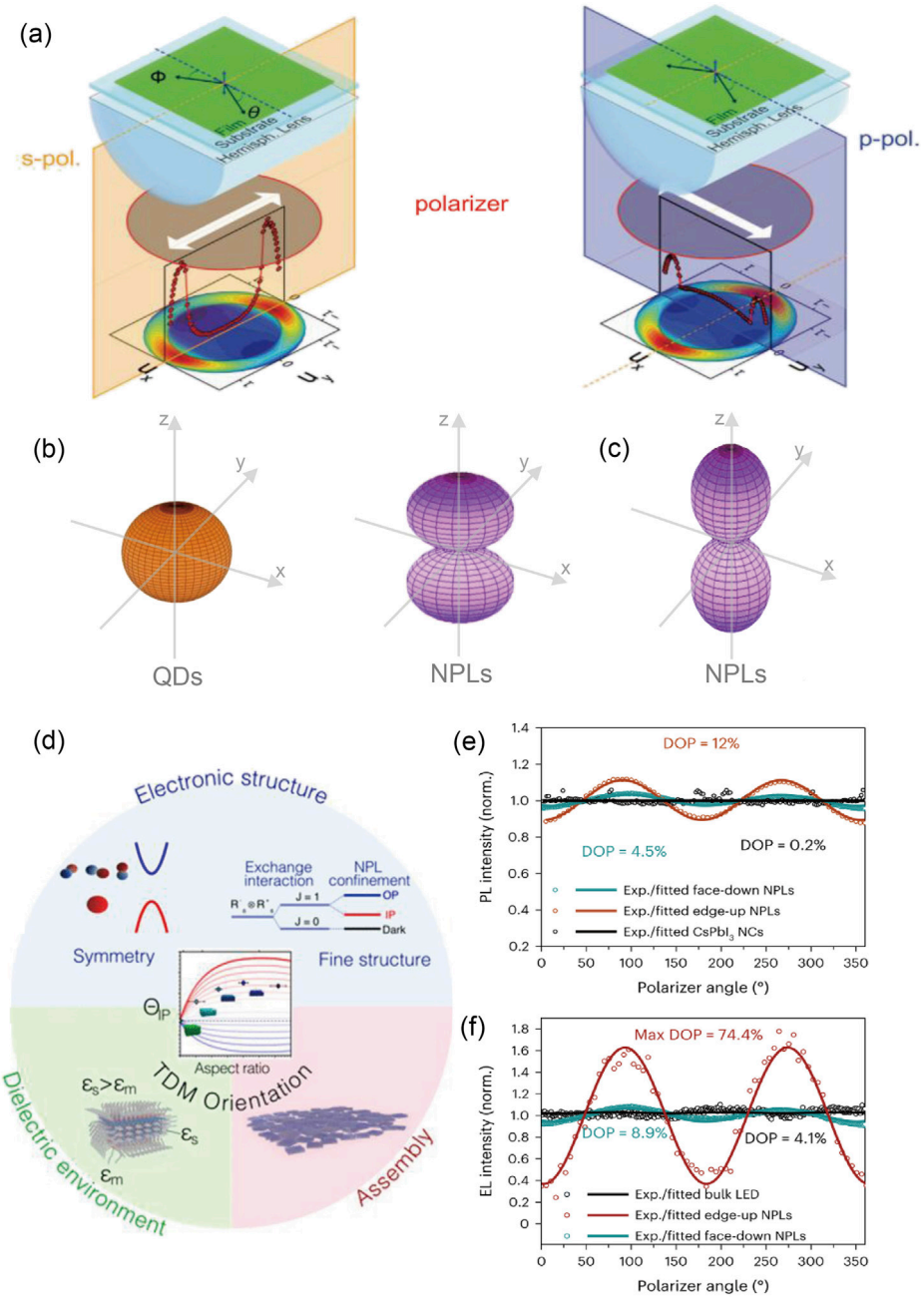

FIGURE 1
(a) Schematic illustration of the angular- and polarization-differentiated radiation patterns (s- and p-polarized emission). Adapted from (Marcato et al., 2022) **(b)** schematic diagram of radiation intensity pattern of nanoplatelets (violet) and quantum dots (orange) of the pure electronic contribution to the emission. **(c)** External radiation patterns of nanoplatelets, taking dielectric environment factors into account. **(d)** The physical origins of tunable TDM orientation. Adapted from (Marcato et al., 2022). Polarization dependences of the PL **(e)** and EL **(f)** for CsPbI3 nanocrystals with different geometry and FAPbI3 bulk, respectively. Adapted from (Ye et al., 2024).

can be divided into three main categories based on principle: self-assembly, solid-phase synthesis, and epitaxial growth (Lei et al., 2022; Li et al., 2024; Blach et al., 2025; Liang et al., 2025). These methods enable fabrication of superlattices with high structural order and tunable optical properties. These inherent attributes position perovskite superlattices as a transformative platform for realizing polarized emission sources without requiring external polarization optics. This paper introduces the strategies for manipulating TDM orientation and highlight the breakthroughs in this emerging field. In addition, critical challenges toward practical implementation of ultra-bright polarized LEDs are further discussed.

2 Manipulating transition dipole moment orientation

The photon emission characteristics in halide perovskite nanocrystals are mediated by the TDMs strength and orientation

(Scott et al., 2017; Liu C. et al., 2025). Specifically, the TDM is a vector quantity that describes the strength and direction of the electric dipole transition responsible for light absorption or emission in a material. It is correlated with the electronic Bloch states and represents the coupling between the initial and final electronic states during an optical transition. The modulus square of the transition electric dipole moment is proportional to the transition probability, and its direction determines the polarization direction of the emission (Hu et al., 2001; Scott et al., 2017; Marcato et al., 2022).

Emitters located within the sample plane (x–y plane) can possess both out-of-plane (OP) dipoles oriented along the z-axis and in-plane (IP) dipoles. The OP and IP dipoles contribute differently to s- and p-polarized emission: s-polarization contains only radiation from IP dipoles because the electric field oscillates perpendicular to the plane of incidence, which aligns with the IP dipole orientation. However, p-polarization contains contributions from both IP and OP dipoles since the electric field oscillates in the plane of incidence. The relative contributions of these dipoles strongly influence the radiation patterns of emitters (Figure 1a). The radiation intensity patterns are derived by convolving the TDM distribution $|\mu(\theta,\phi)|^2$ with the radiation pattern of a Hertzian dipole (Scott et al., 2017). Thus, the TDM directly influences the polarization direction and intensity of emitted light.

Taking into account the interplay of electronic structure, dielectric environment and orientational distributions (Figure 1d), many strategies engineered for fine-tuning TDM orientation to enhance the emission anisotropy (Cui et al., 2021; Kumar et al., 2022; Marcato et al., 2022; Xu et al., 2023; Liu H. et al., 2025; Shi et al., 2025): 1) nanocrystals geometry. Numerous theoretical and experimental researches suggest that the TDMs of anisotropic nanocrystals with reduced dimensions, especially nanoplatelets, possess high orientation compared with dots, depicted in Figure 1b (Achtstein et al., 2012; Schuller et al., 2013; Scott et al., 2016; Scott et al., 2017). Additionally, the thickness and lateral dimensions of NPLs regulate the anisotropy of Bloch states, quantum confinement, and exciton fine structure, which collectively tune the TDM orientation in electronic structure level. 2) Dielectric environment. Dielectric confinement effects modify the exciton fine structure by altering the spatial distribution and energy levels of excitons within perovskite nanocrystals. This dielectric anisotropy impacts the anisotropy of the Bloch states and consequently the TDM orientation. Variations in the local dielectric environment, such as changes in the surrounding matrix or substrate, can thus modulate the exciton radiative properties and the balance between IP and OP dipole components. For instance, when consider oleic acid ligands surrounding, the emission becomes even more directed for NPLs (Figure 1c) (Scott et al., 2017). 3) Ordered assembly. Assembly dictates TDM anisotropy by controlling nanocrystals orientation and interactions. Ordered structures enhance anisotropy through aligned TDMs, while disordered systems exhibit isotropy. The specific assembly type, such as superlattice, and inter-particle coupling further modulate these effects. In this regard, Perovskite superlattices influence the transition dipole moment (TDM) primarily through their anisotropic dielectric environment and ordered assembly. The superlattice structure induces dielectric confinement and anisotropy, which modifies the local electric field distribution around the NCs, thereby affecting the orientation and magnitude of the TDM. Specifically, anisotropic NC superlattices rescale the radiation patterns of horizontal (in-plane) and vertical (out-of-plane) dipoles, enhancing light emission within the critical angle and improving light outcoupling efficiency (Ye et al., 2024). Additionally, the controlled self-assembly of nanoplatelets into superlattices allows fine tuning of their orientation (face-up or edge-up), which directly governs the macroscopic TDM orientation and results in highly polarized emission (Luo et al., 2025). This ordered arrangement and confinement effect enable tuning of the TDM orientation by regulating exciton fine structure and dielectric anisotropy (Marcato et al., 2022). Thus, perovskite superlattices can serve as a powerful platform to manipulate TDM orientation and enhance optical properties in optoelectronic devices. For example, this effect is evident in nanoplatelet solids where increasing order parameter S (introduced to quantify the uniaxial orientational distribution of a given film) from −0.5 to one shifts the average orientation from face-on to edge-on, enhancing directional emission and polarization ratio (Marcato et al., 2022).

3 Directed emission in perovskite superlattices

In the recent groundbreaking work, Ye et al. firstly realized direct linearly polarized EL from strongly quantum-confined $CsPbI_3$ perovskite NPLs assembled with controlled orientation (Ye et al., 2024). By manipulating the solvent evaporation rate, the authors achieved precise self-assembly of NPLs into face-down or edge-up orientations. It was found that edge-up orientations favored stronger out-of-plane dipole emission with higher DOP values and achieved a record-high degree of linear polarization (74.4%) in EL LEDs without the need for external photonic structures or polarizers. In addition, PbI_2 ligand passivation was carried out to significantly boost photoluminescence quantum yield (PLQY) from ~48% to ~65% by mitigating trap states and non-radiative recombination pathways. This chemical treatment furtherly improved external quantum efficiencies (EQE), reaching up to 2.8%, alongside enhanced operational stability.

The study also elucidated the fundamental photophysical mechanisms contributing to the high polarization. Strong quantum and dielectric confinement in the $CsPbI_3$ NPLs induced significant exciton fine-structure splitting (~11–20 meV), which, combined with uniform NPL alignment, leads to highly linearly polarized PL and EL (Figures 1e,f). Interestingly, the EL polarization surpassed that of PL, a phenomenon attributed to electric-field-induced modifications of exciton states and charge transfer dynamics under device operation. This nuanced understanding opens avenues for further tailoring excitonic properties via device engineering.

Overall, this work established a comprehensive framework combining controlled nanoplatelet orientation, surface passivation, and detailed photophysical analysis to realize highly polarized and efficient EL devices. It represents a meaningful stride toward practical polarized light sources in perovskite optoelectronics and inspires future research to refine and expand these promising materials and device concepts.

Interestingly, Luo et al. demonstrated unexpected polarized superradiance arising from superlattices of $CsPbBr_3$ quantum dots (QDs), however, each QD, being cubic in shape, inherently

lacks intrinsic anisotropy in its optical properties (Luo et al., 2025). In generally, without intrinsic anisotropy in the exciton transition of individual nanocrystals—like nanoplatelets and nanorods—or extrinsic anisotropy introduced by the superlattice geometry, the superlattice is not expected to perform emission anisotropy. And they conjectured that anisotropic interdot electronic coupling affected by quantum confinement (QD size) and ligand chemistry, could be responsible for the unique feature. These findings open new avenues for designing polarized coherent light sources without relying on inherently anisotropic materials, which could simplify fabrication and integration in photonic devices.

4 Discussion

The recent advancements in achieving direct polarized emission from perovskite superlattices, particularly through TDM orientation control, mark notable progress in polarized optoelectronics and hold transformative potential across multiple optoelectronic and quantum domains. Aligned dipoles in superlattices direct photon emission perpendicular to substrates, significantly boosting light extraction as well as eliminating the need for external polarizers in three-dimensional displays. In the field of lasers, polarized emission control in superlattices can significantly reduce lasing thresholds while enhancing beam quality. Moreover, through precise manipulation of dipole orientations within superlattices, macroscopic quantum state control can be achieved at room temperature, which enable to generate high-intensity, short-pulse quantum light sources ideal for supplying coherent photons in quantum communication and computing systems.

However, three critical challenges persist. First, imperfect nanoplatelet alignment and insufficient device stability under operational bias limit commercial viability. Second, the quantum mechanical origins of TDM orientation in superlattices remain ambiguous, particularly the emergence of anisotropic electronic coupling from isotropic quantum dot constituents-a fundamental barrier to rational design. Third, the structure-polarization correlation requires systematic investigation through polarization-resolved spectroscopy coupled with atomic-scale strain mapping to resolve nanoscale asymmetries in quantum dot assemblies. Addressing these challenges through advanced characterization and computational modeling will accelerate the development of high-performance polarized LEDs for next-generation photonic technologies.

Author contributions

SY: Writing – original draft, Writing – review and editing. JX: Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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