

Advances in Polymer-based Circularly Polarized Luminescent Materials

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Abstract Recently circularly polarized luminescence (CPL) generated by chiral materials have attracted tremendous attention due to its potential applications such as 3D displays, quantum communication, and information storage. Polymers have emerged as particularly promising platforms for generating and amplifying CPL, owing to their structural designability, inherent helical architectures, and excellent processability. Hence, this review provides a comprehensive overview of recent advances in polymer-based CPL materials, with a central focus on the rational construction of polymer chiral superstructures, including helical polymers bearing chiral centers on side chains for chiral transfer and amplification, helical polymers with chiral centers integrated into the main chain, achiral polymers complexed with small-molecule inducers through non-covalent interactions; and achiral polymers utilizing macromolecular inducers. By discussing representative examples, we elucidate the underlying mechanisms of chirality transfer, amplification, and luminescence that govern CPL. The review concludes by highlighting the key challenges and promising future perspectives in this field, aiming to guide further research and accelerate the practical application of polymer-based CPL materials.

Keywords Circularly polarized luminescence; Helical polymer; Achiral polymer; Chiral induction; Chiral amplification

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INTRODUCTION

Chirality describes the geometric property of an object that is non-superimposable on its mirror image, which is one of the fundamental properties of nature. This asymmetric characteristic is prevalent across multiple scales in nature, ranging from fundamental particles such as photons and Weyl fermions, through essential biological macromolecules including proteins and deoxyribonucleic acid (DNA), to macroscopic structures like climbing plants and spiral galaxies.^[1–4] Research groups have devoted considerable effort to exploring chiral phenomena and their underlying mechanisms, aiming not only to elucidate the origins of chirality but also to develop advanced chiral functional materials.^[5–17] Notably, synthetic chiral materials have demonstrated exceptional potential in diverse applications, including enantiomeric separation, asymmetric catalysis, chiral sensing, three-dimensional displays, information encryption, and high-performance chiroptical devices.^[18–26]

Recent studies have shown that chiral luminescent materials often exhibit unique chiroptical properties, namely circularly polarized luminescence (CPL).^[27–32] CPL refers to the se-

lective emission of left-handed and right-handed circularly polarized light by a substance when excited by light of a certain wavelength. Based on the state in which chirality exists, it can be classified into ground-state chirality and excited-state chirality. Unlike circular dichroism (CD), which reflects the chiral information of the ground state, CPL reflects the chiral information of the excited state. A key metric for characterizing CPL materials is the luminescence dissymmetry factor (g_{lum}), which quantifies the extent of polarization and theoretically varies between -2 and $+2$.^[33] CPL has broad application prospects in high-tech fields such as 3D display, quantum communication, information storage, and biological detection, etc.^[34–38] Therefore, over the years, diverse chiral materials have been developed to generate CPL and amplify the g_{lum} , mainly including organic small molecules, polymers, aggregation-induced emission (AIE) systems, liquid crystals and clusters, etc.^[31,39–46] Among them, polymers have attracted increasing attention in the CPL field due to their advantages such as the designability of their chemical structure, unique helical structure, and processability.

As is well known, chirality and luminescence are two necessary conditions for constructing CPL materials. Hence, this review offers a comprehensive summary of recent advancements in polymer-based CPL materials, with a particular focus on the fabrication of chiral superstructures. To provide a clear roadmap for the reader, we categorize the construction strategies into four distinct types: (1) chiral polymers with

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side-chain chiral centers enabling chiral transfer and amplification (Fig. 1a); (2) chiral polymers with main-chain chiral centers facilitating chiral transfer and amplification (Fig. 1b); (3) achiral polymers incorporating small-molecule inducers via non-covalent bonding (Fig. 1c); (4) achiral polymers utilizing macromolecular inducers through interchain non-covalent interactions (Fig. 1d). Building on these examples, we aim to clarify the rational design of polymer architectures and the complex mechanisms of chiral transfer, amplification, and emission that lead to efficient CPL. The review concludes with a brief discussion of the primary challenges and future opportunities in the field, intended to accelerate further research in-

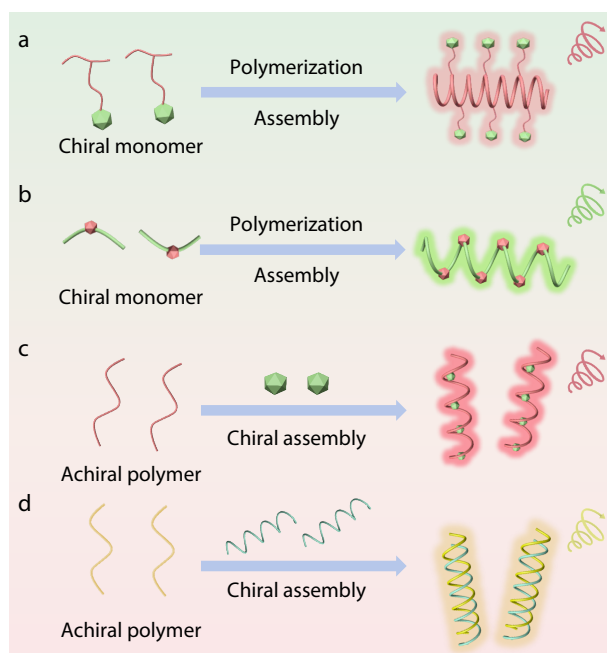


Fig. 1 Schematic illustration of the construction of polymer-based CPL materials. (a) Chiral polymers with side-chain chiral centers; (b) Chiral polymers with main-chain chiral centers; (c) Achiral polymers incorporating small-molecule inducers via non-covalent bonding; (d) Achiral polymers utilizing macromolecular inducers through interchain non-covalent interactions. (The online version is colorful.)

to the construction and practical application of polymer-based CPL materials.

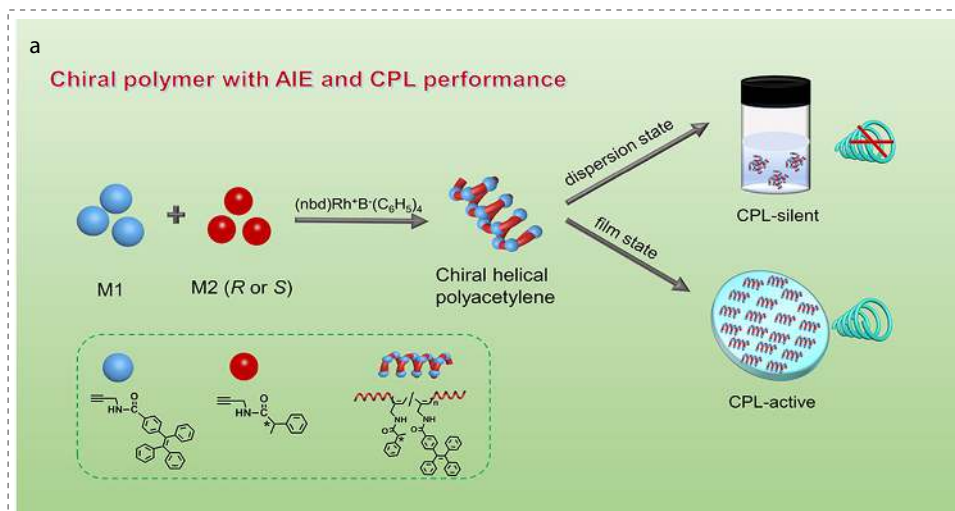
CPL GENERATED BY HELICAL POLYMER SYSTEMS

Helical Polymer with Sides-chain Chiral Centers

Helical polymers, due to their intrinsic helical chirality and chiral amplification effect, have become an important platform for constructing CPL materials. Among dynamic helical polymers, polyacetylenes (PAs) occupies an important position. Introducing chiral structures into the side chains of optically inactive PAs often results in the construction of a chiral backbone with excess helix. Besides, the PAs skeleton has a variety of conformations, and its extension and direction of rotation can be controlled by external conditions such as solvent, temperature, light, acid and alkali, metal ions, etc.

Therefore, introducing luminescent groups into the side chains of chiral PAs is an effective method for constructing polymer-based CPL materials.

Deng's group has made systematic progress in the construction of PA-based CPL materials.^[47–50] In 2020, Deng and Zhao *et al.* introduced tetraphenylethylene (TPE) functional groups with AIE properties into the side chains of chiral PAs, successfully constructing CPL materials that possess both high asymmetric emission factors and AIE properties (Fig. 2a).^[47] First, achiral substituted alkyne monomers containing TPE functional groups were designed and synthesized. These monomers were then copolymerized with chiral alkyne monomers to prepare chiral fluorescent helical substituted polyacetylene. The introduction of the TPE groups endowed the polymer with typical AIE properties. Furthermore, the authors found that the synthesized chiral polymer did not exhibit CPL properties in solution due to the unsuccessful chiral transfer, but showed a strong CPL signal in thin films, with an emission asymmetry factor as high as 3.6×10^{-2} . Based on this phenomenon and related experimental results, the authors proposed a new design concept for constructing CPL materials based on the "CD-fluorescence wavelength matching rule". This work provides a new approach for constructing CPL materials with high g_{lum} and high solid-state lumines-



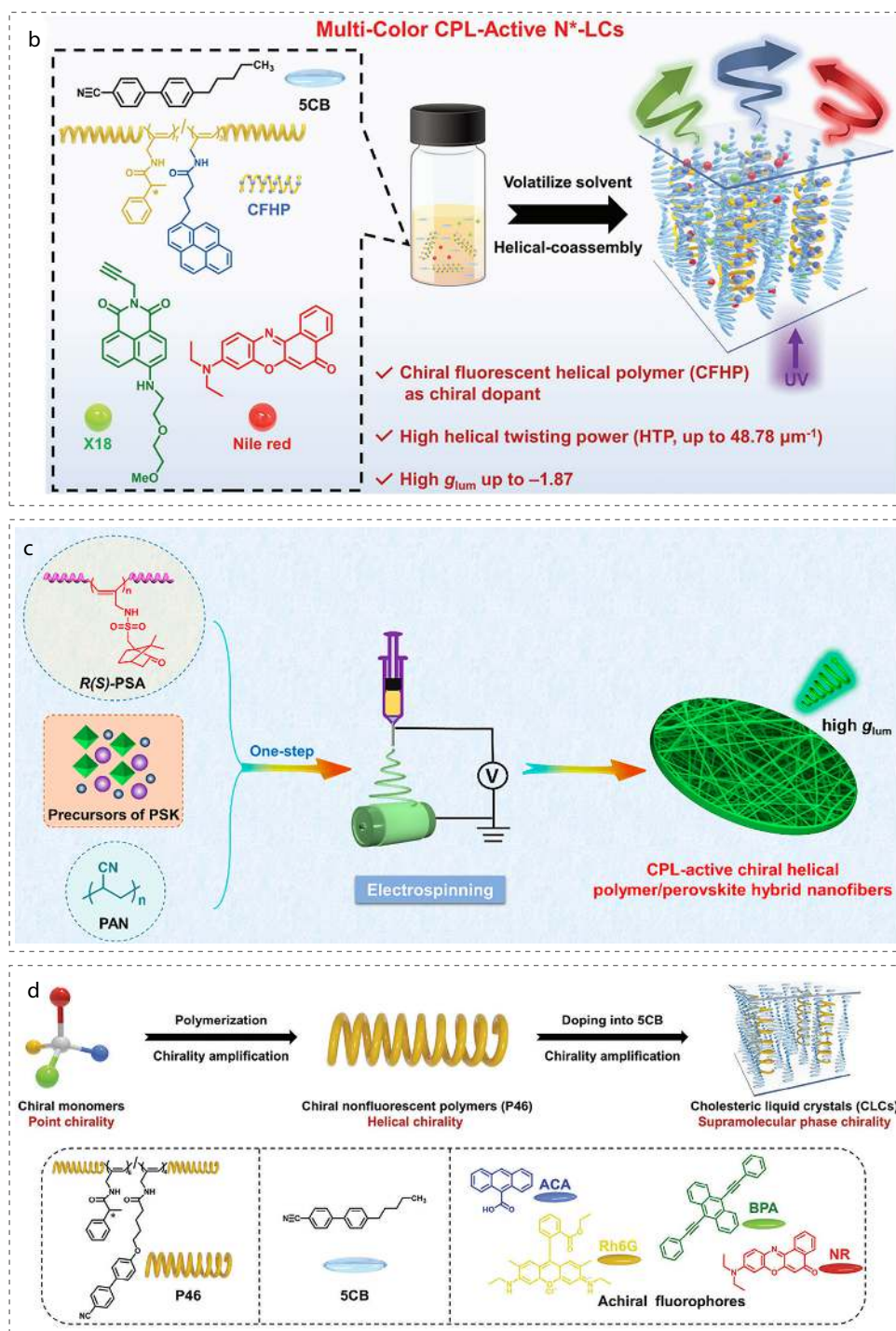


Fig. 2 (a) Schematic illustration of preparing chiral polymers with AIE on the side chain and CPL (Reproduced with permission from Ref. [47]; Copyright (2020), American Chemical Society). (b) Schematic illustration of the fabrication of PA-based chiral nematic liquid crystals (N*-LCs) generating multi-color CPL (Reproduced with permission from Ref. [48]; Copyright (2023), Wiley). (c) Schematic representation for the preparation of chiral helical polymer/perovskite hybrid nanofibers through electrospinning exhibiting intense CPL (Reproduced with permission from Ref. [49]; Copyright (2021), American Chemical Society). (d) Schematic representation of three-level chirality transfer from configurationally point chirality of small molecules to conformationally helical chirality of helical polymers and finally to supramolecular phase chirality of cholesteric liquid crystals for CPL (Reproduced with permission from Ref. [50]; Copyright (2024), Wiley). (The online version is colorful.)

cence efficiency.

Luminescent chiral nematic liquid crystals (N*-LCs) with periodic helical supramolecular structures can generate strong

CPL, and their considerable luminescent g_{lum} makes these materials promising for a wide range of applications. Hence, the team proposed a novel chiral fluorescent helical polymer

(CFHP) dopant including chiral site and luminescent group of the side chain, which was incorporated into the nematic liquid crystals (N-LCs) molecule 5CB, successfully preparing luminescent chiral nematic liquid crystals (N*-LCs) with ideal CPL performance (Fig. 2b).^[48] Thanks to the relatively high helical twisting power of CFHP, the selective reflection band of the N*-LCs could be tuned to completely cover its emission band. At a doping concentration of 9 wt%, a near-pure CPL signal with a g_{lum} as high as -1.87 was obtained.

Besides covalently introducing luminescent groups into the side chains of PA, blending chiral helical PA with luminescent molecules can also produce CPL.^[49–51] In 2021, as shown in Fig. 2(c), the group prepared chiral helical polymer/perovskite hybrid nanofibers with excellent CPL properties via a one-step method, using chiral helical PA, perovskite nanocrystals, and polyacrylonitrile as the chiral source, fluorescence source, and matrix, respectively.^[49] Experimental results show that the prepared chiral perovskite hybrid nanofibers exhibit excellent fluorescence properties, with a luminescence asymmetry factor reaching the order of 10^{-2} . Chiral helical polyacetylene, used as a circularly polarized fluorescence filter, achieved highly efficient circularly polarized fluorescence emission from perovskite without any non-covalent bonding. Furthermore, the *in situ* formation of perovskite nanocrystals avoided cumbersome preparation and purification processes. Simultaneously, the polyacrylonitrile substrate effectively protected the perovskite, giving it good stability in air; no significant decrease in fluorescence performance was observed within one month. This method offers advantages such as low cost, simple operation, and ease of large-scale production. As shown in Fig. 2(d), this group successfully achieved a three-level chirality transfer and amplification strategy, from the configurational chirality of small molecules to the helical conformational chirality of chiral non-fluorescent PA, and then to the supramolecular chirality of cholesteric liquid crystals (CLCs).^[50] Notably, the helical twisting force of the polymer is 5 times that of its monomer. By introducing achiral fluorescent molecules as the third components, they successfully constructed full-color CPL-active CLCs with a maximum g_{lum} of 1.54 and a maximum photoluminescence quantum yield (QY) of 63.8%. Through the synergistic effect of helical supramolecular assembly and selective reflection, a white-light CPL with a $|g_{lum}|$ as high as 1.46 was achieved. The three-level chirality transfer and amplification strategy established in this work not only deepens the understanding of chiral induction and amplification between different structural levels, but also provides a convenient and effective approach for constructing excellent CPL materials.

Optically inactive helical PA can also work as a chirality amplifier to generate and modulate multi-color CPL.^[52] The group further combined chiral fluorescent small molecules without CPL properties with racemic helical PA, achieving CPL signals in the chiral fluorescent small molecules through chiral transfer and amplification between the two components, thus preparing a multi-color CPL-emitting small molecule/polymer composite film material. Chiral small molecules transfer their chirality to the PA backbone through non-covalent interactions, inducing helical chirality and exhibiting a

chiral amplification effect. With the assembly and aggregation of components during film formation, the induced helical chirality is further transferred to chiral fluorescent small molecules, ultimately endowing the composite film with CPL activity and achieving a leap from zero to one in terms of CPL performance. Subsequently, through a circularly polarized fluorescence energy transfer process, the aforementioned multi-color CPL composite film was used as an energy donor to successfully excite achiral Nile red molecules to achieve red CPL emission. Based on this method, it is expected that more novel CPL materials will be continuously developed in the future.

In addition to introducing luminescent groups, Wan's group explored the CPL properties of PA polymers with main-chain luminescence capabilities.^[53–57] Monosubstituted PAs mostly exhibit an extended *cis-transoid* conformation, and their main chain has always been considered non-luminescent. In 2021, Wan and Zhang *et al.* reported for the first time a CPL material of monosubstituted PA based on a tight *cis-cisoid* PA backbone, breaking the traditional understanding that monosubstituted PA backbones do not emit light (Fig. 3a).^[53] Its molecular design was based on a 3,5-bisamide substitution structure. Strong intramolecular hydrogen bonds stabilized the tight *cis-cisoid* conformation, restricting molecular motion and lowering the $1B_u$ energy level of the PA backbone, making $E(1B_u) < E(2A_g)$. Even without introducing fluorescent groups into the side groups, the polymer exhibited strong yellow-green fluorescence. The polymer exhibited both chiral and fluorescent properties, displaying excellent CPL performance. Utilizing the solvent and temperature responsiveness of hydrogen bonding, a reversible transition between the *cis-cisoid* and extended *cis-transoid* helical conformations was achieved, thus enabling reversible modulation of fluorescence and CPL. In chiral nematic liquid crystal films, the g_{lum} value can reach the order of 10^{-1} . The helical conformation and CPL properties in the film state exhibited a very rapid response to trifluoroacetic acid (TFA) vapor. Alternating treatment with TFA and tetrahydrofuran (THF) vapor allowed for reversible modulation of the transition between the *cis-cisoid* and *cis-transoid* helical conformations, thereby enabling the on/off switching of the CPL.

In 2025, as shown in Fig. 3(b), this team further proposed a biomimetic strategy using conjugated chiral poly(phenylacetylene) (PPA) derivatives with DNA-like helical groove structures as assembly units.^[56] By controlling molecular structure and assembly dynamics, they assembled vortex-like two-dimensional assemblies in solution, achieving programmable mesoscopic chirality and significantly amplifying the g_{lum} of CPL with similar PA backbone luminescence. Among them, the two-dimensional vortex sheet exhibited significantly enhanced CPL ($g_{lum}=2.8 \times 10^{-2}$), which is superior to the two-dimensional hexagonal sheet with mirror symmetry obtained under thermodynamic steady state ($g_{lum}=1.3 \times 10^{-2}$). This study not only deepens the understanding of the multi-level chirality transfer mechanism, but also provides new ideas for the design of CPL materials.

Different from dynamic helical polymers, static helical polymers (such as polyisocyanates, PIs) possess stable rigid helical structures and high helical inversion energy barriers. Their

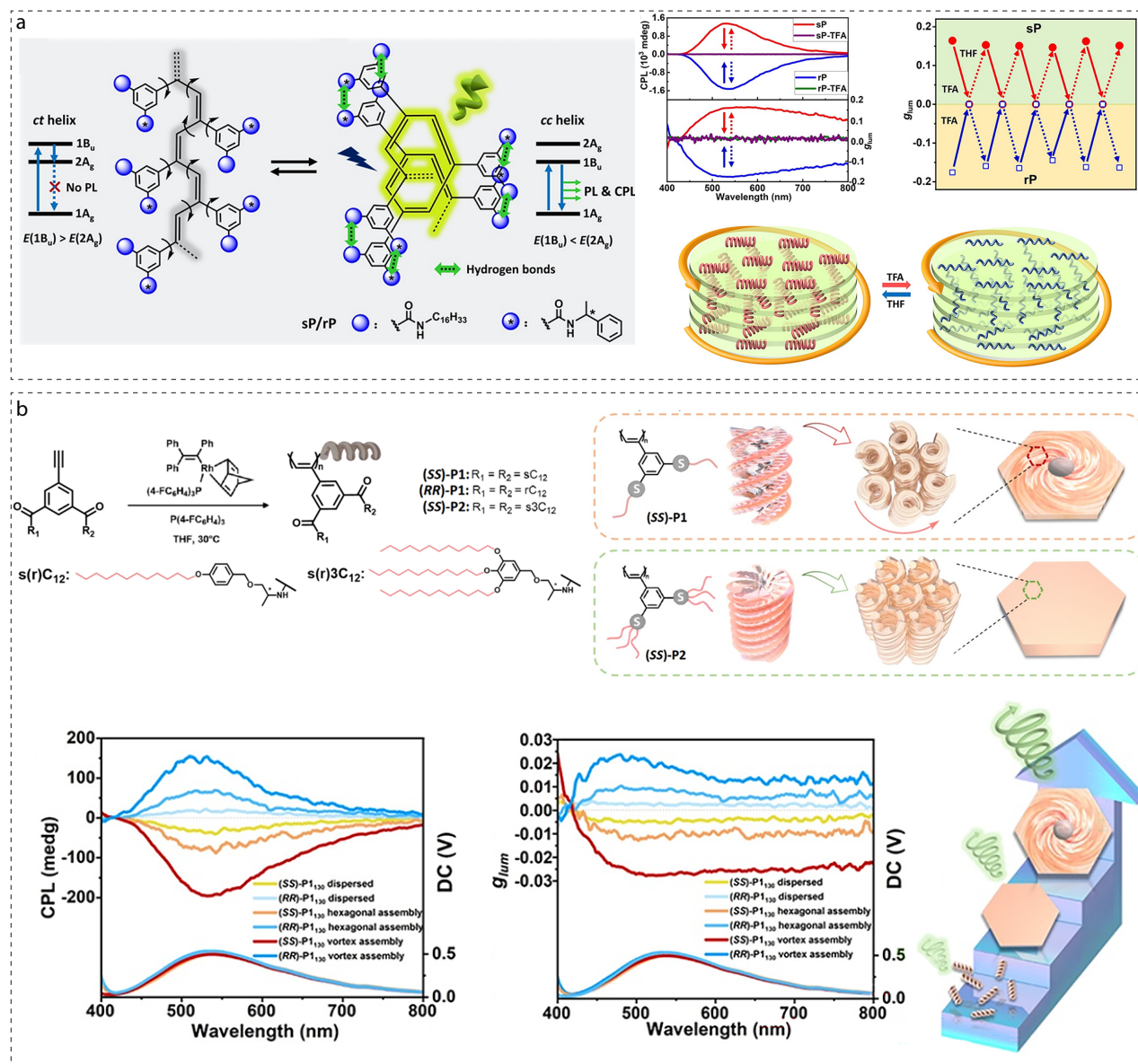


Fig. 3 (a) Schematic illustration of the proposed strategy to obtain switchable fluorescence and CPL in monosubstituted PA (Reproduced with permission from Ref. [53]; Copyright (2021), Wiley). (b) Schematic illustration of the synthesis, assembly, and CPL amplification of monosubstituted poly(phenylacetylene) (PPA) derivatives (Reproduced with permission from Ref. [56]; Copyright (2025), American Chemical Society). (The online version is colorful.)

helical conformation is kinetically controlled, and their response to external stimuli is extremely weak or negligible. They are also important candidates for constructing CPL materials. Wu's group has made significant progress in chiral polyisocyanide-based CPL materials.^[58–63] As shown in Fig. 4(a), in 2020, they reported a significant advancement in the controlled self-assembly of π -conjugated block copolymers and introduced the concept of crystallization-driven asymmetric self-assembly (CDASA) to fabricate single-handed helical nanostructures with tunable optical properties.^[58] They synthesized amphiphilic block copolymers consisting of poly(3-hexylthiophene) (P3HT) and optically active helical poly(phenyl isocyanide) (PPI) *via* one-pot sequential living polymerization. Leveraging the crystallizable nature of P3HT

and the chirality of the PPI segment, well-defined, monodisperse helical nanofibers with controlled length and helicity were formed. The handedness of the assemblies was dictated by the chiral PPI block, which enabled precise control over supramolecular chirality. Notably, the helical assemblies exhibited white CPL, and the g_{lum} can be tunable by varying the length and handedness of the nanofibers.

Furthermore, the group reported the one-pot synthesis of optically active polyfluorene-block-poly(phenyl isocyanide) (PF-*b*-PPI) copolymers with controlled molecular weights and narrow dispersities (Fig. 4b).^[59] Benefiting from the π -conjugated PF block and the helical PPI block, these copolymers self-assembled into single-handed helical nanofibers in selective solvents, with chirality transferred from the PPI segments

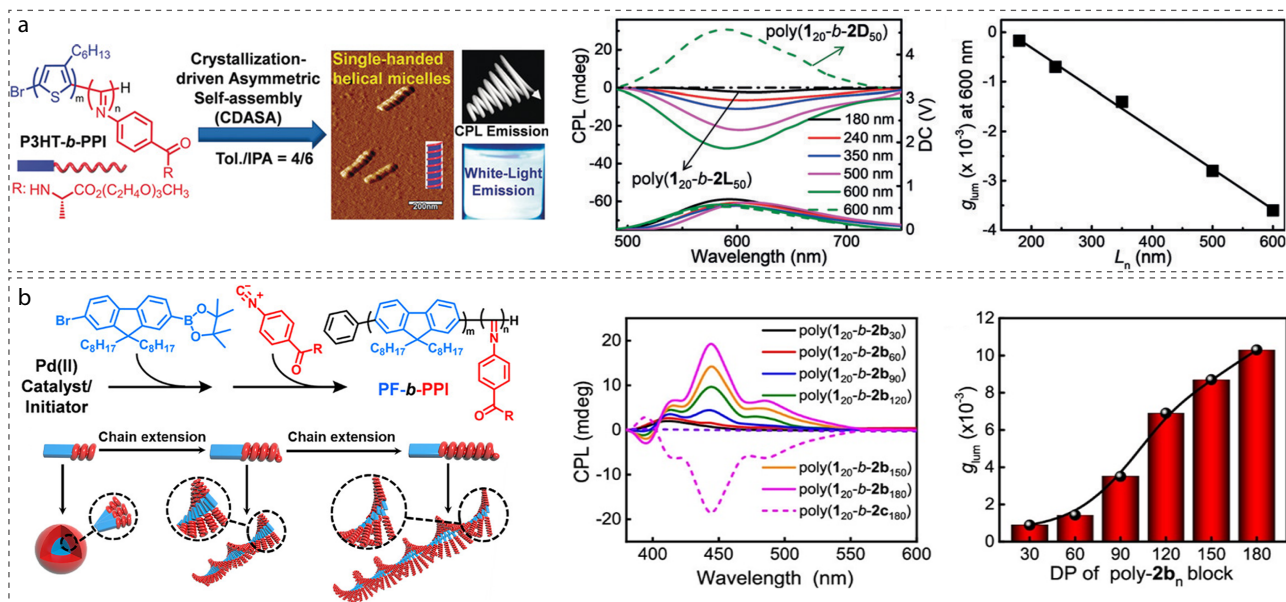


Fig. 4 (a) Schematic illustration of the white-light emission and intense CPL by the helical assembly of the chiral block copolymer (Reproduced with permission from Ref. [58]; Copyright (2020), Wiley). (b) Schematic illustration of the synthesis, assembly, and CPL amplification of chiral PI-based block copolymers (Reproduced with permission from Ref. [59]; Copyright (2023), American Chemical Society). (The online version is colorful.)

to the supramolecular structures. Notably, the resulting helical assemblies exhibited CPL with significantly enhanced dissymmetric factors g_{lum} in the aggregated state, demonstrating potential for advanced optoelectronic applications.

The above discussion demonstrates that dynamic helical polymers, due to their dynamically tunable helical conformation, can generate dynamic CPL signals, which will be applicable to future high-order information encryption fields. In contrast, static helical polymers, due to their higher helical inversion energy barrier and good stability, are suitable for constructing highly stable optical devices. In terms of dynamism and stability, both have their own advantages and disadvantages.

In addition, recently Li and Yin *et al.* achieved stimulus-responsive dynamic CPL in a static helical polymer. As shown in Fig. 5, they developed a novel, covalent, and green synthetic strategy to construct a static helical supramolecular polyisocyanate with AIE properties through helical selective cationic copolymerization of an AIE-initiated chiral monomer (*D/L*-menthol ester-substituted aryl isocyanides) and an achiral stimulus-responsive monomer (azobenzene-substituted aryl isocyanides) catalyzed by a novel carbocation initiator (PhEt)⁺[(Cl)B(C₆F₅)₃]⁻.^[64] This material exhibited multiple stimulus-responsive CPL properties in the liquid state: humidity-enhanced CPL, Fe³⁺ ion quenching CPL, and light/pH reversible “switch” CPL. Molecular simulations showed that the reversible *cis-trans* isomerization of the azobenzene side groups lowered the energy barrier for helical conformational transitions, enabling reversible transformation of the main chain from a helical to a disordered conformation. By doping with different fluorescent dyes, full-color and white CPL composite films were also prepared, and their applications in advanced anti-counterfeiting and information encryption were demonstrated.

Circularly polarized phosphorescent materials can also be

prepared in chiral polymer systems. Pure organic room-temperature phosphorescent (RTP) materials, due to their large Stokes shift, long-life emission, and good processability, hold immense promise for applications in bioimaging, sensors, and anti-counterfeiting materials. Among the numerous molecular designs for constructing RTP materials, systematically studying molecular function and material properties based on chiral structures has gradually become a cutting-edge scientific research area. To date, the design and fabrication of RTP materials with CPL properties have received considerable attention. Circularly polarized RTP materials have been successfully designed by restricting the movement of chiral aromatic molecules through crystal engineering or rigid polymers.^[65–67]

In 2022, Ma and co-workers designed and synthesized a chiral substituted acetylene monomer (BrNpA) containing bromonaphthalimide, and then copolymerized it with a chiral acetylene monomer (*R/S*-phNA) to obtain a chiral helical substituted polyacetylene with potential phosphorescence emission (Fig. 6a).^[65] A flexible film exhibiting circularly polarized phosphorescence (CPP) was obtained through a simple molding process with poly(methyl methacrylate) (PMMA). The chiral helical structure of the substituted polyacetylene exhibited significant optical activity, endowing the material with a high luminescence asymmetry factor, reaching up to 0.019. The oxygen-consuming properties of the film under ultraviolet light irradiation endowed the material with dynamic chiroptical functions, allowing for the modulation of CPP *via* ultraviolet light, exhibiting significant advantages such as non-contact and fatigue resistance. Furthermore, by altering the internal composition of the substituted polyacetylene and controlling the oxygen permeability, the programmable retention time of CPP was achieved, which helps this system become an important candidate material for stimulus-controllable chiral devices.

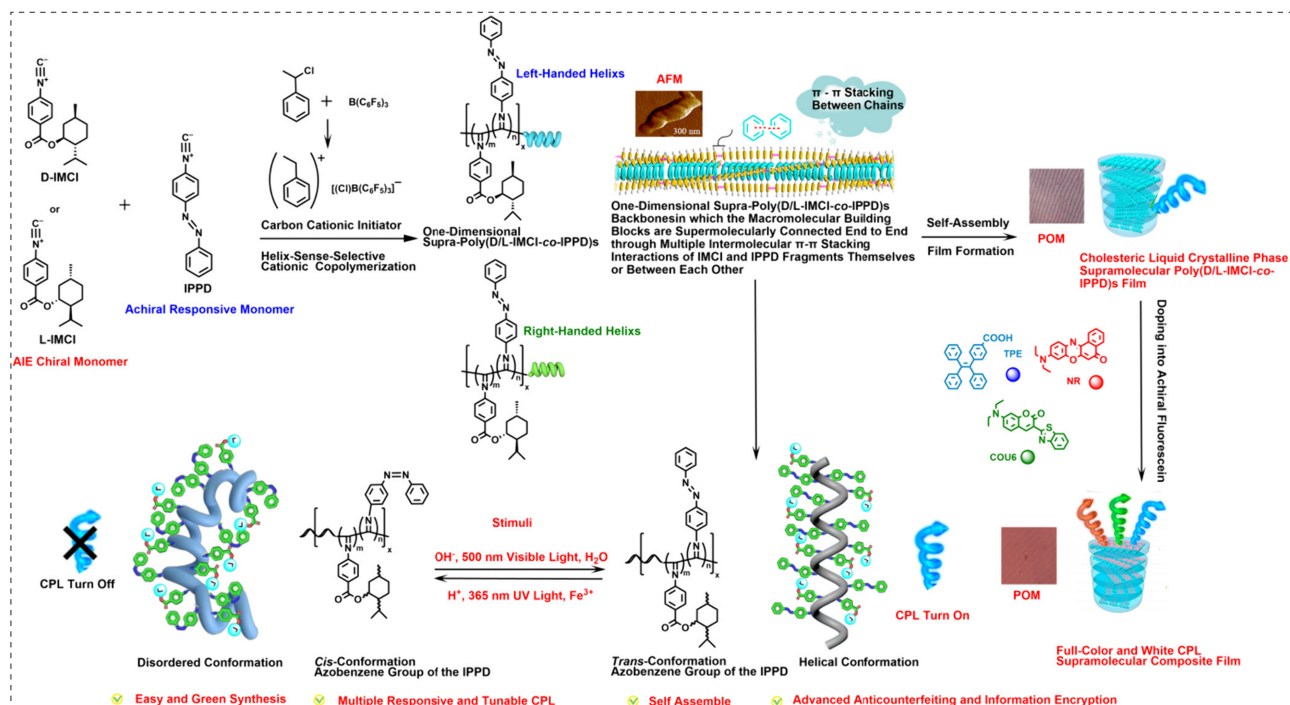


Fig. 5 Schematic illustration of the novel, green, and covalent synthetic strategy for constructing static helical supramolecular polyisocyanides with multi-responsive and tunable CPL (Reproduced with permission from Ref. [64]; Copyright (2026), American Chemical Society). (The online version is colorful.)

In 2025, Huang and co-workers proposed a new strategy for the fabrication of blue CPP materials through covalent confinement of isolated chiral chromophores within a polymeric network (Fig. 6b).^[67] The establishment of strong hydrogen bonds within the polymer matrix ensured that the chiral chromophores remain in a well-isolated and stabilized molecular configuration, resulting in a blue emission centered at 414 nm, a prolonged lifetime of 3.0 s, and a luminescent dissymmetry factor of approximately 10^{-2} . By exploiting synergistic energy transfer involving both afterglow and chiral characteristics, full-color CPP systems are achieved through the incorporation of various fluorescent dyes into the designed blue-emitting polymers, thereby enabling broad application potential. This study establishes a streamlined pathway for constructing blue CPP materials and extends the scope of such systems into emerging fields.

Helical Polymer with Main-chain Chiral Centers

Introducing chiral sites into the polymer backbone is also an effective strategy for constructing helical polymers with CPL properties. Cheng's group introduced axially chiral binaphthalene into the backbone of different luminescent polymers, obtaining a series of helical polymers and generating CPL.^[68–71] In 2022, Cheng's group selected and synthesized two chiral polymers with different binaphthalene dihedral angles (*R/S*-P1 and *R/S*-P2) and constructed two chiral co-assemblies, *R/S*-P1-NPy and *R/S*-P2-Npy, with an achiral fluorescent dye (pyrene-naphthalimide dye, NPy, CPL emitter) through intermolecular π - π stacking interactions (Fig. 7a).^[70] The results showed that the chiral polymers with anchored dihedral angles not only possessed strong chiral characteristics but also exhibited excellent chiral induction ability for the achiral fluorescent molecule NPy. After

heat annealing at 120 °C, the CPL signal ($|g_{\text{em}}|$) of the ordered helical nanofibers (*R/S*-P2)_{0.6}-(NPy)_{0.4} formed by the strong π - π stacking interactions between *R/S*-P2 and the achiral NPy reached as high as 5.6×10^{-2} , which is approximately 6 times amplified compared to (*R/S*-P1)_{0.6}-(NPy)_{0.4}. According to molecular dynamics simulations, during chiral co-assembly, the fluorene group in *R*-P2 and the pyrene group in NPy exhibited a short intermolecular distance ($d=2.86$ Å) and a strong intermolecular binding energy (-10.67 kcal·mol⁻¹). This indicates that the rigid chiral polymer *R/S*-P2, anchored to dihedral angles, was more likely to form a stable and ordered helical chiral co-assembly through intermolecular π - π stacking interactions with the achiral luminescent component NPy, thereby achieving chiral transfer and amplification effects. More importantly, this ordered helical nanofiber (*R/S*-P2)_{0.6}-(NPy)_{0.4} as the emitting layer of circularly polarized organic light-emitting diodes (CP-OLEDs), demonstrated stable and excellent CP-EL performance ($|g_{\text{EL}}|=4.8 \times 10^{-2}$).

Another representative work from this group was shown in Fig. 7(b). They developed novel axially chiral binaphthyl-based conjugated polymers with AIE activity via click polymerization.^[71] These polymers exhibited strong aggregation-induced CPL in both aggregate states and cast-spin films, with dissymmetry factors (g_{lum}) reaching up to 6.97×10^{-3} and 1.45×10^{-2} , respectively. The enhanced CPL response was attributed to the formation of supramolecular self-assembled helical nanowires in high-water-fraction environments ($f_w=90\%$), as confirmed by SEM imaging. The study highlights the potential of AIE-active main-chain chiral conjugated polymers as promising candidates for CPL-based optical sensors, 3D displays, and other photoelectric applications.

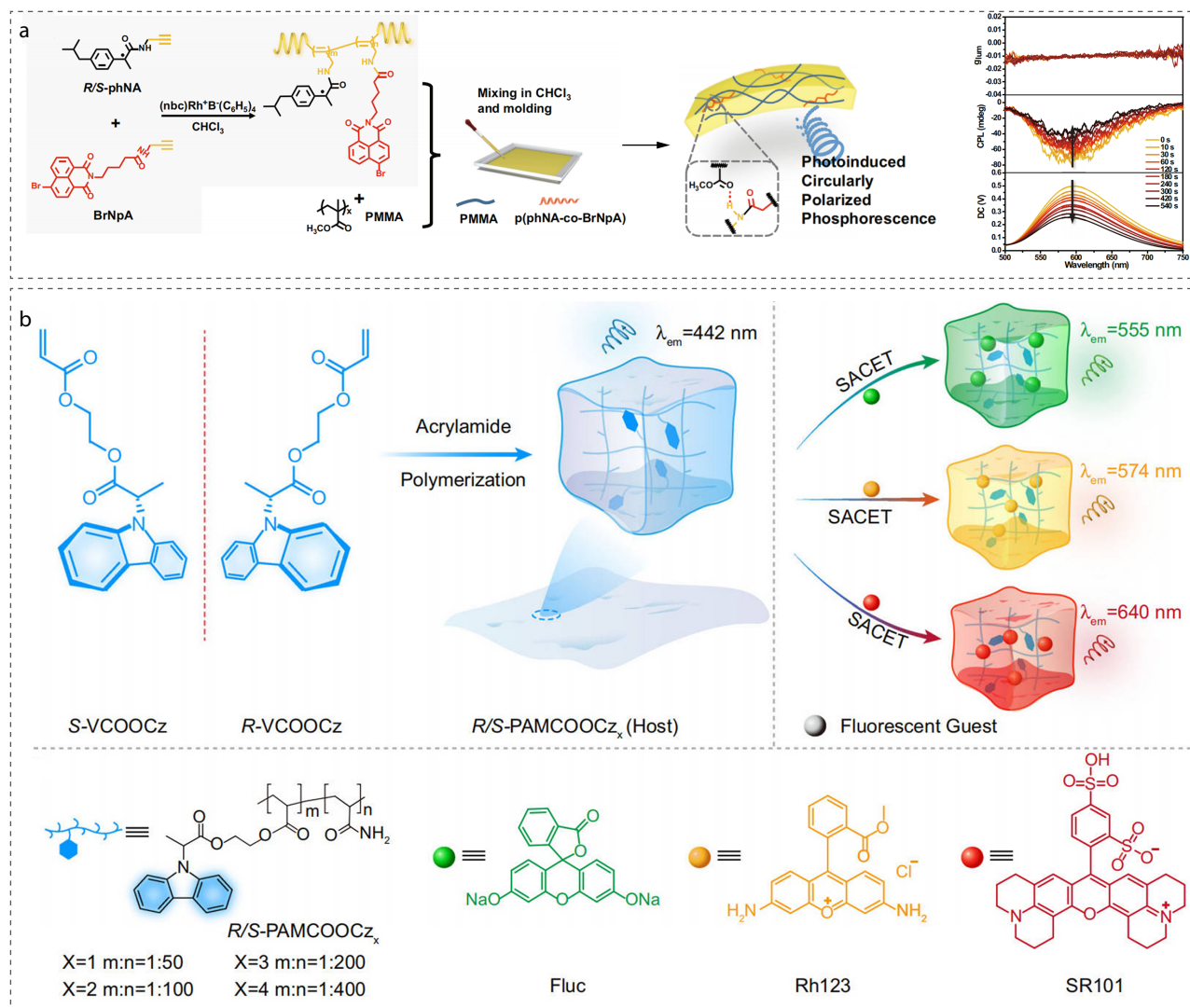


Fig. 6 (a) Schematic illustration of the structure and preparation of the p(phNA-co-BrNpA)-PMMA film exhibiting photoinduced CPP, in which the chiral p(phNA-co-BrNpA) copolymer bearing amide groups interacts with PMMA to form a hydrogen-bonding crosslinked network (Reproduced with permission from Ref. [65]; Copyright (2022), Springer). (b) Schematic illustration of the blue CPP copolymer through covalent self-confinement of isolated chiral chromophores within a polymeric matrix and synergistic afterglow and chirality transfer for achieving full-color CPP polymers (Reproduced with permission from Ref. [67]; Copyright (2024), Springer). (The online version is colorful.)

The above studies have shown that in PAs and Pls, side-chain chiral centers are more favored, while in main-chain conjugated polymers, main-chain chiral centers are more favored. A more suitable chiral transfer style will result in a higher g_{lum} .

CPL GENERATED BY ACHIRAL POLYMER SYSTEMS

Chirality is ubiquitous in nature and closely related to life phenomena. The origin of homochirality in nature remains one of the most challenging scientific questions in the world today. Although this phenomenon has been extensively studied and explored, most current viewpoints remain controversial, and scientific methods for verification are lacking. Studying chiral superstructures composed of achiral molecules helps to understand the homochirality phenomenon in the process of biologi-

cal evolution. Especially from an evolutionary perspective, exploring how chirality arises from achiral environments and is further transferred from the molecular level to supramolecular and even higher levels has profound significance for both basic scientific research and practical applications.^[72] The fabrication of CPL materials from achiral polymers offers a significant advantage, as it eliminates the complex synthesis required for chiral polymers, as well as the racemization problems inherent to their helical counterparts.

CPL Materials Constructed by Chiral Transfer from Small Molecule Inducers to Achiral Polymers

Using inexpensive and easily synthesized chiral small molecules as chiral inducers is one of the effective methods for constructing achiral polymer-based CPL materials. Our group has conducted a series of CPL studies focusing on chiral small molecule limonene. In 2023, we introduced a "multipath transfer" strate-

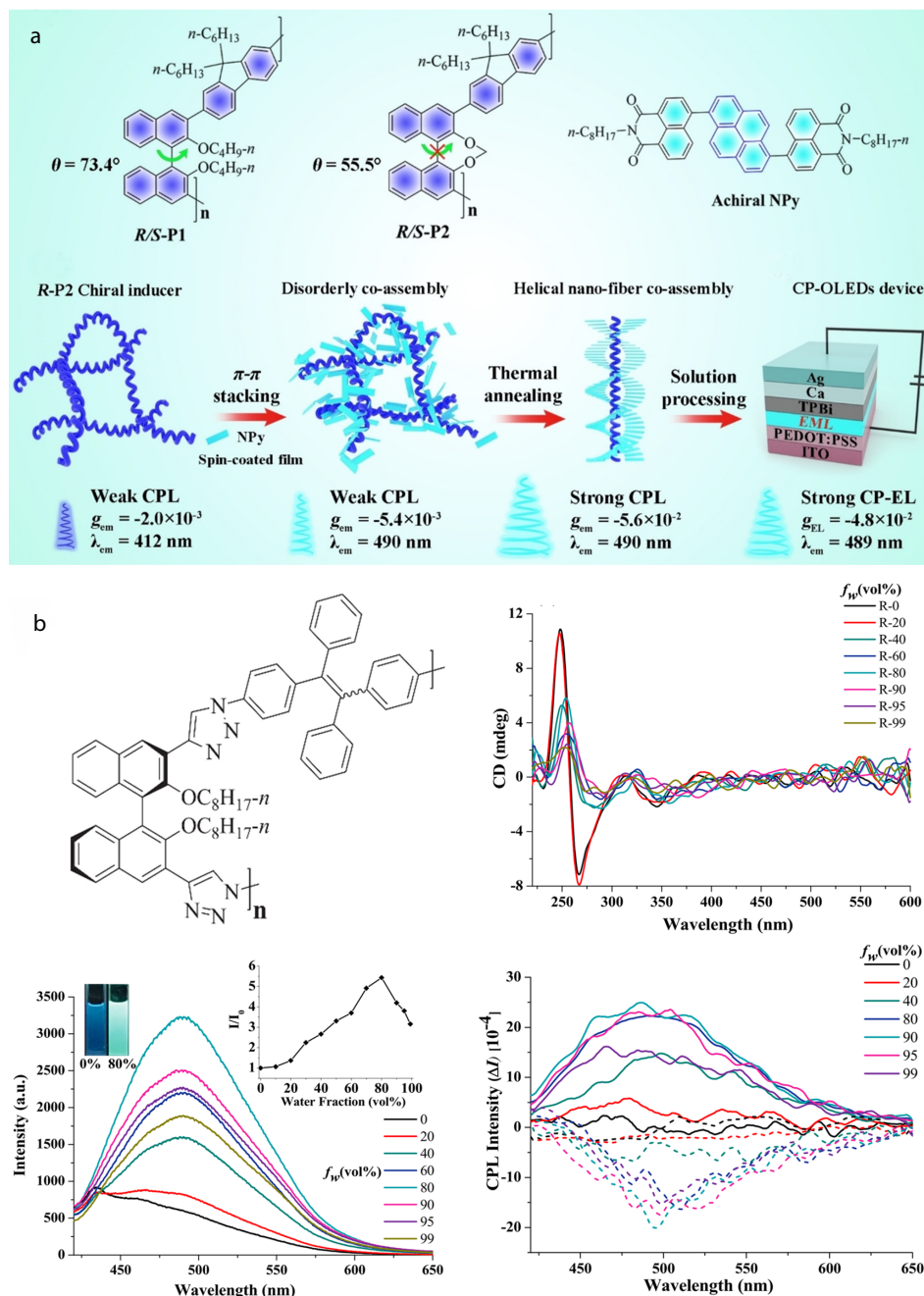


Fig. 7 (a) Schematic illustration of chemical structures of two different chiral polymers with chiral sites on the main chains and the chiral co-assembly of $(R\text{-}P_2)_{0.6}\text{-(NPy)}_{0.4}$ for CP-OLEDs (Reproduced with permission from Ref. [70]; Copyright (2022), Wiley); (b) Chemical structure of axially chiral binaphthyl-based conjugated polymer and the strong aggregation-induced CPL (Reproduced with permission from Ref. [71]; Copyright (2018), Elsevier). (The online version is colorful.)

gy for the fabrication of full-color CPL materials.^[73] This work employed the poly(9,9-di-*n*-octylfluorene) (PF8)/limonene system as a chiral template to systematically investigate the multi-step chirality transfer (MCT) process from chiral small molecules to achiral polymers, and subsequently to various achiral luminescent small molecules (Fig. 8a). Additionally, we examined the sequential fluorescence resonance energy transfer (SFRET) process from PF8 to Coumarin 6 and then to Nile Red. Through controlled assembly process, we successfully achieved full-color CPL. Notably, the study revealed that once a stable polymer he-

lical superstructure was formed, even after complete removal of the initial chiral source limonene, the CPL performance of PF8 and its co-assembled films remained nearly unchanged, demonstrating a pronounced "CPL memory" effect. Molecular simulations and structural analyses indicated that the rigid helical framework formed by PF8 provided a stable chiral microenvironment for guest molecules, which was critical for achieving chiral fixation and memory. This strategy thus provided a novel approach for the development of chiroptical materials with memory functionality.

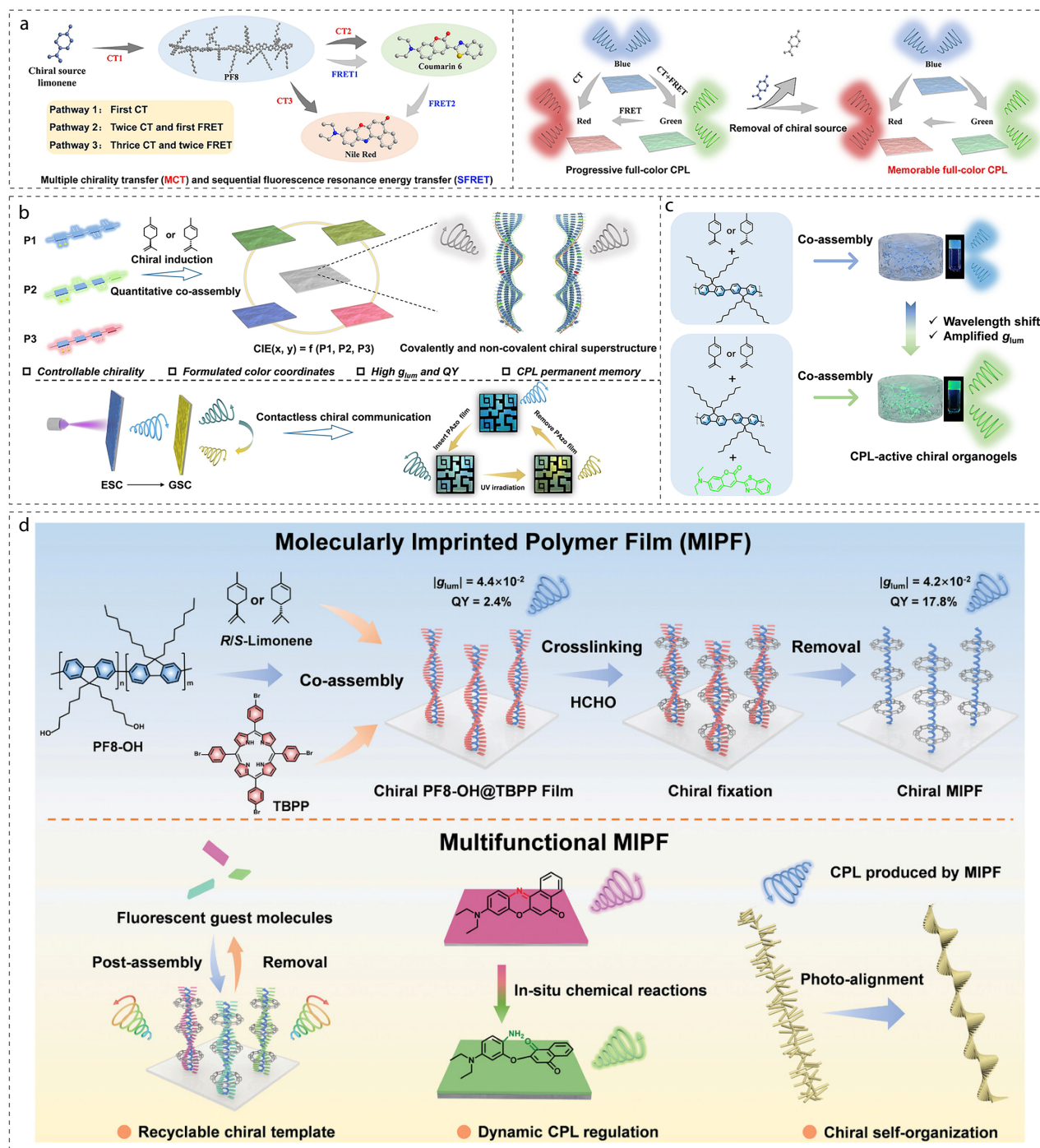


Fig. 8 Schematic illustration of the different preparation strategies of polymer-based CPL materials by achiral polyfluorene derivatives and chiral small molecule (*R/S*)-limonene. (a) Full-color CPL formed by multi-step chiral transfer and energy transfer (Reproduced with permission from Ref. [73]; Copyright (2023), Springer); (b) Precise and stable CPL generated by quantitative co-assembly of different achiral polyfluorene derivatives and chemical crosslinking (Reproduced with permission from Ref. [74]; Copyright (2024), Wiley); (c) CPL-active gels formed by achiral polyfluorene and chiral limonene (Reproduced with permission from Ref. [75]; Copyright (2023), Royal Society of Chemistry); (d) Dynamic full-color CPL formed by recyclable chiral polymer films (Reproduced with permission from Ref. [76]; Copyright (2025), Wiley). (The online version is colorful.)

Subsequently, our group designed and synthesized a series of achiral conjugated polyfluorene derivatives (named P1, P2, and P3) by rationally controlling the donor-acceptor (D-A) monomer structure and polymerization ratio.^[74] These three polymers were co-assembled in a quantitative ratio under the

induction of the chiral solvent limonene to obtain CPL films with precise color control across the entire color gamut (additive principle). Notably, a highly stable white light CPL film was constructed via a two-step method: solvent immersion to remove limonene and chemical crosslinking. The crosslinked

CPL film remained stable in water for an extended period, and the CD and CPL spectra remained unchanged before and after crosslinking. Furthermore, we designed a two-film system of polyfluorene derivatives and a side-chain azobenzene polymer (PAzo), effectively controlling CPL attenuation, inversion, and enhancement through a dynamic chiral communication mechanism between the excited and ground states (subtractive principle). Finally, based on this, we designed and constructed a high-order dynamically switchable quick response code (Fig. 8b). Furthermore, we extended this achiral polyfluorene and chiral limonene system to flexible gel materials, which exhibited significant CPL signals and adjustable colors (Fig. 8c).^[75]

In 2025, our team utilized a molecular imprinting strategy to prepare high-performance CPL polymer films *via* interfacial supramolecular assembly (Fig. 8d).^[76] First, achiral polyfluorene and porphyrin derivatives (TBPP) were co-assembled in a chiral limonene environment. In this process, limonene acted as a chiral inducing agent, while TBPP played a crucial role as a chiral enhancer and imprinting molecule. Subsequently, interchain crosslinking further improved chiral fixation and the stability of the chiral polymer film. Finally, the solvent effect effectively removed all small molecules, resulting in a chiral molecularly imprinted polymer film (MIPF). The removal of TBPP provided chiral sites for various fluorescent guest molecules, including AIE and aggregation-induced quenching (ACQ) molecules. Full-color CPL emission could be achieved through a post-assembly chiral transfer process. White CPL could also be obtained by quantitatively mixing AIE and ACQ guest molecules. The chiral MIPF can be used as an interfacial microreactor to achieve dynamically tunable CPL emission through *in situ* chemical reactions. Furthermore, due to its high figure of merit, chiral MIPFs can be used as chiral light sources to induce chiral alignment in achiral azobenzene polymer films. Chiral MIPFs exhibit stable and superior CPL properties and diverse functionalities, demonstrating broad application prospects.

Besides chiral limonene, axially chiral binaphthyl compounds have also been extensively studied due to their rigidity and strong chiral induction ability.^[77–82] In 2025, Lu *et al.* successfully constructed a color-changing, uniform chiral CPL film with a high luminescence asymmetry factor ($g_{lum} \sim 0.11$) by co-assembling a liquid crystal block copolymer (ethylene oxide-dimethyl methacrylate containing cyanostilbene groups) with an axially chiral diamine derivative (*R/S*-DINBPA).^[77] Mechanistic investigations revealed that the efficient π - π stacking between *R/S*-DINBPA and the cyanostilbene chromophores, synergized with the orientational ordering imposed by the liquid crystal field, collectively governed the chiral transfer and amplification processes. Notably, the dynamic covalent bonds inherent to the cyanostilbene units not only imparted chiral fixation capability to the film but also enabled precise photocontrol over the CPL emission band upon ultraviolet light irradiation. This photo-responsive behavior rendered the film highly suitable for applications in chiral-patterned anti-counterfeiting encryption. This co-assembly strategy provided a versatile platform for the rational design of advanced intelligent chiroptical materials (Fig. 9a).

Furthermore, the group designed and synthesized a series of binaphthalene-based chiral dopants with different dihe-

dral angles, and co-assembled them with the liquid crystal polymer PMACB and fluorescent dyes to prepare thin film materials with tunable CPL properties (Fig. 9b).^[78] Through systematic experimental characterization and molecular simulation, they revealed the key influence of the matching degree between the dopant dihedral angle and the liquid crystal structure on the CPL enhancement effect, and proposed the "dihedral angle matching rule". The study found that when the dihedral angle of the dopant and the liquid crystal units were similar, the π - π stacking effect was enhanced, the chiral amplification effect was most significant, and the g_{lum} value can reach up to 0.61. In addition, the CPL inversion phenomenon caused by the competition between chiral luminescent molecules and the selective reflection of liquid crystal was also observed.

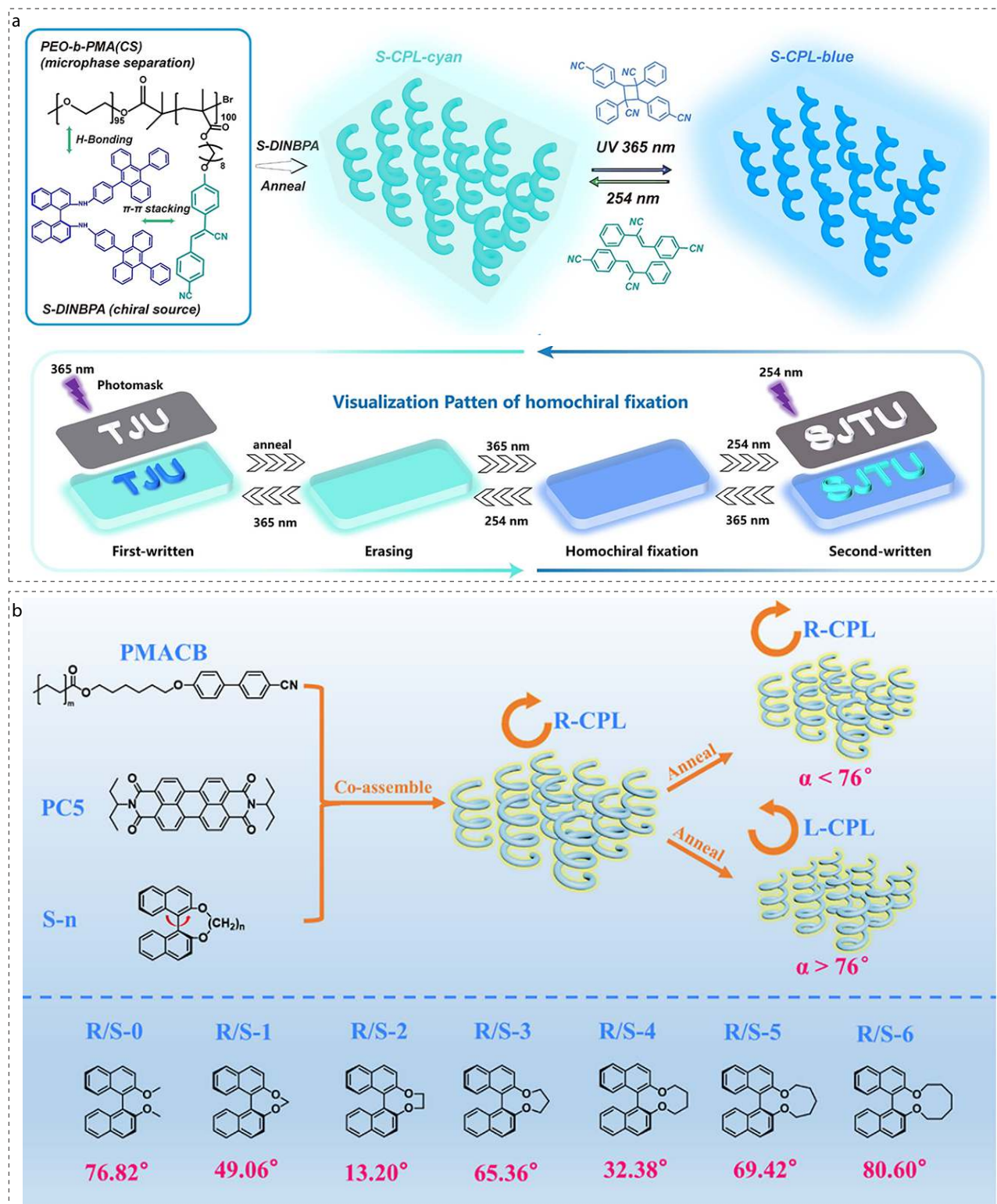
Recently, Cheng's group proposed a simple and efficient *in-situ* photopolymerization strategy to construct a rigid cholesteric liquid crystal polymer network (ChLC-PN), innovatively developing a novel electroluminescent layer material for CP-OLEDs (Fig. 9c).^[79] The team designed and synthesized a class of UV-active room-temperature nematic liquid crystals. Introducing the axially chiral inducers *R/S*-Cz into this achiral liquid crystal matrix yielded a chiral co-assembly, cholesteric liquid crystal monomer film (ChLC-MF), possessing cholesteric liquid crystal characteristics. Subsequently, *in situ* photopolymerization of ChLC-MF yielded the rigid ChLC-PN. This strategy not only preserves the periodic helical structure of CLCs but also endows ChLC-PN with excellent thermal stability, solvent resistance, and mechanical processability, enabling successful application in CP-OLEDs to achieve circularly polarized electroluminescence.

In addition, Lin, Kim, Lu, Kotov and Yang *et al.* have developed a general strategy for the co-assembly of achiral amphiphilic star-shaped block copolymers (BCPs) with chiral small molecules to construct hierarchical chiral supramolecular structures, enabling the fabrication of highly efficient and reversible CPL-active materials (Fig. 10).^[83] Specifically, a 21-arm star-shaped poly(acrylic acid)-block-polystyrene (PAA-*b*-PS) copolymer was designed to form stable, nanoscale unimolecular micelles featuring a hydrophilic PAA core and a hydrophobic PS shell. This architecture facilitated hydrogen bonding between the star-shaped PAA-*b*-PS and (*R*)- or (*S*)-mandelic acid (MA), inducing supramolecular chirality. Time-dependent studies and molecular dynamics (MD) simulations revealed a thermodynamically favorable evolution from achiral star-shaped PAA-*b*-PS to chiral star-shaped PAA-*b*-PS/(*R/S*)-MA complexes, which further assemble into nanoribbons and eventually into microfibers. Incorporation of achiral fluorescent dyes or perovskite nanocrystals into the assemblies yielded CPL-active materials with promising g_{lum} on the order of 10^{-1} , surpassing those achieved with linear BCP-based systems. The solvent evaporation rate and the concentration of star-shaped BCPs play critical roles in determining the kinetically trapped chiral structures formed during co-assembly, leading to chiral inversion. This work establishes a versatile supramolecular co-assembly approach based on star-shaped BCPs for constructing complex chiral architectures and highly efficient, tailorable CPL materials, with potential applications in optoelectronics, anti-counterfeiting, and spintronics.

CPL Materials Constructed by Chiral Transfer from Macromolecule Inducers to Achiral Polymers

Chiral transfer and amplification are not limited to small molecule doped systems. Chiral macromolecules can also act as efficient chiral inducers, driving achiral polymers to assemble into chiral superstructures through non-covalent interactions be-

tween polymer chains, thereby generating CPL signals.^[84–86] In 2017, Fujiki *et al.* systematically studied the non-covalent interactions between two different chiral macromolecules, cellulose triacetate (CTA) and cellulose acetate butyrate (CABu), and achiral polyfluorenes with different degrees of polymerization. The results showed that the two different chiral macromolecules can



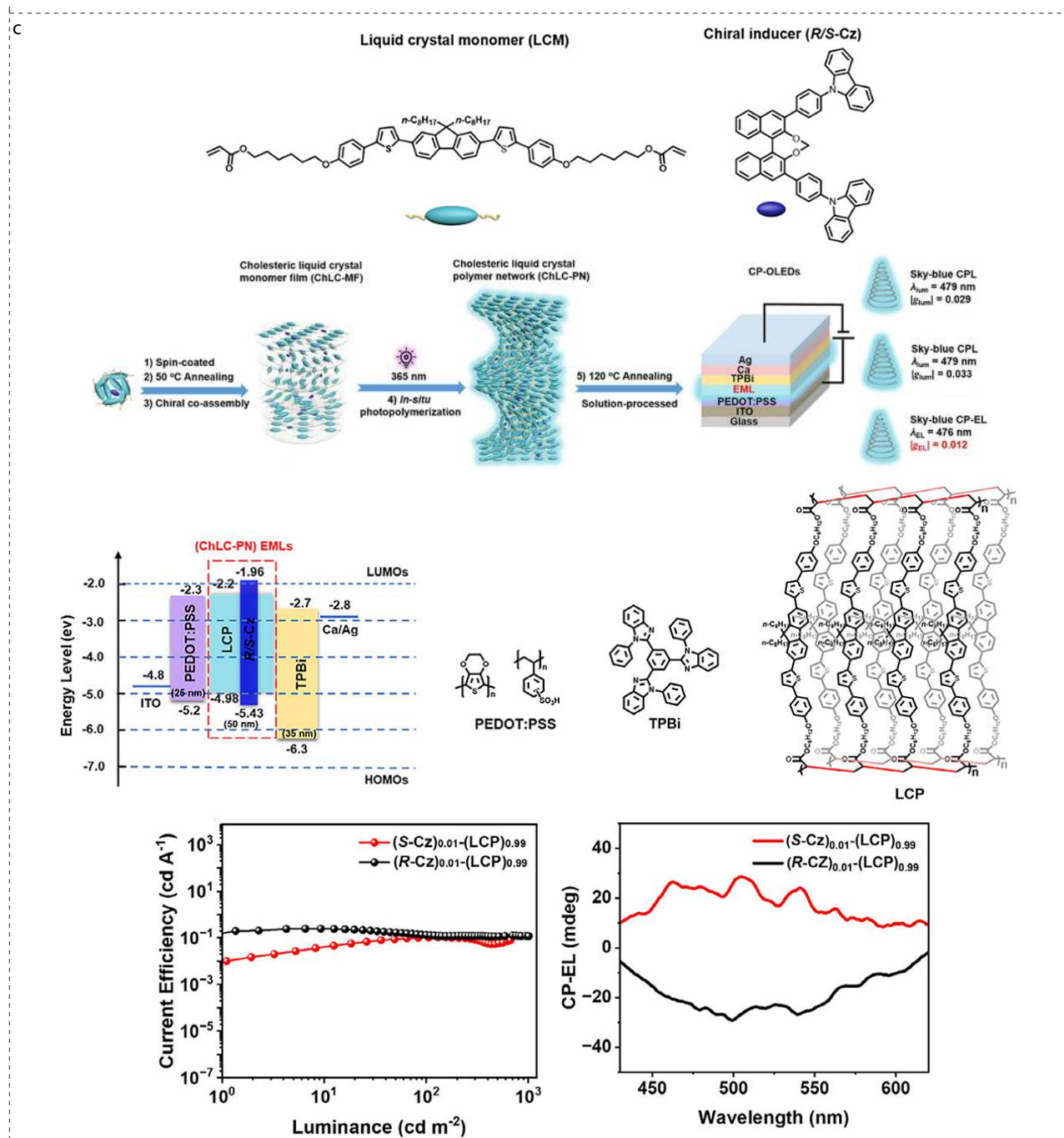


Fig. 9 (a) Schematic illustration of helical assembly of liquid crystal block copolymers driven by exogenous axial chiral small molecules for amplified CPL and visualization of chiral storage-writing (Reproduced with permission from Ref. [77]; Copyright (2025), Wiley); (b) Schematic illustration of CPL amplification and inversion modulated by dihedral angle in exogenous chirality-induced LC polymer films (Reproduced with permission from Ref. [78]; Copyright (2025), Wiley); (c) Schematic illustration of Chemical structures of liquid crystal monomers and chiral inducers, chiral co-assembly process, and *in situ* photopolymerization for high-performance CP-OLEDs (Reproduced with permission from Ref. [79]; Copyright (2025), Wiley). (The online version is colorful.)

induce opposite CPL signals (Fig. 11a).^[84]

In 2022, Deng and Zhao's group successfully demonstrated the use of a chiral helical macromolecule (chiral poly(lactide)) to induce and regulate the helical chirality of achiral macromolecules (racemic PA), proving that effective chirality transfer could occur between two types of helical polymer chains. The research indicated that hydrogen bonds played a

crucial role in this process. More intriguingly, this induced helical chirality was further transferred to externally added achiral fluorophore molecules, enabling them to emit full-color and white CPL. This work presented an unprecedented two-step chirality transfer process for the first time, achieving not only the generation of helical chirality in achiral polymers but also the regulation of full-color CPL emission in achiral fluo-

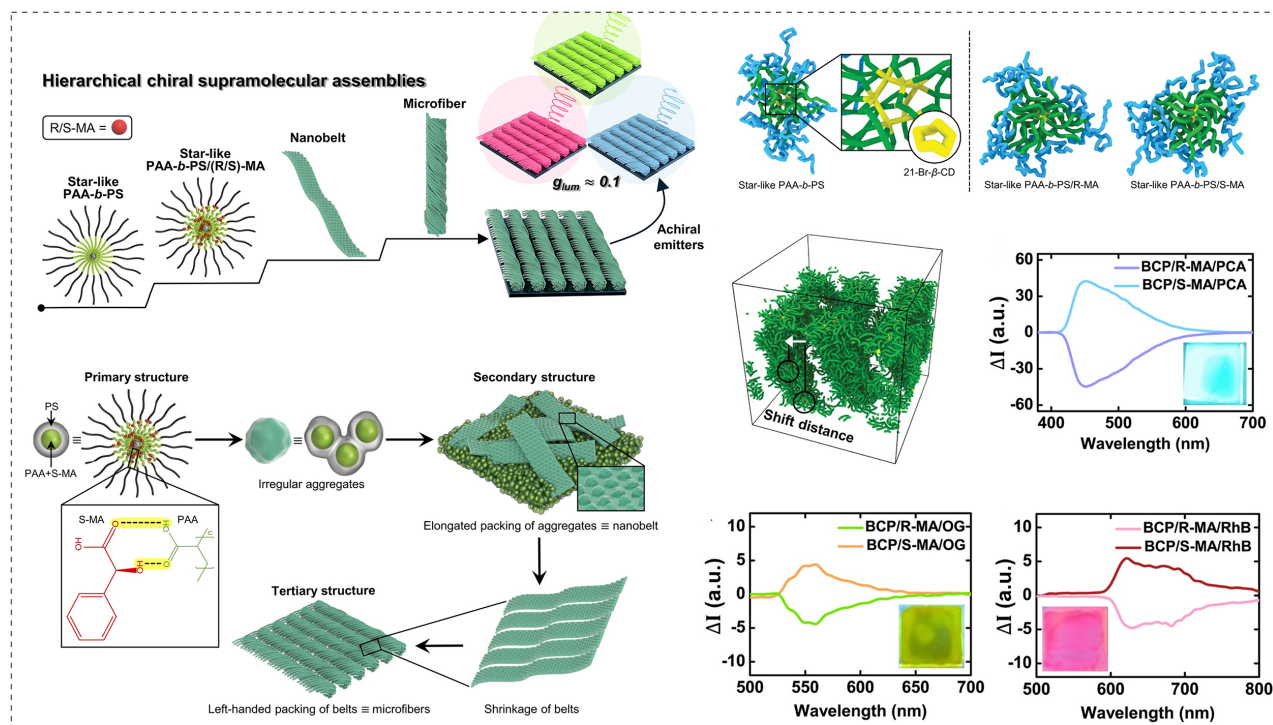
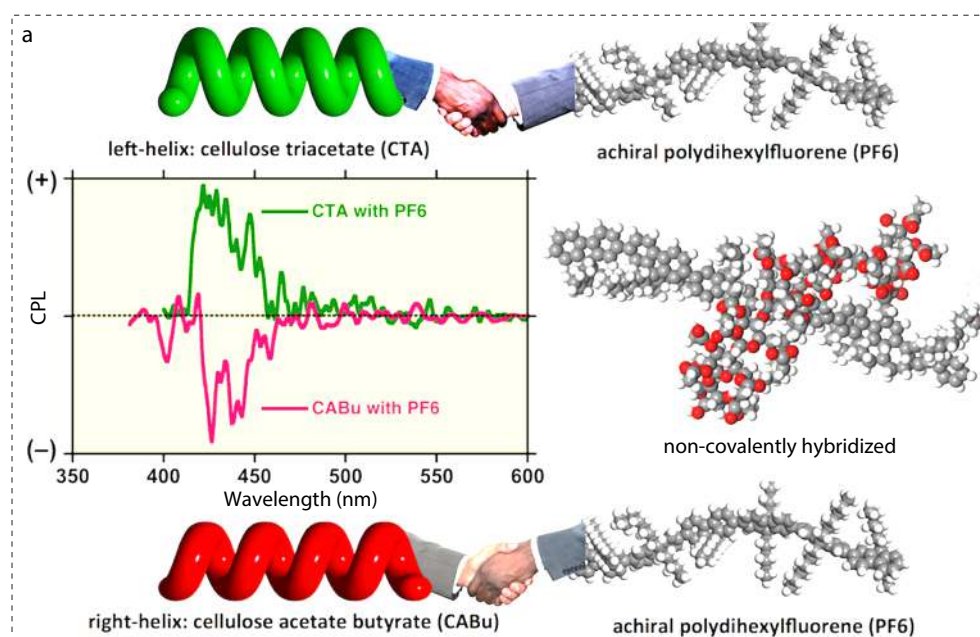


Fig. 10 Schematic illustration of full-color, highly efficient CPL-active materials through hierarchical chiral supramolecular assemblies formed by achiral amphiphilic block copolymers (BCPs) 21-arm star-like poly(acrylic acid)-block-polystyrene (PAA-*b*-PS) and chiral inducer *R/S*-mandelic acid (Reproduced with permission from Ref. [83]; Copyright (2025), American Association for the Advancement of Science, AAAS). (The online version is colorful.)

rescent compound systems.

Subsequently, in 2025 this team reported the first successful achievement of full-color and white CPL through chiral transfer and amplification from chiral macromolecular cellulose derivatives to achiral helical polymers (Fig. 11b).^[86] This chiral transfer was found to be dependent on the hydrogen-bond-accepting ability of the solvent, which enabled facile

and precise modulation of the chiral intensity by using single or mixed solvent systems. Moreover, the chirality induced in the helical polymers was further transferred to an introduced racemic fluorescent dye, producing full-color and white CPL emission with a maximum luminescence dissymmetry factor (g_{lum}) of 1.5×10^{-2} and a photoluminescence QY of up to 62.9%. By spatially separating the chiral and fluorescent com-



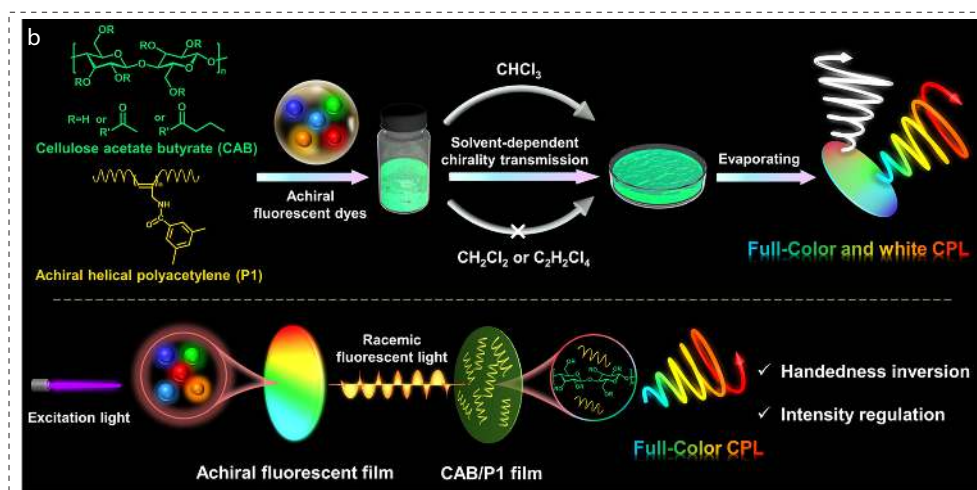


Fig. 11 (a) Two different chiral macromolecules, cellulose triacetate (CTA) and cellulose acetate butyrate (CABu), induce achiral polyfluorene to produce opposite CPL signals (Reproduced with permission from Ref. [84]; Copyright (2017) American Chemical Society). (b) Schematic diagram illustrating the generation of full-color and white CPL in a composite film through solvent-dependent chirality transfer, as well as the modulation of CPL handedness and intensity in a double-layer film via fluorescence-selective absorption (Reproduced with permission from Ref. [86]; Copyright (2025) Wiley). (The online version is colorful.)

ponents, the reversal of CPL handedness and the precise control of CPL intensity were achieved. Notably, circularly polarized white organic light-emitting diodes (CP-WOLEDs) and chiral logic gates capable of multiple information outputs were successfully demonstrated. This work not only advances the construction of chiral cellulose-based materials but also provides deeper insights into chiral transfer phenomena between macromolecules and synthetic helical polymers.

CONCLUSIONS AND PERSPECTIVES

In summary, this review focuses primarily on the construction of polymer-based CPL materials in recent years. As is well known, chirality and luminescence are necessary conditions for constructing CPL materials. Therefore, the key parameters (g_{lum} and QYs) of representative polymer-based CPL systems are given in the Table 1. This review classifies polymer-based CPL systems into four categories based on the source of polymer chirality: (1) chiral polymer with chiral sites on the side chains, (2) chiral polymer with chiral sites on the main chains, (3) achiral polymer with small molecule-based chiral inducer, and (4) achiral polymer with macromolecule-based chiral inducer. The research results indicated that both chiral and achiral polymers, as well as luminescent and non-luminescent polymers, can be used to construct CPL materials. In chiral polymers, the position of chiral sites can be flexibly controlled, including on the main chains and side chains. In achiral polymers, by selecting appropriate chiral inducers, whether small molecules or macromolecules, through non-covalent interactions polymer-based supramolecular or macromolecular chirality can be induced, thereby generating CPL.

Each strategy has its own characteristics. The first strategy can prepare dynamic CPL materials, which will be suitable for the field of dynamic information encryption. However, without the aid of a liquid crystal environment, its g_{lum} still needs to be further improved. The second strategy can construct conjugated helical polymers, which, due to their good con-

ductivity, processability, and optical properties, will be suitable for the field of novel CP-OLEDs, but the types of polymers are still limited. The third strategy can construct polymer-based CPL materials from inexpensive and readily available small molecules in nature, reducing the complexity of synthesis and saving material costs. It can also construct highly stable CPL materials through chemical crosslinking, suitable for demanding applications, but the efficiency of chiral transfer needs to be further improved. The fourth strategy can induce achiral polymer CPL materials from macromolecules. The good processability of polymers makes them suitable for applications requiring specific processing. However, due to the complexity of polymer chain structures, the chiral transfer mechanism still needs further investigation. Thus, it can be found that polymers, due to their flexible chemical structure, processability, and good film-forming properties, are key candidates for moving from theoretical research to practical application in the field of CPL.

Despite the promising prospects of using polymers to construct CPL materials, the following challenges remain. Firstly, given that g_{lum} and Φ are critical benchmarks for assessing CPL material performance, developing polymer-based materials that achieve excellence in both areas remains a formidable challenge. Currently, apart from polymer liquid crystal systems, other systems have relatively low g_{lum} . We believe that appropriate chemical structure design, ordered polymer assembly and new polymer liquid crystal systems can effectively improve both Φ and g_{lum} value simultaneously. Secondly, currently the contradiction between the stability and high g_{lum} of polymer CPL materials is difficult to balance, which limits their further application. For example, although polymer liquid crystal systems can achieve high g_{lum} , their stability is often weak due to their fluidity. Thirdly, the practical applications of polymer CPL materials are still in the exploratory stage and require further development. How to move from theoretical research to practical application is a problem that needs to be solved in the future.

Table 1 Summary of key parameters of representative polymer-based CPL systems.

Polymer system	$ g_{lum} $	QY (%)	Ref.
Helical PA with AIE	3.60×10^{-2}	–	[47]
Helical PA in LCs	1.87	–	[48]
Helical PSA/perovskite	3.00×10^{-2}	–	[49]
Chiral P46 in LCs	1.54	63.8	[50]
Monosubstituted PA in LCs	1.80×10^{-1}	12	[53]
Monosubstituted PPA	2.80×10^{-2}	7.3	[56]
P3HT- <i>b</i> -PPI	3.70×10^{-2}	–	[58]
PF- <i>b</i> -PPI	1.03×10^{-2}	–	[59]
poly(D-IMCI50- <i>ran</i> -IPPD50)-C	4.70×10^{-3}	32.5	[64]
p(phNA- <i>co</i> -BrNpA)	1.90×10^{-2}	3.5	[65]
PAMCOOCz	1.02×10^{-2}	24.7	[67]
Binaphthalene-based PF	5.60×10^{-2}	–	[70]
binaphthyl-based AIE copolymer	1.45×10^{-2}	–	[71]
PF8/limonene	1.48×10^{-2}	30.7	[73]
PF8 derivatives/limonene	1.40×10^{-2}	80.8	[74]
PF8@Cou6/limonene	1.20×10^{-2}	37.3	[75]
PF8-OH/limonene	4.20×10^{-2}	17.8	[76]
PEO- <i>b</i> -PMA/DINBPA	1.10×10^{-1}	–	[77]
PMACB/binaphthalene	6.10×10^{-1}	–	[78]
ChLC-PN	3.30×10^{-2}	–	[79]
PAA- <i>b</i> -PS/MA	1.10×10^{-1}	29.2	[83]
Achiral PA/CTA	1.50×10^{-2}	62.9	[86]

LCs: liquid crystals.

Polymer-based CPL materials are attracting growing attention from researchers due to their unique intrinsic attributes. Based on the above analysis, future research directions can focus on the following three aspects: first, optimizing polymer structures, such as introducing more highly efficient luminescent groups like thermally-activated delayed fluorescence (TADF) groups, and deeply analyzing the chiral multiple interaction mechanism; second, breaking through traditional preparation methods and introducing advanced technologies such as radiation-induced polymerization, 3D printing, and electrospinning; and finally, integrating artificial intelligence methods and using machine learning to achieve CPL performance prediction and monomer and polymer structure design.

BIOGRAPHIES

Zhi-Wei Zhao received his Ph.D. degree from Sichuan University in 2008. Then he joined the School of Material Science and Engineering, Henan University of Technology, in 2008 and was appointed the Dean of the School of Materials Science and Engineering in 2024. Now he leads a new metal-ceramic matrix composites group working on ultrafine cemented carbide, superhard materials, and ceramic abrasives.

Wei Zhang received his B.S. degree from Anhui University in 2001 and his Ph.D. degree from Soochow University in 2006 under the supervision of Prof. Xiulin Zhu. After postdoctoral research at the Nara Institute of Science and Technology (2009–2011) with Prof. Michiya Fujiki, he was appointed a full professor in 2013 at Soochow University and moved to Zhengzhou University as a distinguished professor in 2025. His research interests include polymer synthesis, supramolecular chemistry, and chiral assembly.

Conflict of Interests

The authors declare no interest conflict.

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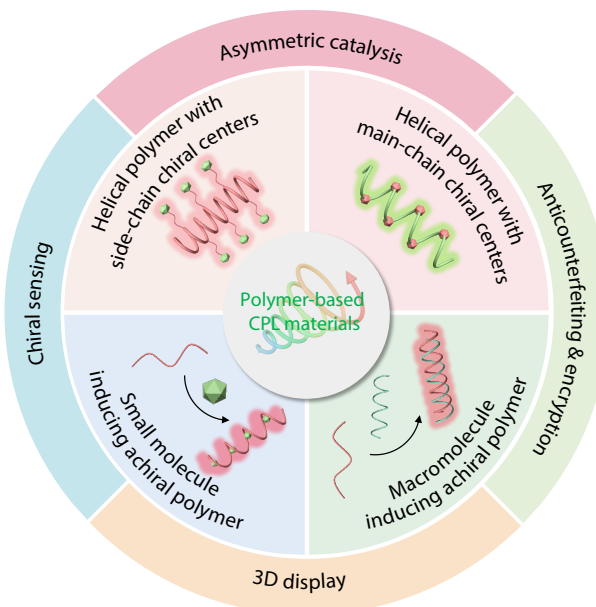
Graphical Abstract

Advances in Polymer-based Circularly Polarized Luminescent Materials

Gong Zhang, Zi-Xiang He, Zhi-Wei Zhao, and Wei Zhang

Henan University of Technology; Zhengzhou University

This review summarizes polymer-based circularly polarized luminescence (CPL) materials, focusing on chiral architectures from helical polymers and achiral polymer/chiral inducer systems. It discusses the chiral induction and amplification mechanisms, and the challenges and future application prospects in this field.



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