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Circularly Polarized Luminescence Based on Helical Polymers: Structure-Property Relationships and Regulation Mechanisms

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Abstract Circularly polarized luminescence (CPL) materials have attracted considerable attention because of their unique chiroptical properties and promising applications. However, the simultaneous achievement of a high luminescence dissymmetry factor (g_{lum}), high photoluminescence quantum yield, excellent processability, and environmental stability remains challenging. Chiral helical polymers, featuring single-handed helical conformations, have emerged as versatile and powerful platforms for constructing high-performance CPL systems by utilizing their inherent chiral amplification effects, tunable conformational dynamics, and ability to form hierarchically ordered structures. This review systematically summarizes recent advances in CPL materials based on chiral helical polymers, focusing on the regulation of chiroptical properties through polymer conformation, mesoscopic ordered structures, and photophysical pathways. CPL systems are categorized into three main classes: monocomponent chiral helical polymers, multi-component organic composites, and organic-inorganic hybrids. For each category, representative molecular design strategies, fabrication methodologies, and CPL performance were elaborated, emphasizing the underlying structure-property relationships. The key mechanisms governing CPL generation and amplification are discussed in depth, including chirality transfer, solvent- and state-dependent chiral inversion, selective absorption/filtering, and cholesteric liquid-crystal-mediated photonic amplification. Furthermore, representative breakthroughs, such as near-infrared CPL, room-temperature phosphorescence, and long-persistent CPL, are highlighted. Finally, the current challenges and future directions are outlined, providing a guideline for the rational design and practical application of next-generation helical polymer-based CPL materials.

Keywords Circularly polarized luminescence; Helical polymers; Monocomponent chiral helical polymers; Multi-component organic composites; Organic-inorganic hybrids

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INTRODUCTION

Circularly polarized luminescence (CPL) refers to the differential emission of left- and right-handed circularly polarized light by chiral luminescent systems in the excited state. It represents a unique combination of chirality and luminescence at the molecular level and is also one of the rapidly developing research directions in the field of chiral optics.[1−4] Different to traditional linearly polarized luminescence, CPL has many irreplaceable advantages, including excellent anti-light scattering and anti-background interference capabilities, non-destructive chiral resolution characteristics, and unique spin-polarized photon transmission performance.[5,6] These unique properties enable CPL-active materials to overcome the limitations of traditional luminescent materials, showing broad and irreplaceable application potential in many cutting-edge fields, including high-density optical information storage and encryption,[7−10] full-color 3D stereoscopic displays,[11−14] circularly polarized organic light-emitting diodes,[15] bioimaging and biosensing,[16−21] and chiral catalysis.[22−27] However, the practical industrial application of CPL materials has long been severely restricted by an inherent contradiction: the simultaneous achievement of a high luminescence dissymmetry factor (g_{lum}), high photoluminescence quantum yield (PLQY), excellent solution/solid-state processing performance, and good environmental stability remains a highly challenging task in the fields of materials science and chemistry.[28] This has also become a bottleneck that restricts the development of high-performance CPL systems and hinders their transition from laboratory research to practical applications.

To address this bottleneck in the development of CPL materials, chiral helical polymers, as a unique class of macromolecules with single-handed excess helical conformations, have provided a universal and powerful material platform for constructing high-performance CPL systems and have become a research focus in the CPL field in recent years.[29−31] Small-molecule CPL emitters often suffer from prominent problems such as poor film-forming processability, limited structural tunability, insufficient chiral amplification efficiency, and aggregation-caused quenching (ACQ), which severe-

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ly restrict their practical application.[30,32] In contrast, the single-handed excess helical structure of the polymer not only has a significant chiral amplification effect but can also effectively suppress the ACQ phenomenon, thus achieving CPL materials with both high g_{lum} values and high PLQY.[33] Moreover, the dynamically reversible helix-to-random coil transition characteristics of helical polymers endow CPL materials with excellent responsiveness to external stimuli (such as solvent polarity, temperature, pH value, and guest molecules), enabling the reversible regulation of CPL intensity and even chiral inversion without cumbersome enantiomer synthesis processes, which greatly reduces the material preparation cost. More notably, chiral helical polymers can easily construct hierarchically ordered mesostructures through self-assembly, including cholesteric liquid crystals (CLCs),[33−35] porous frameworks,[36] and supramolecular assemblies.[37−40] These ordered structures can achieve significant amplification of g_{lum} through the photonic bandgap effect and chiral selective absorption/filtration, further improving the CPL performance.[41] Owing to these unique advantages, chiral helical polymers, such as polyacetylenes,[41−47] polyisocyanides,[48,49] and biomass chiral polymers[50] have become the most widely studied and promising systems among polymer-based CPL materials, with a large number of innovative design strategies, performance regulation methods, and mechanistic understanding emerging in recent years. Therefore, systematically summarizing the design strategies, performance regulation mechanisms, and application progress of CPL materials based on chiral helical polymers, and in-depth analysis of their structure-performance relationships, are of great theoretical and practical significance for breaking through the bottleneck of CPL materials and promoting the sustainable development of the CPL field.

In this review, we provide a systematic overview of recent progress in CPL materials based on chiral helical polymers. Particular emphasis was placed on tunable chiroptical emission regulated by polymer conformation, mesoscopic ordered structures, and photophysical pathways. Based on the material composition, we classified these CPL systems into three major categories: monocomponent chiral helical polymers, multi-component organic composites, and organic–inorganic hybrid materials. For each category, we elaborate on the representative molecular design strategies, fabrication methodologies, and CPL performance, with an emphasis on the structure-property relationship between the chiral architecture and chiroptical output. Subsequently, we summarize the mechanism governing CPL generation and amplification in helical polymer systems, including chirality transfer based on helical structures, solvent/state-dependent emission chirality inversion, selective absorption/filtering *via* chiral polymer media, and chirality amplification through CLCs ordering. Furthermore, we highlight representative breakthroughs in this field, such as the trade-off between high g_{lum} value and favorable processability achieved by dynamic helical backbones, the significant enhancement of apparent dissymmetry by liquid crystalline and porous mesoscopic configurations, and the functional expansion into near-infrared and long-lifetime emission regions *via* polymer-inorganic hybridization. Finally, we outline current challenges and critical bottlenecks in this field. We anticipate that this review will provide systematic guidelines and valuable insights for the rational design and practical application of high-performance helical-polymer-based CPL materials.

DESIGN AND REGULATION OF POLYMER-BASED CPL MATERIALS

In this section, a variety of CPL-active systems are presented and organized into three primary groups based on their chemical composition: monocomponent chiral helical polymers, multi-component organic composites, and organic-inorganic hybrid materials. To facilitate a comprehensive assessment, the fundamental performance metrics are systematically outlined in Table 1.

Monocomponent Systems

Monocomponent CPL-active polymers are chiral macromolecules in which luminescent units are covalently linked; they represent an archetypal strategy for achieving CPL with molecular-level integration.[51−53] In this system, the precise covalent

Table 1 Performance comparison of CPL materials across different systems.

Three major categories	System	Emission peak maximum (nm)	$\lvert g_{\mathrm{lum}}\rvert$	Maximum quantum yield (QY_{max},%)	Ref.
Mono-component Systems	P37	480	+0.112 / −0.147	–	[52]
	sP/rP	530	+0.17 / −0.18	12	[57]
	poly-(S)-2	520	$\pm1\times10^{-3}$	44	[60]
	rc-poly(2-*g*-3_{120})$_m$	420	$\pm3.37\times10^{-4}$	20	[64]
Multi-component systems	H-PA	470	0.323	–	[42]
	P46/5CB	450	1.54	63.8	[51]
	CAB/P1	568	1.5×10^{-2}	62.9	[70]
	PI	511	5.7×10^{-3}	–	[71]
	polyHIPE	404	-2.6×10^{-2}	–	[72]
	PBPA	480	–	–	[76]
	Star-PAA-*b*-PS/MA	450	0.11	29.2	[77]
Hybrid systems	CNC$_{se}$/PbS@CdS	1430	−0.330	–	[81]
	RDD/SDD	420	$\pm6.9\times10^{-4}$	31	[82]
	RUBD/SUBD	470	$\pm5.5\times10^{-3}$	36	[83]
	C-dots/PSA	445	−0.14	20	[84]
	BP/PSA	488	$\pm3.0\times10^{-2}$	–	[85]

linkage of chiral moieties and emissive units to the polymer backbone or side chains enables an accurate spatial arrangement of the two components, thereby facilitating efficient chirality transfer from the ground-state helical scaffold to the excited-state emissive centers. The resulting one-handed helical structure with excess helicity exhibits not only a remarkable chiral amplification effect, but also effective suppression of the ACQ phenomenon, thereby yielding CPL materials with both a high g_{lum} value and a high PLQY. Moreover, owing to the conformational degrees of freedom of helical polymers, which are often responsive to external stimuli, such materials can display tunable optical properties. These include reversible modulation of CPL intensity and even inversion of CPL handedness upon alteration of helical sense.

Pan *et al*.[51] demonstrated a powerful strategy for generating processable, stimuli-responsive CPL-active polyacetylenes by copolymerizing achiral pyrene-bearing monomers with chiral monomers. In solution, polyacetylene (P37) exhibits blue CPL emission with a modest g_{lum} of approximately 1×10^{-3}, yet when P37 is cast into thin solid films, the sign of the CPL inverts and the g_{lum} is amplified by more than two orders of magnitude, reaching values as large as 0.112 and −0.147 in *S*- and *R*-derived films, respectively (Fig. 1a). This remarkable state-dependent behavior can be attributed to the simultaneous operation of two fundamentally distinct chirality transfer pathways that dominate under different physical conditions. In solution, the dominant mechanism is local chirality transfer from the chiral pendant units to the adjacent pyrene substituents, a process that imprints a weak conformational chirality directly onto the pyrene emission. In contrast, in the film state, the polyacetylene backbones adopt a higher-order, more aggregated arrangement that produces an intense circular dichroism (CD) signal overlapping the emission band and therefore generates CPL through the handed-selective absorption of one circular polarization. In addition, this work also demonstrates that the solvent- and thermally driven helix-to-coil transitions of the dynamic polyacetylene backbone modulate backbone absorption, side-chain packing, and the proximity of pyrene chromophores, thereby enabling facile and reversible control of the fluorescence intensity and chiroptical output *via* mild external stimuli such as solvent composition and temperature.

In addition to the widely adopted strategy of introducing

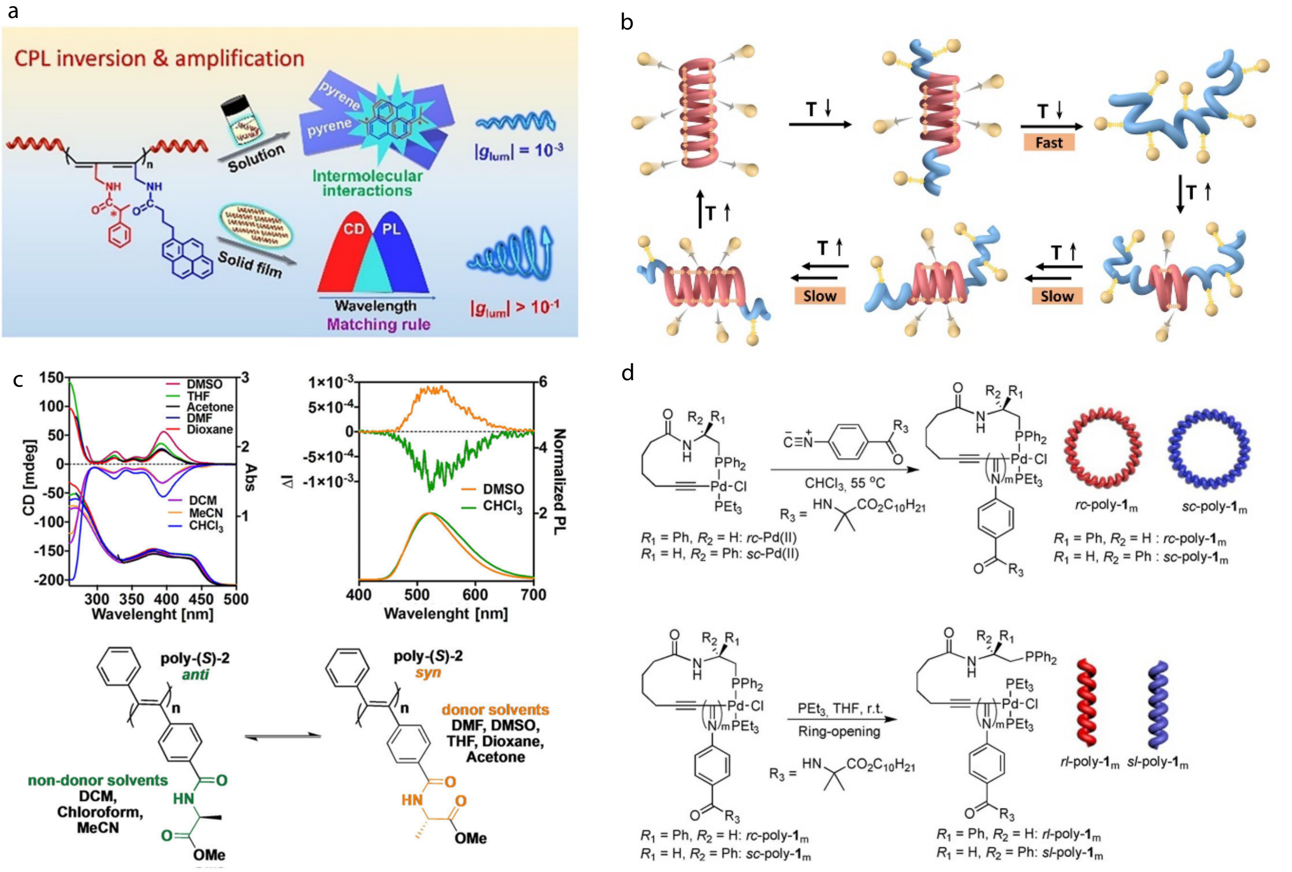


Fig. 1 (a) Schematic representation of handedness inversion and amplification of circularly polarized luminescence in chiral helical polyacetylenes (Reproduced with permission from Ref. [51]; Copyright (2021), American Chemical Society); (b) Representation of conformational transition of sP during the cooling and heating processes (Reproduced with permission from Ref. [56]; Copyright (2021), Wiley-VCH); (c) ECD and UV spectra of poly(*S*)-2 in different solvents (0.5 mg/mL, 1 mm path length) and circularly polarized luminescence (CPL, λ_{Exc} = 365 nm, 0.3 mg/mL) of poly(*S*)-2, along with a schematic showing solvent-induced side chain conformational changes that promote helix inversion (Reproduced with permission from Ref. [59]; Copyright (2022), Wiley-VCH); (d) Synthesis of CPL-active cyclic polymers and linear analogues (Reproduced with permission from Ref. [63]; Copyright (2022), Wiley-VCH).

traditional chromophores into polymer side chains, chiral helical CPL materials have also been reported in many studies to exhibit fluorescent emission characteristics derived from the conformation of the main chain itself.[54–58] The luminescent center is transferred from the traditional side-chain chromophores to the conjugated main chain of the polymer so that the luminescent behavior can be regulated by adjusting the main chain conformation, thereby realizing the controllable regulation of circularly polarized luminescence, which provides a new idea for the regulation of CPL performance. Wang *et al*.[56] designed and synthesized poly(phenylacetylene) containing 3,5-diamide substituents. In the molecular structure of this polymer, strong intramolecular hydrogen-bond interactions occur between adjacent amide groups. This hydrogen bond interaction can effectively lock the main-chain conformation, inhibit conformational disorder, and thus stably form a compact cis-cisoid conformation (Fig. 1b). Owing to the highly compact conformational state of the polymer main chain, the conformational restriction effect and intramolecular interactions together formed a stable luminescent state, generating obvious CPL emission signals. In addition, reversible on-off of CPL signals can be achieved by changing the external conditions, such as solvent polarity and temperature. This stimulus-responsive effect is directly related to the conformational transition of the polyacetylene main chain. Changes in solvent polarity affect the strength of intramolecular hydrogen bonds, and changes in temperature regulate the mobility of the main chain, both of which induce reversible conformational transitions of the main chain, thereby regulating CPL performance. These results indicate that, in helical polymer-based CPL materials, the main chain conformational dynamics play an equally important role as the side chain structure in determining the circularly polarized luminescence performance, providing an important theoretical basis for the subsequent design of new conformation-regulated CPL materials.

Both carbon atoms of the double bond in the main chain of polydiphenylacetylene were substituted with phenyl rings, and this substitution endowed the polymer with intrinsic photoluminescence properties. Tarrío *et al*.[59] demonstrated that chiral poly(diphenylacetylene) manifests a mirror-opposite CPL in dimethyl sulfoxide and chloroform, with a g_{lum} on the order of 1×10^{-3} (Fig. 1c). They attributed the solvent-driven inversion of the CPL signal to the solvent-induced reorganization of side-chain conformations (specifically between anti and syn forms), which alters the preferred helical sense of the polymer. In a subsequent study, the same group showed that an asymmetric poly(diphenylacetylene) bearing chiral benzamide pendants undergoes reversible inversion between the M and P helical senses as the donor character of the solvent is varied, and critically, the induced helical sense can be retained after the solvent is removed, thereby providing a simple route to solvent-programmable and memory-bearing CPL switching.[60]

Polyisocyanides are another important class of CPL-active helical polymers.[48,61–63] The polymerization of polyisocyanides can be precisely regulated, enabling the construction of well-defined chiral assemblies with stable helical conformations. Xu *et al*.[63] employed chiral cyclic Pd(II) catalysts to initiate the living polymerization of isocyanides, affording one-handed cyclic polyisocyanides (Fig. 1d). The resulting cyclic polymer brushes bearing polystyrene side chains exhibited CPL activity, the g_{lum} of which was closely related to the degree of polymerization. In this system, the dependence of g_{lum} on the degree of polymerization suggests an interplay between the chain length (or brush density), extent of helical coherence, and effective chiral field experienced by the emissive units. Meanwhile, the cyclic topology and brush-like morphology provide an extra dimension for the structural control of the materials, which can influence not only their chiroptical properties but also their solution behavior, self-assembly, and film-formation characteristics. Overall, this work offers a relatively straightforward strategy for constructing chiral cyclic polymer platforms for CPL and highlights that macromolecular topology serves as a crucial tunable variable in the design of CPL materials.

An empirical rule in monocomponent systems is that despite the clear and intuitive concept of covalent integration, achieving a substantial enhancement in the g_{lum} remains a formidable challenge. The reported g_{lum} values in the literature are mostly on the order of 10^{-3}, which reflects the intrinsic difficulty of generating strongly asymmetric emission at the molecular level and underscores the high sensitivity of CPL to conformational distributions, aggregation states, and local microenvironments. In view of these inherent limitations, the research objectives in this field have gradually shifted from the pursuit of larger absolute g_{lum} values to multi-dimensional strategies, that is, balancing the amplification of chiroptical signals with the functional robustness and practical applicability of materials. Correspondingly, dynamic controllability, characterized by switchability, reversible inversion, and memory effects, as well as stimulus-responsiveness, have become key indicators for evaluating research progress in this field. These indicators complement the goal of maximizing the emission dissymmetry, pointing to a more sophisticated route toward the development of practically applicable CPL-active materials. Furthermore, the g_{lum} can be continuously tuned over three orders of magnitude by varying the composition of the film-forming solvent, providing an extremely simple and precise method for regulating the intensity and direction of the chiroptical signals.

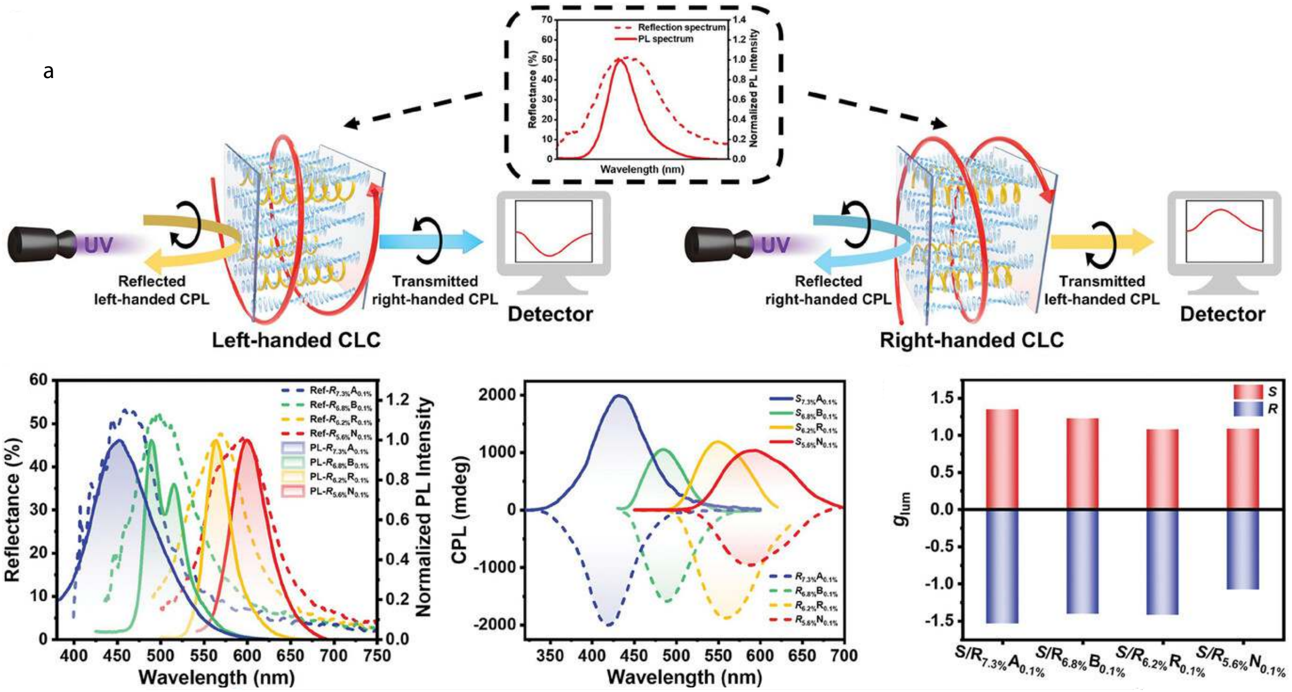
Multi-component Systems

Monocomponent helical polymers with CPL generally suffer from inherent limitations in direct solid-state applications, whereas the practical utilization of most optical technologies and optoelectronic devices is fundamentally based on solid-state systems. In contrast, multi-component organic composite systems, typically constructed by blending chiral polymers with organic luminophores, can achieve highly efficient solid-state (especially thin-film) CPL emission, thus effectively breaking through the aforementioned application bottlenecks. Such composite materials possess broad component tunability and design flexibility.[64–68] In these composite systems, chiral polymers can serve as chiral templates, structure-directing agents, photonic media, or selective absorbers, while luminophores provide intense fluorescence emission for the system. The main feature of this system is that no covalent linkage is required between the chiral and luminescent units. Although the complexity of such systems is significantly elevated in terms of phase behavior, component compatibility, and aggregation morphology control, this functionally decoupled design exhibits prominent advantages: it enables the independent optimization of the luminescence efficiency and chiral assembly behavior of the system within a certain range, thus showing great application potential.

For multi-component systems, Zhong *et al*.[41] proposed a matching rule for multi-component chiral luminescent systems. This rule indicates that when the absorption band in the CD spectrum of a chiral luminescent material effectively overlaps with its fluorescence emission band in wavelength, CPL emission can be achieved without introducing specific interactions between the chiral and luminescent units. This rule was established based on the experimental observations of typical multi-component systems represented by chiral polyacetylenes. This clarifies that the wavelength matching effect can facilitate the selective formation of chiral excited states and efficient chirality transfer, which not only provides a critical theoretical foundation for the rational design of high-performance CPL materials from the perspective of molecular structure engineering and aggregation state regulation, but also has emerged as a guiding principle for the performance optimization of advanced chiral luminescent systems. Li *et al*.[69] successfully fabricated full-color CPL composite films on film-forming substrates *via* facile blending of chiral polyisocyanides with various fluorescent dyes. This blending strategy, based on the matching rule, provides a facile and universal approach for the construction of CPL-active materials, enabling high-performance CPL emission without tedious synthetic procedures.

In contrast to small-molecule chiral systems, helical polymers can achieve high-performance CPL emissions by constructing ordered and efficient assemblies. Wang *et al*.[70] constructed polymerized high internal phase emulsions using chiral helical polyacetylenes as building blocks, which were then employed as three-dimensional chiral matrixes with adsorption properties to fabricate CPL-active porous materials, with a maximum g_{lum} of -2.6×10^{-2}. Using the emulsion template method, we constructed a hierarchical porous structure while utilizing the efficient adsorption property of the material to confine achiral fluorophores in the as-constructed chiral microenvironment. Through precise regulation of the local interactions and spatial arrangement between the dyes and polymers, a synergistic chiral assembly was promoted, and a significant enhancement of the g_{lum} value was achieved. Notably, the chiroptical emission of this system does not originate from direct chirality transfer at the molecular level but is based on the fluorescence selective absorption mechanism, which is highly consistent with the matching rule mentioned above.

The introduction of mesoscopic ordered liquid crystal structures is an efficient strategy for the amplification of CPL signals. The cholesteric liquid crystal structure generates a photonic bandgap that selectively filters and enhances specific chiral light emission *via* Bragg reflection. Simultaneously, the ordered array acts as a chiral template to guide the oriented arrangement of luminescent molecules, enabling a significant amplification of the CPL asymmetry factor through molecular-scale signal filtering and chirality transfer. Among them, CLCs can produce wavelength-selective reflection of circularly polarized light and thus can serve as photonic amplifiers for chiral emission to achieve significant enhancement of CPL performance. Wang *et al*.[71] constructed a three-stage cascade chirality transfer system, in which the molecular configurational chirality of small-molecule monomers was transferred to the backbone of non-luminescent polyacetylene *via* copolymerization, affording chiral polyacetylenes with conformational helical chirality. The as-prepared chiral polyacetylenes were then co-doped with achiral fluorophores into a nematic liquid crystal host, which finally induced the assembly of the liquid crystal matrix to form a CLC structure with supramolecular mesoscopic chirality (Fig. 2a),



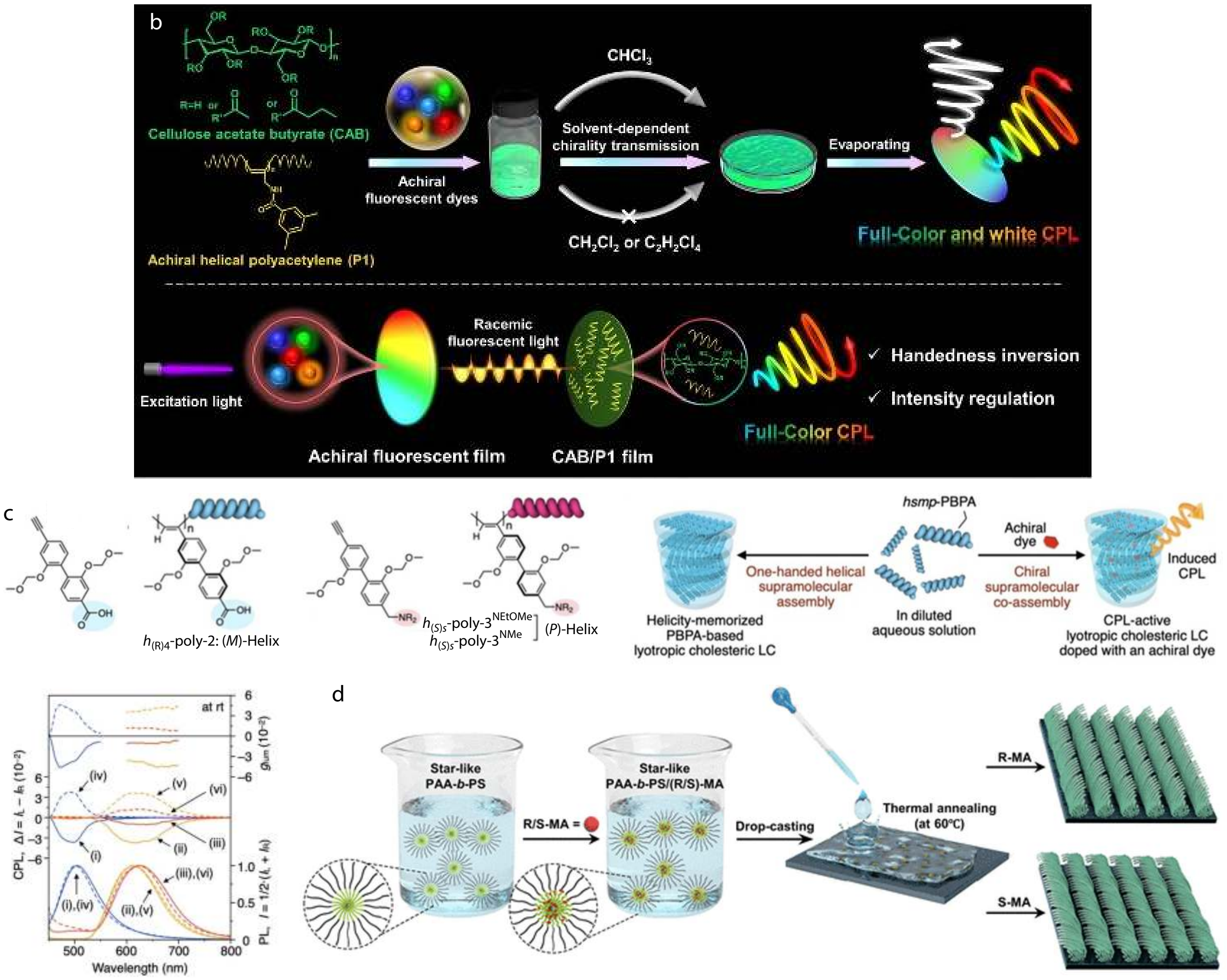


Fig. 2 (a) A schematic diagram illustrating the achievement of a high degree of CPL through the selective reflection of CLC when the selective reflection band coincides with the PL emission peak in CPL measurements, along with the material's reflection spectrum, PL spectrum, CPL spectrum, and the spectrum of the maximum glum value (Reproduced with permission from Ref. [71]; Copyright (2024), Wiley-VCH); (b) A schematic diagram showing the generation of full-color and white circularly polarized light in composite films using solvent-dependent chiral induction, and the modulation of the chirality and intensity of circularly polarized light in bilayer films through fluorescence selective absorption (Reproduced with permission from Ref. [50]; Copyright (2025), Wiley-VCH); (c) Schematic diagram of water-soluble helical memory PBPAs with carboxyl groups ($h_{(R)4}$-poly-2) and tertiary amino groups ($h_{(S)5}$-poly-3^{NEtOMe} and $h_{(S)5}$-poly-3^{NMe}), schematic of h_{smp}-PBPA chiral organized liquid crystal orientation formation, and schematic of CPL induced in chiral asymmetric dyes through supramolecular chiral transfer in hsmp-PBPA chiral liquid crystals. Normalized PL (bottom), CPL (middle), and g_{lum} (top) spectra of non-chiral materials at room temperature. (λ_{Exc}=365 nm) (Reproduced with permission from Ref. [75]; Copyright (2024), Wiley-VCH); (d) Schematic illustration depicting the route to hierarchical chiral structures through thermal annealing–driven co-assembly of achiral star–like PAA-*b*-PS BCPs with chiral (*R*/*S*)-MA at 60 °C for 24 h (Reproduced with permission from Ref. [76]; Copyright (2025), The American Association for the Advancement of Science).

thus achieving CPL emission with a high g_{lum}. The helical twisting power of this chiral polyacetylene dopant was significantly higher than that of the corresponding chiral monomer, enabling the precise regulation of the position of the selective reflection band of the cholesteric matrix to achieve accurate matching with the emission spectrum of the fluorophores, which fully conforms to the principle of wavelength matching described above. When the above spectral matching condition was satisfied, the apparent CPL intensity of the system was significantly enhanced, with a maximum g_{lum} of 1.54 measured in the liquid crystal cell. The excellent CPL performance of the system originates from the intrinsic photonic bandgap effect of CLCs, which can selectively reflect circularly polarized light consistent with their own helical chirality, while efficiently transmitting circularly polarized light of the opposite handedness. This mesoscopic photonic ordered structure can boost the detected CPL signal by several orders of magnitude, ultimately realizing a remarkable amplification of the g_{lum} value.

Beyond the aforementioned multi-component construction strategy based on blending chiral polymers with fluorescent dyes, the fabrication of CPL-active materials from achiral monomers or polymers is a highly promising and valuable research direction from both academic innovation and practical application perspectives. This strategy can not only greatly reduce the dependence on high-cost chiral monomers, but more importantly, provides an ideal model system for investigating the mechanisms of chirality origin, amplification, and transfer. The scientific issues involved are closely related to fundamental scientific problems such as the origin of homochirality in nature.[30,72–74] Among them, inducing achiral helical polymers to form single-handed helical conformations through interactions between inherently chiral biomass derivatives and achiral polymers without the introduction of chiral monomers is a promising alternative strategy with great potential for large-scale applications. Zhong *et al*.[50] achieved efficient chirality transfer *via* specific intermolecular N—H···O hydrogen bonding formed between the side chains of polyacetylene and the ester groups of cellulose derivatives during the solvent evaporation film-forming process. This hydrogen bonding interaction drove the transition of the polymer backbone from a racemic conformation to a single-handed helical conformation with enantiomeric excess and successfully transferred and amplified the molecular chirality information of cellulose acetate butyrate to the achiral helical polyacetylene system. Finally, full-color and white-light CPL materials with excellent stability were fabricated (Fig. 2b). Notably, this chiral induction process exhibits pronounced solvent dependence: solvents with strong hydrogen bond accepting ability compete with cellulose derivatives for the N—H hydrogen bonding sites on the polyacetylene side chains, thereby inhibiting the chiral imprinting effect of the system. By tuning the ratio of mixed solvents with different hydrogen-bond accepting abilities, precise and nearly linear regulation of the CD signal intensity of the system can be realized. In the excited state, the efficient regulation of the intensity and handedness of the CPL signal can also be achieved. It not only theoretically reveals the regulatory mechanism of environmental factors on the chirality transfer process between biobased polymers and synthetic helical polymers, but also develops a facile and scalable general strategy for the preparation of CPL materials. Programmed regulation of the emission wavelength, CPL signal intensity, and chiral sign of the materials can be realized only through the screening of solvent systems and the design of film-forming structures.

In addition to the supramolecular chiral induction strategy, helix-sense-selective polymerization is another effective strategy for the preparation of chiral helical polymers from achiral monomers. Okuda *et al*.[75] realized helix-sense-selective memory polymerization of achiral biphenylacetylene monomers in an aqueous medium (Fig. 2c). The chirality information of the obtained polybiphenylacetylenes was "recorded" during the polymerization process and further assembled to form lyotropic CLCs in an aqueous solution. The supramolecular chirality of the cholesteric phase can be further transferred to achiral fluorescent dyes co-doped in the system, finally achieving CPL emission. Furthermore, achiral block copolymers provide a universal approach for the construction of chirality-induced CPL active assemblies. Kim *et al*.[76] co-assembly achiral amphiphilic star-shaped block copolymers with chiral mandelic acids. The hierarchical assembly structure formed in this multi-component system can serve as both a chiral amplifier and a chirality transfer medium, converting the weak chiral perturbation introduced by the small-molecule chiral reagent into a mesoscopic chiral structure that endows achiral dyes with CPL properties (Fig. 2d).

In summary, the above-mentioned multi-component organic composite systems not only expand polymer-based CPL materials from traditional solution systems to solid-state forms with practical application value, effectively breaking through the application bottleneck of monocomponent systems, but also provide a multi-dimensional and mutually independent regulation space for performance optimization. Specifically, the tunable dimensions include the type of fluorescent dyes (regulating emission wavelength and PLQY), polymer backbone structure (determining chirality origin and mechanical properties of materials), selection of matrix materials (optimizing film-forming processability and environmental stability), and introduction of liquid crystal ordered structures (realizing amplification of g_{lum}).

Hybrid Systems

Organic-inorganic hybrid systems with inorganic luminescent materials as the emitting units are also promising polymer-based high-performance CPL materials. Inorganic luminescent materials, including semiconductor quantum dots (QDs), carbon dots (CDs), perovskite nanocrystals, and inorganic phosphors, have been widely composited with chiral polymers to fabricate high-performance CPL-active materials owing to their high PLQY, excellent photochemical stability, widely tunable optical properties, and anti-photobleaching performance.[77–79] From the perspective of The mechanism of CPL generation mainly originates from three pathways: intermolecular chirality transfer at the organic/inorganic component interface, chiral ordered arrangement of inorganic luminophores in the chiral polymer matrix, and selective optical filtering effect intrinsic to the chiral polymer medium. In these hybrid materials, chiral polymers usually provide chirality origin, excellent film-forming processability, and structural stability for the system, while the inorganic luminescent units endow the material with efficient intrinsic luminescence performance. Their emission spectra can cover a wide range of ultraviolet, visible, and near-infrared bands, which is expected to overcome the spectral limitations of traditional organic fluorescent dyes. Lu *et al*.[80] successfully fabricated CPL-active composite films by blending cellulose nanocrystals with PbS@CdS core-shell QDs, which achieved a CPL with a maximum g_{lum} of −0.33 in the second near-infrared (NIR-II) window (Fig. 3a). The NIR-II window has irreplaceable application value in the fields of bioimaging and biomedical optics. This work further combines NIR-II CPL performance with in situ tumor detection, fully demonstrating the great application potential of polymer-based chiral photonic materials in the field of biomedical translation.

CDs, a representative class of inorganic-based luminescent nanomaterials, have exhibited tremendous application potential in the field of CPL owing to their prominent merits, including facile synthesis, widely tunable luminescence spectra, and excellent photophysical properties. Gao *et al*.[81,82] hybridized a helical polyacetylene matrix with CDs featuring fluorescent or room-temperature phosphorescent characteristics (Fig. 3b). By leveraging the intrinsic helical structure of the polymer, they constructed a chiral interfacial microenvironment to precisely manipulate the spatial orientation and

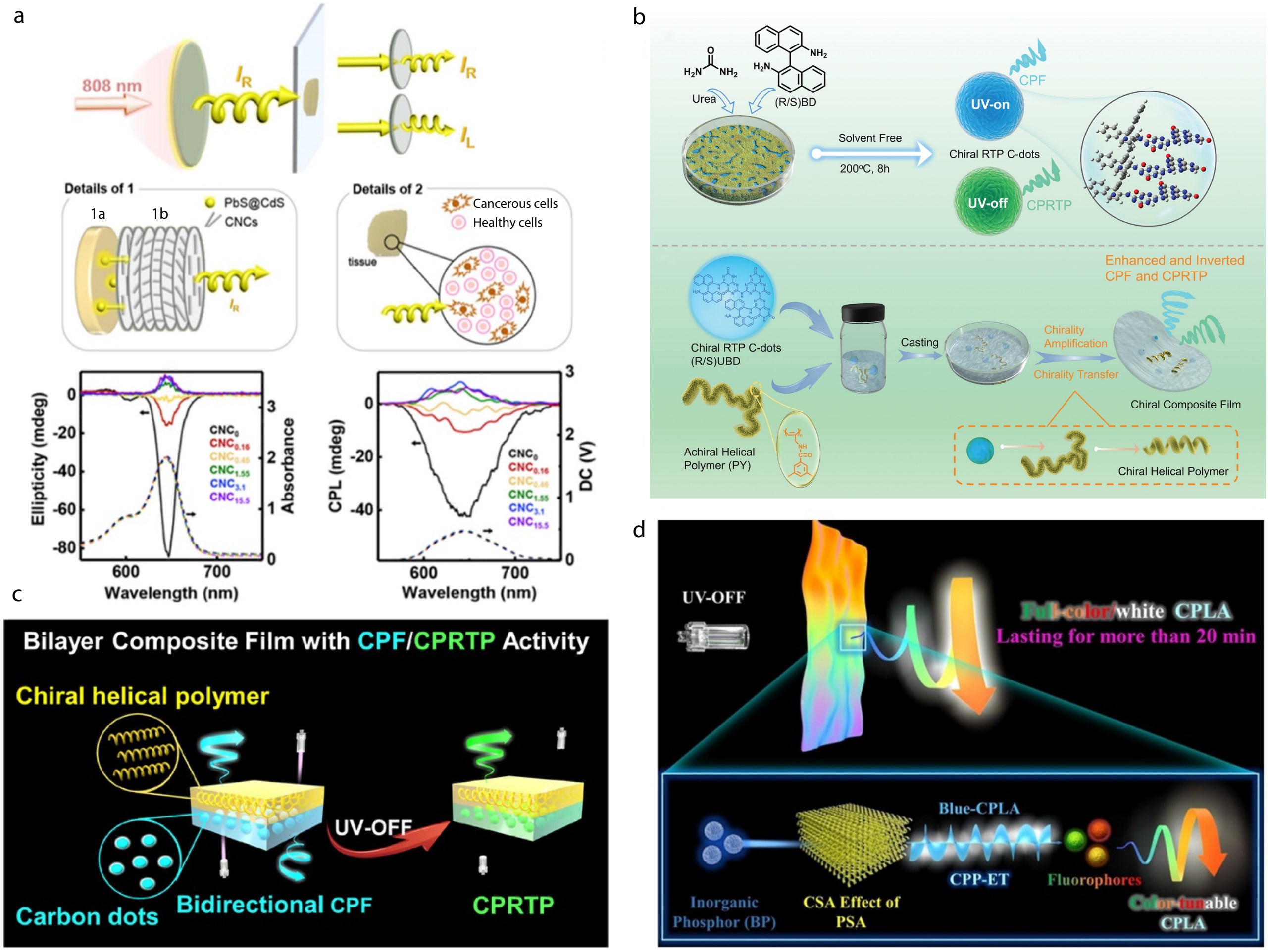


Fig. 3 (a) Schematic diagram of chiral photonic films used for cancer detection generating near-infrared II circularly polarized light, along with the circular dichroism and circularly polarized luminescence spectra of the material (Reproduced with permission from Ref. [80]; Copyright (2022), American Chemical Society); (b) Illustration showing the preparation of chiral room temperature phosphorescence (RTP) C-dots with intrinsic circularly polarized fluorescence (CPF)/circularly polarized room temperature phosphorescence (CPRTP) emissions, and the realization of enhanced and inverted CPF/CPRTP properties in chiral Chiral carbon dots(C-dots)/achiral helical polymer composite films (Reproduced with permission from Ref. [82]; Copyright (2024), Wiley-VCH); (c) Illustration of imparting CPL activity to carbon dots *via* the filtering effect of chiral helical polyacetylene (Reproduced with permission from Ref. [83]; Copyright (2023), American Chemical Society); (d) Schematic diagram of combining circularly polarized phosphorescence energy transfer (CPP-ET) with the chiral selective absorption (CSA) of chiral polyacetylene to construct full-color tunable circularly polarized long afterglow (CPLA) (Reproduced with permission from Ref. [84]; Copyright (2024), Wiley-VCH).

packing mode of the luminescent nano-units and modulated the light transmission path *via* the mesoscopic photonic effect. Ultimately, a composite system with intense circularly polarized emission was successfully developed, whose g_{lum} reached the order of 10^{-2}. Chiral helical polyacetylenes can also endow achiral luminophores with prominent CPL performances through chiral filtering or selective absorption mechanisms. Ma *et al.*[83] directly exploited the intrinsic chiral filtering effect of chiral helical polyacetylenes to construct a corresponding CPL system. When the emitted light propagates in this chiral polymer medium, the helical structure exerts selective transmission and differential attenuation on one of the circularly polarized components of the optical signal, ultimately endowing achiral phosphorescent CDs with intense CPL emission performance (Fig. 3c). These studies demonstrate that integrating inorganic-based luminescent units with tailorable performance and superior photophysical properties with structurally stable helical polymers enables the independent regulation of the emission color, emission lifetime, and polarization characteristics of the resulting materials. These strategies provide a novel design paradigm for the development of multifunctional CPL materials compatible with solution processing and device integration.

In the functional expansion direction of polymer-based organic-inorganic hybrid CPL systems, long-persistent CPL materials, which organically couple the time-dimensional characteristics of long-persistent luminescence with the polarization properties of chiroptics, can achieve multi-dimensional optical regulation that is difficult to realize with traditional single-function materials, and thus have become a key cutting-edge direction in the current field of chiral photonics and chiral luminescent materials. Yang *et al.*[84] composited chiral helical polyacetylenes with inorganic LPL materials based on the intrinsic chirality-selective absorption properties of the chiral helical polyacetylene backbone. Through selective filtering of the non-polarized long-lived emission from Eu^{2+}, Dy^{3+} co-doped $Sr_2MgSi_2O_7$ blue inorganic long-persistent phosphor by the chiral polymer, blue circularly polarized long-persistent luminescence with a g_{lum} of up to the order of 10^{-2} was finally obtained (Fig. 3d). By introducing conventional fluorescent dyes that can absorb blue LPL emission and re-emit light in the long-wavelength band, the composite film can convert transient fluorescent acceptors into circularly polarized luminophores with minute-level long-lived emission *via* the long-persistent circularly polarized light energy transfer process. The intrinsic luminescence lifetime of the fluorophores was extended from the nanosecond to the minute scale, with an emission duration of over 20 min and a g_{lum} value close to 10^{-3}. Furthermore, full-color white-light circularly polarized long-persistent luminescence was successfully realized. This work demonstrates that combining helical polymers with novel luminescence mechanisms, such as long-persistent luminescence, can effectively expand the functional scope of CPL materials from traditional transient fluorescence systems to broader application fields, including time-resolved optical imaging, information encryption, and anti-counterfeiting.

In summary, in the above-mentioned organic-inorganic hybrid systems, chiral polymers, as the functional component and chirality origin, can convert the non-polarized fluorescence emission of inorganic luminescent units into CPL. The generation of the CPL signal can be achieved through a variety of pathways, including direct chirality transfer at the organic-inorganic component interface, the chiral ordered arrangement of inorganic luminophores in the chiral polymer matrix, the chiral amplification effect, and the intrinsic selective optical filtering effect of chiral polymers. Benefiting from its emission spectrum extendable to the NIR band, compatibility with multiple luminescence modes, including transient fluorescence, phosphorescence, and long-persistent luminescence, as well as excellent film-forming processability and device adaptability, this type of hybrid system exhibits remarkable performance advantages and broad development prospects in practical application scenarios.

SUMMARY AND OUTLOOK

CPL materials based on helical polymers have received sustained and extensive research attention in recent years owing to their excellent processability and ability to enable precise regulation of chiroptical responses through the construction of hierarchical chiral structures. However, owing to the essential differences in the preparation strategies and CPL generation mechanisms, there are still significant gaps in the performance of different systems. Remarkably, introducing chiral helical polymers as chiral dopants into LCLs can achieve significant amplification of chiroptical signals *via* the photonic bandgap selective reflection mechanism, with a maximum g_{lum} value of over 1.5. In contrast, it remains extremely challenging to achieve a similarly high g_{lum} value in monocomponent polymer systems, where the CPL signals mostly originate directly from the radiative transition of the intrinsic chiral excited state of the molecule rather than the signal amplification effect of mesoscopic photonic structures. The above performance gap is not solely determined by the molecular structure, but is rooted in a deeper fundamental physical limitation: a high g_{lum} usually relies on highly optimized coupling of chiral excited states or is realized with the aid of ordered photonic structures at the mesoscopic scale, and the latter can regulate CPL properties more efficiently than the intrinsic chirality of single molecules.

At present, the strategy to realize CPL emission based on the fluorescence-selective absorption (optical filtering) effect is still mainly concentrated in polyacetylene-based chiral polymer systems.[41] This strategy can introduce significant apparent CPL signals and high g_{lum} values to achiral or weakly chiral luminophores without altering the intrinsic photophysical properties of the emitters, thus showing strong universality and expansion potential. Future research should focus on extending this optical filtering mechanism to a wider range of chiral helical polymer systems. Achieving this goal lies in the design and screening of polymer backbone structures that combine a stable single-handed helical conformation, controllable absorption band matching the emission spectrum of the luminophores, excellent film-forming ability, and uniform film morphology. Extending this chiral optical regulation strategy to non-polyacetylene systems can not only further broaden the spectral response range of the materials, but also introduce diverse functional properties, such as higher thermal stability and multiple stimulus responsiveness, thereby promoting the rational design and development of high-performance polymer-based CPL materials. For instance, Feng *et al*.[85] achieved multimodal dynamic encryption by integrating structural color, Zhang *et al*.[86] realized CPL chirality inversion and white-light emission through MOF confinement, Li, Liao, *et al*.[87] utilized metal halide phase transitions to achieve humidity responsiveness, Nie *et al*.[88] developed force-insensitive circularly polarized mechanoluminescence, and Liu *et al*.[89] optimized white-light CPL *via* an assembly strategy. In the future, multi-dimensional synergistic regulation will drive industrial applications in high-security and smart display fields.

In summary, helical polymers provide a highly versatile and structurally tunable scaffold for CPL functional materials. The related systems covered in this review mainly include three categories: monocomponent helical polymers with intrinsic chirality, multi-component organic composite materials with both morphology control and photonic design, and organic-inorganic hybrid systems incorporating inorganic luminescent units. The future breakthrough development of this field may rely on collaborative innovation in the following three dimensions: first, improving the intrinsic g_{lum} factor of monocomponent systems through precise molecular structure design; second, achieving efficient amplification of CPL signals *via* photonic effects through the regulation of ordered structures at the mesoscopic scale; third, developing standardized and high-precision CPL characterization methods and testing specifications. In addition, the integration of such chiral polymer materials into optoelectronic devices introduces complex factors. Therefore, it is urgent to deeply investigate the interaction between device structures and chiral assemblies and systematically elucidate the intrinsic generation and evolution mechanism of CPL signals under device operating conditions to lay a theoretical foundation for the practical application of these materials.

Finally, it should be emphasized that both polymer and non-polymer systems have been reported for the construction of functional materials with non-reciprocal CD and CPL properties.[90−97] However, relevant research must maintain a rigorous and prudent scientific attitude: interfering factors such as linear dichroism, linear birefringence, and fluorescence anisotropy commonly existing in solid-state thin-film systems, as well as instrumental artifacts of the testing system, may be misjudged as the intrinsic nonreciprocal optical behavior of the materials.[98−102] This issue is particularly critical for polymer thin films and composite systems, where the morphological anisotropy, difference in molecular orientation order, and film thickness inhomogeneity, which are difficult to completely eliminate, will significantly interfere with the polarization optical test results. Therefore, a strict experimental design, reasonable blank control experiments, and standardized instrument calibration procedures are essential. When the reported experimental phenomena involve weak symmetry breaking or nonreciprocal chiroptical properties, a complete experimental verification system must be established to ensure the validity and reliability of the conclusions.

BIOGRAPHIES

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Conflict of Interests

The authors declare no interest conflict.

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Graphical Abstract

Circularly Polarized Luminescence Based on Helical Polymers: Structure-Property Relationships and Regulation Mechanisms

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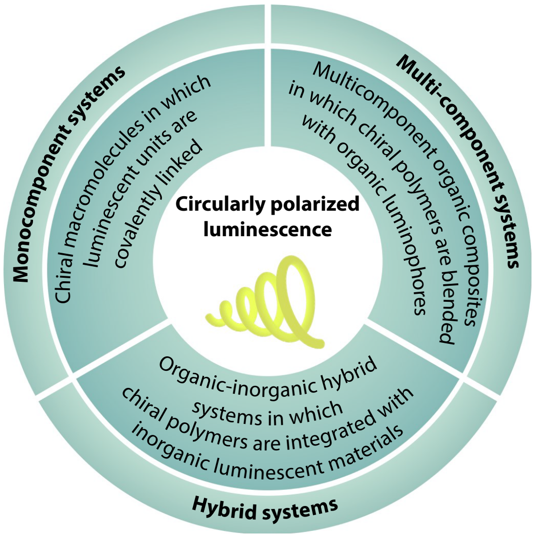
This schematic categorizes helical-polymer-based CPL materials into monocomponent, multicomponent, and hybrid systems, while elucidating the pivotal mechanisms that dictate chiroptical amplification, including chirality transfer, responsive inversion, and photonic modulation. These insights provide a systemic blueprint for rational integration of high-performance chiroptical systems with tailored properties.



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