

Recent advances in organic circularly polarized room-temperature phosphorescence: Materials and applications

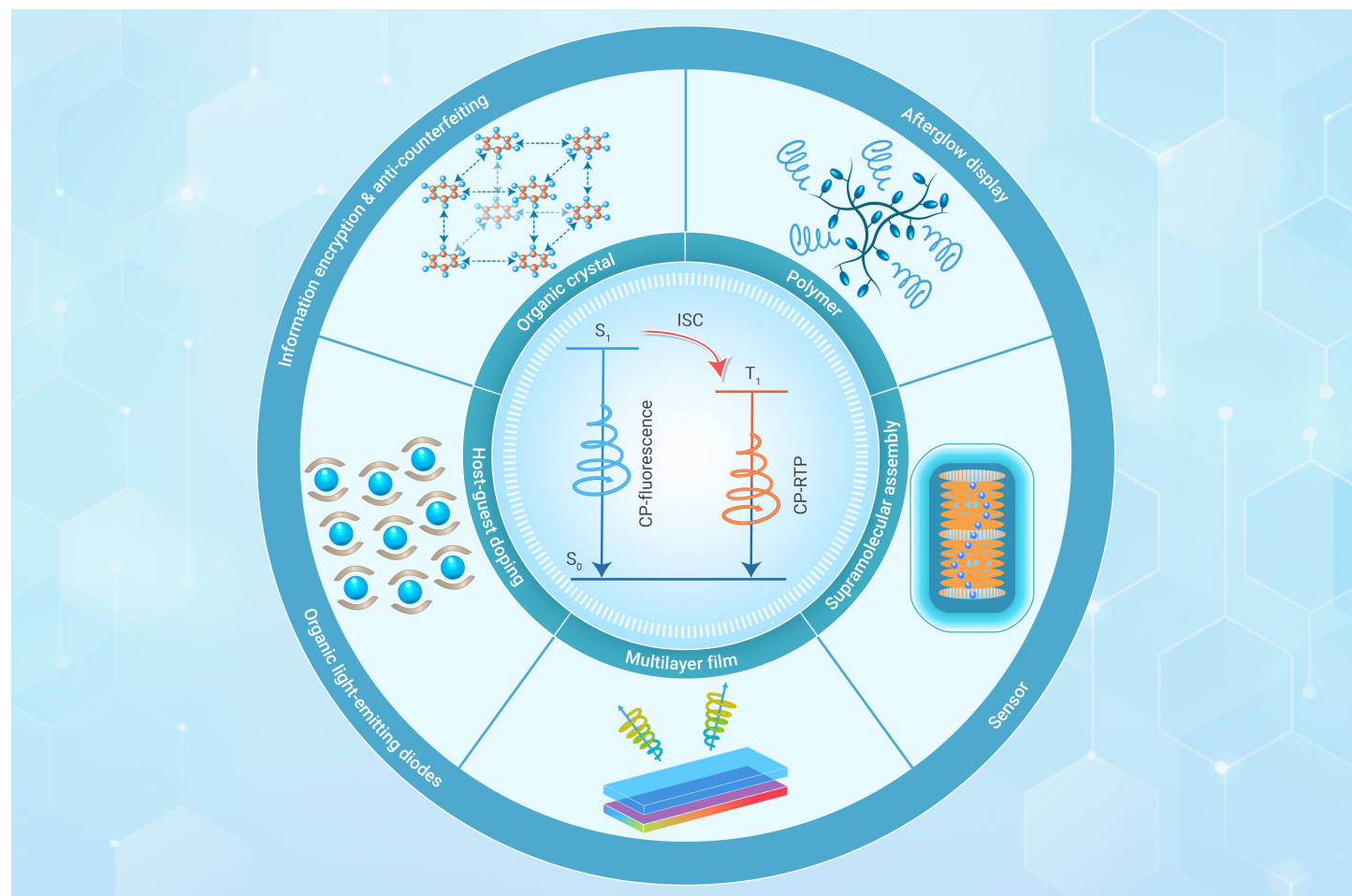
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Overview of organic circularly polarized room-temperature phosphorescence (CP-RTP) materials.
- Emphasis on molecular design strategies, structure-property relationships, and key material systems.
- Discussion of application prospects and challenges in achieving high-performance CP-RTP systems.

Recent advances in organic circularly polarized room-temperature phosphorescence: Materials and applications

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Circularly polarized luminescence (CPL) has attracted significant attention for its potential in chiral recognition, 3D displays, and asymmetric catalysis. Among CPL-active systems, organic circularly polarized room-temperature phosphorescence (CP-RTP) materials stand out by combining long-lived emissive lifetimes with chiroptical activity, offering promising avenues in organic electronics. This review highlights recent advances in CP-RTP materials, emphasizing molecular design strategies, structure-property relationships, and emerging applications. Key material systems are systematically discussed, including organic crystals, polymers, host-guest doping systems, supramolecular assemblies, and multilayer systems, along with their emerging applications in information encryption and anti-counterfeiting, organic light-emitting diodes, afterglow display, and sensor. Additionally, we discuss the challenges and future opportunities in developing high-performance CP-RTP materials, with the aim of inspiring ongoing innovation in this rapidly advancing field.

INTRODUCTION

Chirality is a pervasive feature of nature, spanning all scales—from symmetry breaking in elementary particles to the enantioselective interactions of biomolecules such as amino acids, sugars, and DNA.^{1–11} In the field of chiral optics, circularly polarized luminescence (CPL) stands as a representative form of chiral emission.^{12–17} Initially, CPL was realized through purely physical methods (Figure 1A), where natural light is first transformed into linearly polarized light by a polarizer, and subsequently passes through a quarter-wave plate to produce left- or right-handed circularly polarized light.^{18,19} However, this method incurs considerable energy loss and necessitates additional optical components.^{20,21} In 1948, Samoilov directly detected CPL signals in a chiral actinide complex crystal of sodium uranyl acetate.²² This approach, which enables the direct generation of CPL from chiral luminescent materials under unpolarized light excitation (Figure 1B), effectively reduces energy loss and opens a new pathway for CPL generation.^{23,24}

In recent years, considerable attention has been devoted to the design and development of novel organic optoelectronic materials exhibiting CPL properties. These materials mainly encompass chiral fluorescent organic luminophores,^{25–27} chiral thermally activated delayed fluorescence (TADF) molecules,^{28–30} and chiral phosphorescent materials.^{31–34} Notably, circularly polarized room-temperature phosphorescence (CP-RTP) materials represent a unique research branch that has further enriched the CPL material system. The combination of long-lived emission and circular polarized characteristics offers new inspiration for expanding the application scope of CPL materials.^{35–37} For example, in organic optoelectronic devices, CP-RTP materials benefit from the near-unity exciton utilization through the phosphorescent process, thereby providing notable advantages in boosting device efficiency. In bioimaging, the long-lived emission of CP-RTP materials effectively reduces interference from short-lived background fluorescence, thereby improving signal-to-noise ratios; moreover, their conformation dependent circular polarized characteristics offers a unique advantage for chiral recognition. In the field of information encryption, CP-RTP materials synergistically couple emission lifetime, color, and circular polarization within a single platform, enabling the construction of multidimensional encryption systems that integrate temporal and polarization domains, thereby enhancing data security and anti-counterfeiting functionality. By integrating the advantages of CPL and room-temperature phosphorescence (RTP), these materials have emerged as a research hotspot in the field of organic optoelectronics, offer-

ing new opportunities for applications in organic devices, information encryption, and bioimaging.³⁸ In light of these developments, this review provides a systematic overview of the recent progress in CP-RTP materials.

THE KEY PARAMETERS FOR CP-RTP

For CP-RTP materials, the key parameters that evaluate their performance include the lifetime (τ), the photoluminescence quantum yield (PLQY, Φ), and the dissymmetry factor (g_{lum}). The τ refers to the average time a molecule remains in the excited state before emitting a photon and is typically determined using equation (1):^{39–42}

$$I(t) = I_0 e^{-t/\tau} \quad (1)$$

where t is the decay time and I_0 represents the initial luminescent intensity at $t=0$. The phosphorescence lifetime is typically obtained by fitting its decay curve and is also defined as the time required for the intensity to decrease to $1/e$ of its initial value.

PLQY is generally defined as the ratio of the number of emitted photons to the number of absorbed photons and is determined by the decay rates of the excited state.^{43,44} The Φ can be calculated based on equation (2):

$$\Phi = \frac{N_E}{N_A} \times 100\% \quad (2)$$

where N_E and N_A are the number of emitted and absorbed photons, respectively. In the steady-state photoluminescence (SSPL) process, both fluorescence and RTP contribute to the total number of emitted photons, with RTP emission accounting for only a portion of the overall emission. Therefore, in the SSPL spectra, the areas corresponding to the fluorescence and RTP components must be individually fitted to determine the proportion of the phosphorescence intensity (η_p) relative to the total luminescence. Consequently, the quantum yield of phosphorescence (Φ_p) can be calculated using the following equation (3):

$$\Phi_p = \Phi \eta_p \quad (3)$$

Based on the difference in emission intensity between right-handed and left-handed CP-RTP, g_{lum} needs to be calculated by equation (4):⁴⁵

$$g_{\text{lum}} = \frac{\Delta I}{0.5I} = \frac{2(I_L - I_R)}{I_L + I_R} \quad (4)$$

where I_L and I_R represent the emission intensities of L-CPL and R-CPL, respectively. The g_{lum} ranges from -2 to $+2$.⁴⁶ Experimentally, g_{lum} is usually directly obtained from the CPL spectrum using specialized software, as given by equation (5):

$$g_{\text{lum}} = \frac{2 \times \frac{\text{ellipticity}}{32980/\ln 10}}{\text{total fluorescence intensity}} \quad (5)$$

All the above parameters are crucial indicators for characterizing CP-RTP performance and should be comprehensively considered when evaluating CP-RTP materials.

MATERIALS FOR CP-RTP EMISSION

CP-RTP materials are constructed by synergistically integrating chirality with triplet exciton stabilization. Key strategies including chiral crystal engineering, polymer confinement, host-guest doping, supramolecular assembly

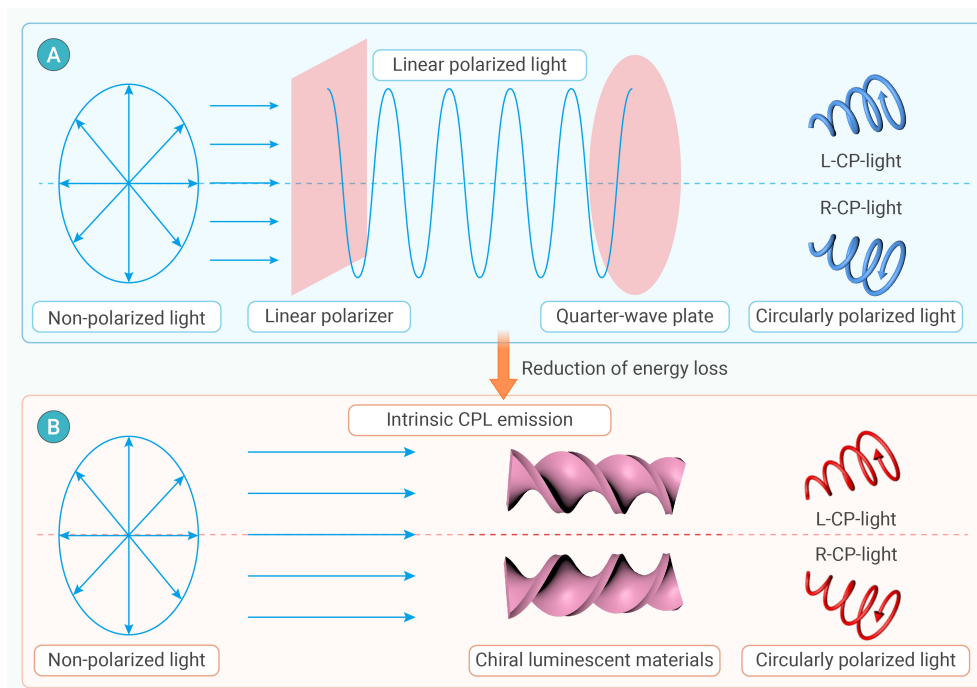


Figure 1. Mechanisms of circularly polarized light generation (A) Physical method for producing circularly polarized light. (B) Direct generation of circularly polarized light from chiral luminescent materials under non-polarized light excitation.

and multilayer heterostructures decoupling chirality transfer and exciton confinement have been reported for precise control of molecular symmetry, stacking, and suppression of non-radiative decay in CP-RTP materials. In this section, we will systematically summarize varied molecular systems.

Organic crystal systems

Organic ionic crystals. Strong ionic and hydrogen bonding interactions in ionic crystals enable efficient CP-RTP emission. In 2018, Duan et al. realized the CP-RTP in chiral organic ionic crystals by co-crystallizing terephthalic acid (TPA) with chiral α -phenylethylamine (PEA), forming TPA-(*R/S*)-PEA crystals (Figures 2A-B).⁴⁷ These crystals exhibited distinct RTP with a lifetime of 862 ms. CPL spectra showed strong signals in both fluorescence and phosphorescence regions, with $|g_{lum}|$ values of 1.1×10^{-2} for fluorescence and 2.0×10^{-2} for phosphorescence. An et al. developed chiral optical ionic crystals (*R/S*-DNP) via ionization-induced assembly, where chiral counterions tightly confined isolated chromophores.⁴⁸ The resulting materials exhibited efficient CP-RTP with PLQY of 43.2%, lifetime of 22.81 ms, and remarkable $|g_{lum}|$ of 0.13.

Cocrystal. In 2025, Zhang et al. reported the creation of chiral cocrystals (*S*-Cocrystal and *R*-Cocrystal) by co-crystallizing *R/S*-1-(1-Naphthyl)ethanol (*R/S*-1-nea) with 1,2,4,5-Tetracyanobenzene (TCNB).⁴⁹ The robust π - π interactions and extensive hydrogen-bonding networks stabilize triplet excitons and suppress nonradiative decay, facilitating RTP emission. Moreover, the chirality of the donor molecule induces a discontinuous helical tilt in the supramolecular stacking, enhancing exciton chiral coupling and significantly improving the g_{lum} . As a result, the *R*-Cocrystal achieves a phosphorescence lifetime of 28.48 ms, a PLQY of 31%, and an outstanding $|g_{lum}|$ of 0.065.

Organic small molecular crystals. In 2024, Huang et al. developed a dual-mode decay strategy that achieves color-tunable CP-RTP in single-component organic crystals. Using photoimplanted radical ion pairs within axially chiral SEGPHOS crystals, they combined triplet emission of neutral diphosphines with radical doublet emission.⁵⁰ Controlled photo-activation enabled dynamic color tuning across the visible range and a $|g_{lum}|$ of 3.4×10^{-3} , overcoming challenges of tunability and stability in CP-RTP materials.

Huang, Chen, Tao, and co-workers have developed a series of CP-RTP materials based on single-component organic molecular crystals. In 2020, to address the challenge of constructing single-component CP-RTP materials, they proposed a strategy of directly attaching chiral ester chains to achiral phosphors.⁵¹ In addition to imparting chirality, the flexible chiral chains also served as conformation-regulating units, which could effectively modulate molecular packing under external stimuli, enabling a reversible transforma-

tion from CP-RTP to circularly polarized organic ultralong RTP (CP-OURTP). The CP-RTP molecules exhibited a $|g_{lum}|$ of 2.3×10^{-3} and a phosphorescence lifetime of 80 ms. Upon UV light photo-activation, the emission lifetime was markedly extended to 600 ms (Figure 2C). However, realizing color-tunable CP-RTP from single-component systems remains a significant challenge. To address this issue, a molecular design strategy based on chiral clusterization was proposed. By incorporating chiral units into phosphorescent clusters, they effectively constructed size-dependent, cluster-triggered emission centers, achieving excitation-dependent, single-component color-tunable CP-RTP.⁵² The emission color could be tuned over a wide range from 470 to 530 nm (Figure 2D), with a maximum lifetime of up to 587 ms and a $|g_{lum}|$ of approximately 2.3×10^{-3} . These findings offer important guidance for the development of color-tunable CP-RTP materials. Furthermore, in 2023, the team successfully constructed a series of time-dependent multicolor CP-RTP materials (*R/S*-CzCOPEA) by integrating chiral phenylethylamine units into carbazole-based systems via β -diketonate linkers.⁵³ With increasing delay time, the tunable CP-RTP emission color changed from yellow to green, with an ultralong lifetime of 946.44 ms and $|g_{lum}| \approx 10^{-3}$ under ambient conditions.

In organic crystal-based CP-RTP materials, the molecular conformation plays a crucial role in determining the crystal packing structure, which in turn significantly impacts the resulting CP-RTP performance. In 2018, Huang et al. designed and synthesized the chiral compound SPCzT and its racemic counterpart PCzT.⁵⁴ X-ray single-crystal analysis revealed pronounced differences in their crystal structures, with SPCzT adopting a helical conformation, whereas PCzT featured an alternating linear arrangement of dimers. Notably, the RTP lifetime of SPCzT was extended from 229.0 ms (for PCzT) to 419.8 ms, accompanied by a higher PLQY. In 2020, Zhu et al. investigated binaphthyl (BINAP) as a model compound and obtained three configurations (*R*-, *S*-, and *rac*-BINAP) through sublimation, with their high chiral purity confirmed by multiple characterization techniques.⁵⁵ Single-crystal X-ray diffraction revealed distinct differences in their crystal structures, showing that the *rac*-BINAP exhibited a higher crystal density, in line with Wallach's rule. Photophysical studies demonstrated that *rac*-BINAP displayed an Φ_p of 0.42%, approximately four times higher than *R*-BINAP (0.09%) and *S*-BINAP (0.11%), along with a long phosphorescence lifetime of 18.1 ms. This study offered a new perspective for understanding the relationship between molecular packing and RTP performance.

In 2020, Favereau et al. synthesized chiral cyclohexane-based bis-naphthalimide derivatives (*R,R*-, (*S,S*)-, and (*rac*)-Cy(F_2 Pht)₂) and investigated their structures and photophysical properties.⁵⁶ The single-crystal analysis revealed significant structural differences between (*R,R*)-Cy(F_2 Pht)₂ and (*rac*)-Cy(F_2 Pht)₂. In (*R,R*)-Cy(F_2 Pht)₂, molecular packing was dominated by uniform π - π interactions, leading to the formation of more H-aggregates. In contrast, (*rac*)-Cy(F_2 Pht)₂ exhibited fewer H-aggregates and lower molecular network order. As a result, (*R,R*)-Cy(F_2 Pht)₂ demonstrated superior RTP performance, with a quantum yield of 3% and a lifetime of 0.3 s, while (*rac*)-Cy(F_2 Pht)₂ showed a much lower quantum yield of only 0.5%. In 2024, Zhao et al. designed and synthesized four heavy-atom-free chiral small molecules (Figure 2A), *R/S*-An-NH and *R/S*-An-N.⁵⁷ CD spectra confirmed the chirality of the molecules, and theoretical calculations revealed that the twisted conformations of the chiral groups in the excited state affected the formation of intramolecular twisted charge transfer states, ISC processes, and triplet

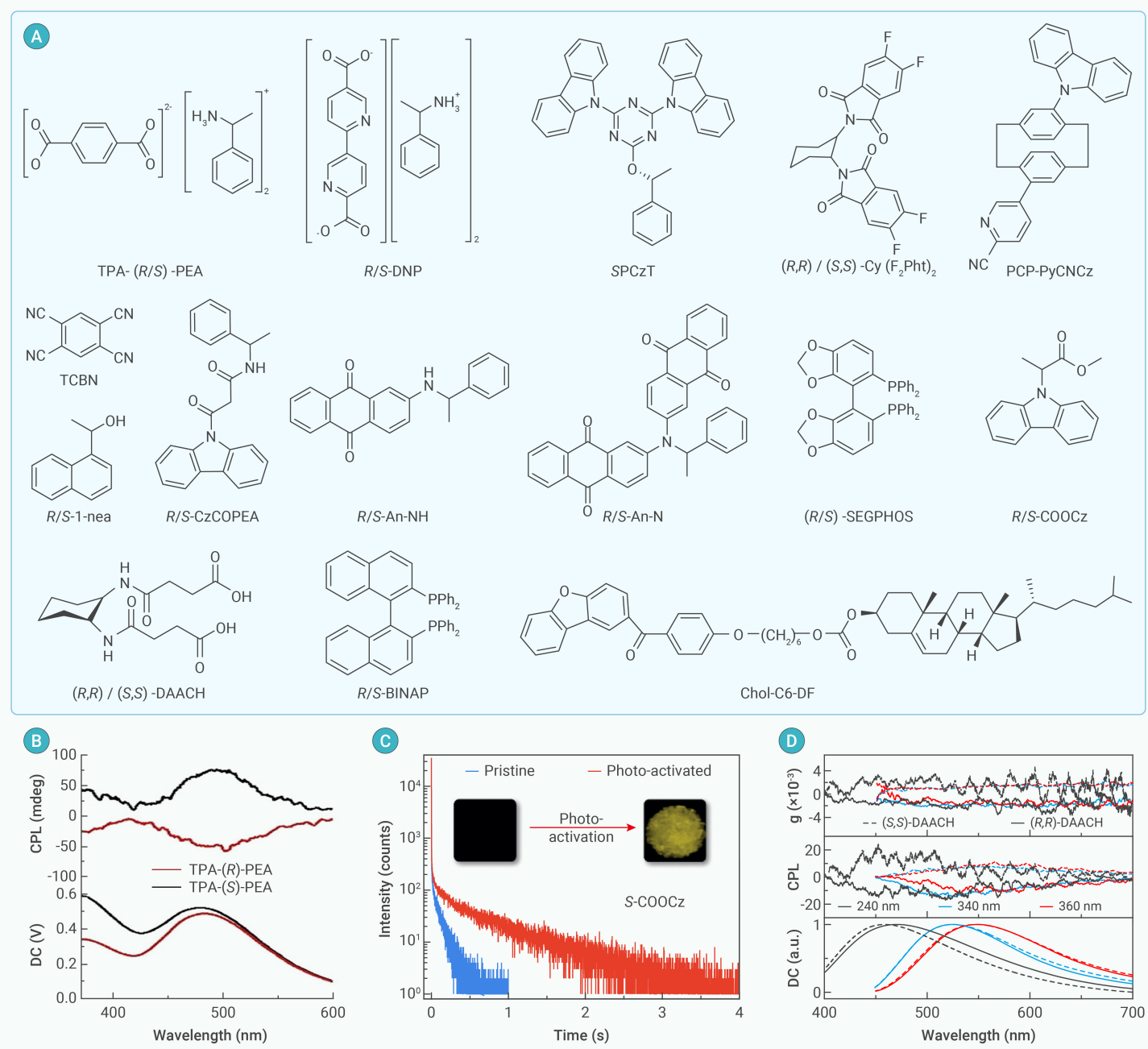


Figure 2. Representative circularly polarized room-temperature phosphorescence (CP-RTP) materials based on organic crystal (A) Molecular structures of CP-RTP materials based on organic crystal systems. (B) Circularly polarized luminescence (CPL) spectra of TPA-(R/S)-PEA. Reproduced with permission. Copyright 2018, Wiley.⁴⁷ (C) Lifetime decay profiles of S-COOCz before and after photo-activation. Reproduced with permission. Copyright 2020, Wiley.⁵¹ (D) CPL spectra of (R,R)/(S,S)-DAACH under different excitation wavelengths. Reproduced with permission. Copyright 2022, Nature Publishing Group.⁵²

excitons stability. *R/S*-An-NH exhibited fewer ISC pathways, leading to competition between fluorescence and phosphorescence, while *R/S*-An-N had more efficient ISC channels, resulting in stronger phosphorescence and weaker fluorescence.

In 2019, Zheng et al. reported [2.2]paracyclophane (PCP)-based organic materials that simultaneously possess RTP and CPL properties.⁵⁸ They employed two synergistic strategies: Bromine doping to boost ISC and the incorporation of electron-withdrawing groups to regulate through-space charge transfer. These brominated derivatives exhibited RTP lifetimes of approximately 100 ms, while the halogen-free PCP-PyCNCz achieved an impressive 528 ms. Notably, the chiral enantiomers demonstrated $|g_{lum}|$ as high as 1.2×10^{-2} in toluene. This work underscores the potential of PCP backbone engineering in realizing the synergistic optimization of RTP lifetime and CPL performance.

Liquid crystal. Liquid crystals represent a promising platform for realizing

efficient CP-RTP emission, characterized by large g_{lum} values.^{59–61} In 2023, Zhang et al. reported a chiral cholesteric liquid crystal-based CP-RTP material, Chol-C6-DF, whose unique helical architecture and selective reflection properties effectively amplified the g_{lum} values.⁶² Upon excitation at 380 nm, the dibenzofuran chromophore exhibited yellow CP-RTP with a $|g_{lum}|$ of 0.19, a lifetime of 567.7 ms, and a quantum yield of 3.2%. Under 460 nm excitation, the cholesteryl moiety gave rise to red CP-RTP with a $|g_{lum}|$ of 0.11 and a lifetime as long as 1.11 s. Moreover, the measured PLQYs under 410, 430, and 470 nm excitation were 19.0%, 20.2%, and 19.1%, respectively. Benefiting from its excellent processability and multicolor properties, this work offers a promising strategy for the development of high-performance CP-RTP materials. Therefore, molecular structure and crystal packing play a vital role in controlling CP-RTP properties of organic crystalline systems. The implementation of rigid molecular frameworks, dense and ordered crystal packing has proven highly effective in suppressing non-radiative decay pathways and

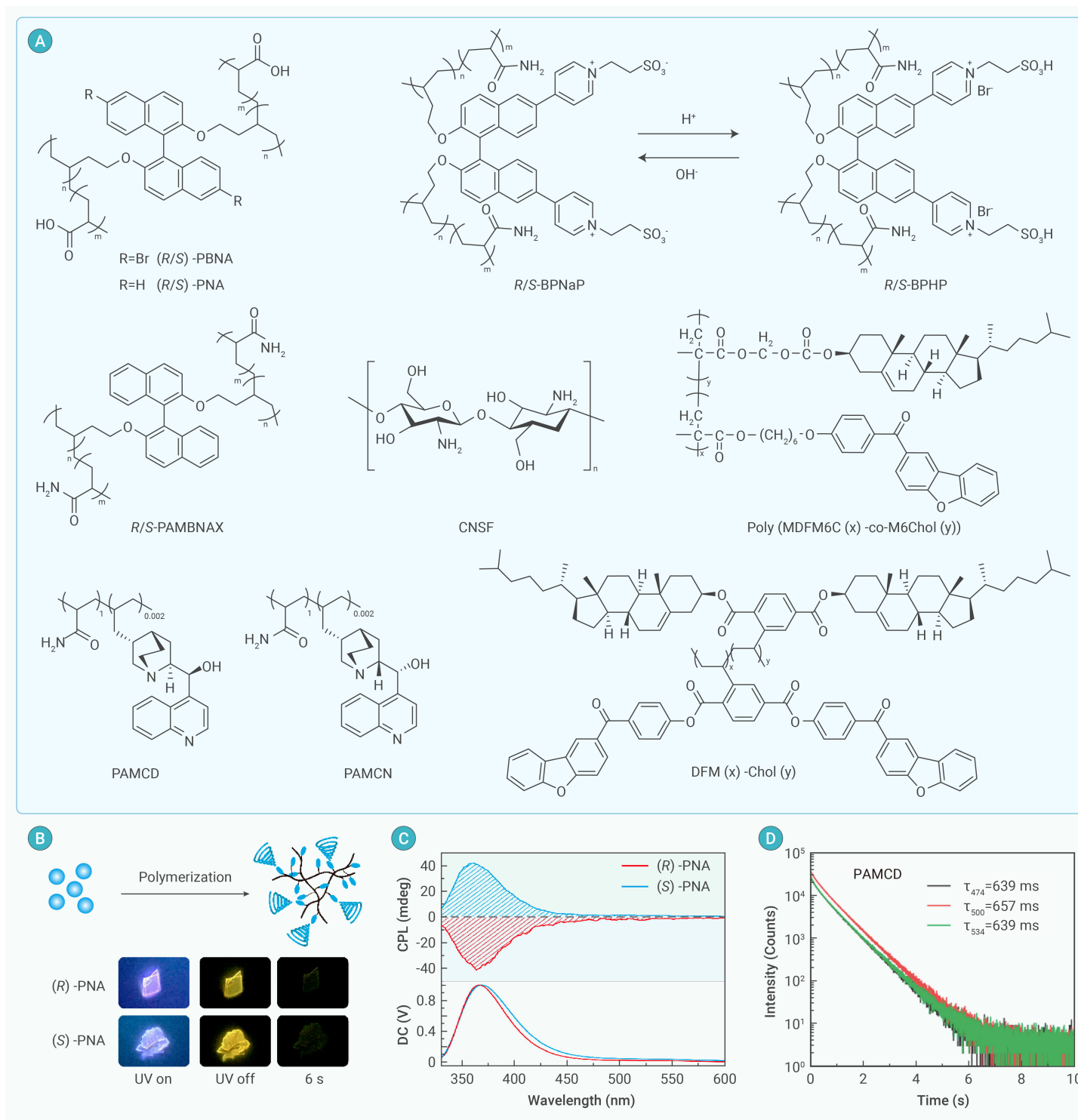


Figure 3. CP-RTP materials derived from bonded polymer systems (A) Molecular structures of CP-RTP materials based on polymer systems. (B) Schematic illustration of molecular design strategy and afterglow photographs of (R/S)-PNA films. (C) CPL spectra of (R/S)-PNA films. Reproduced with permission. Copyright 2021, American Chemical Society.⁶⁸ (D) Lifetime decay profiles of PAMCD. Reproduced with permission. Copyright 2023, American Chemical Society.⁷⁰

stabilizing triplet excitons, thereby affording efficient and long-lived CP-RTP emission. Moreover, the integration of stimuli-responsive units enables the realization of externally controllable CP-RTP characteristics.

Polymeric systems

Polymer matrices offer rigid environments that suppress non-radiative decay, stabilize triplet states and extending phosphorescence lifetimes. Their excellent processability and film-forming ability enable flexible RTP devices and coatings.^{63–67} These advantages make polymers ideal for developing stable, efficient, and tunable organic CP-RTP materials for applications such

as anti-counterfeiting, information encryption, and bioimaging.

Bonded polymer systems. In 2021, Zhao et al. developed a class of chiral polymer RTP materials by incorporating axially chiral chromophores into poly(acrylic acid) (PAA) chains through radical copolymerization (Figures 3A–B).⁶⁸ The resulting copolymer exhibited a CP-RTP quantum yield of up to 30.6%, a high $|g_{lum}|$ value of 9.4×10^{-3} (Figure 3C), and a phosphorescence lifetime reaching 0.68 s. Furthermore, bromine substitution in the copolymer ((R/S)-PBNA) enhanced the phosphorescence efficiency via the heavy atom effect, enabling dual circularly polarized emissions from both fluorescence and phosphorescence. This study presents a novel strategy for designing

polymer-based CP-RTP materials. Additionally, Ma et al. reported a purely organic amorphous copolymers *R/S*-BPNaP, which exhibited both CPL and CP-RTP characteristics.⁶⁹ The introduction of HBr induced intermolecular heavy-atom effects, resulting in a 27.6-fold enhancement of RTP intensity. Moreover, the RTP intensity and lifetime were reversibly tunable through acid-base treatment; for instance, the lifetime of *R*-BPNaP decreased from 109.1 ms to 39.3 ms upon protonation, forming *R*-BPHP. This reversible responsiveness endows the materials with great potential for advanced data encryption applications.

Chen et al. proposed a chiral copolymerization and aggregation engineering strategy to fabricate high-performance amorphous CP-RTP copolymers by radical copolymerization of natural chiral cinchona alkaloids with acrylamide.⁷⁰ Using a water-dissolution-evaporation-induced aggregation process, they further fabricated dense, sheet-like polymer films. The resulting copolymer films exhibit outstanding CP-RTP performance, including a maximum Φ_p of 11.9%, lifetimes exceeding 650 ms (Figure 3D), a $|g_{lum}|$ of up to 3.54×10^{-3} . In 2024, Tao et al. proposed a strategy for spatially confine isolated chiral chromophores within a polymer matrix via radical binary copolymerization.⁷¹ By employing chiral binaphthol derivatives as chromophores and polyacrylamide (PAM) as a rigid matrix, they successfully developed a series of amorphous, single-component copolymers, named *R/S*-PAMBNAX, which exhibited remarkable CP-RTP properties. These copolymers exhibited both fluorescence and RTP emissions, achieving a maximum $|g_{lum}|$ of 1.06×10^{-2} and a lifetime of up to 1.08 s. Qing et al. proposed an innovative “top-down” strategy to convert chitin, extracted from crustacean waste such as shrimp shells, into chiral, self-luminescent chitosan nanostructured films, enabling CP-RTP without external luminophores.⁷² This process retains the naturally occurring left-handed nematic structure of shrimp shells, endowing the resulting material with right-handed CP-RTP emission, characterized by a high $|g_{lum}|$ of up to 0.34 and a phosphorescence lifetime of up to 331 ms. In addition to its CP-RTP properties, the material exhibits optical iridescence, flexibility, biodegradability, and reversible humidity responsiveness.

Liquid crystal polymers also serve as excellent media for achieving CP-RTP.⁷³ In 2024, Zhang et al. developed a polymer-based CP-RTP material by copolymerizing a phosphorescent chromophore with another phosphorescent monomer containing chiral cholesterol mesogen (Figure 3A).⁷⁴ The resulting liquid crystal copolymers, Poly(MDFM6C(x)-co-M6Chol(y)), exhibit CP-RTP properties. The chiral cholesteryl mesogens induced the formation of chiral liquid crystalline phases, and the helical self-assembly structures enabled efficient CPL through selective reflection, achieving a $|g_{lum}|$ of 1.6×10^{-2} . Moreover, the phosphorescence lifetime increased with the content of the PMDFM6C component, reaching up to 549.1 ms. Building upon this work, the team further proposed a strategy to construct CP-RTP materials by exploiting the structural characteristics of mesogen-jacketed liquid crystal polymers (MJLCPs).⁷⁵ The “jacketing” effect, arising from the dense packing of side chains, forces the polymer main chains to adopt an extended conformation, forming rigid structures that effectively suppress nonradiative decay and prolong phosphorescence lifetimes. The copolymer DFM (0.6)-Chol (0.4) exhibited fluorescence and phosphorescence $|g_{lum}|$ values of 4.4×10^{-3} and 7.1×10^{-3} , respectively, with a phosphorescent lifetime of 252 ms. This study provides a new pathway for the design of long-lived CP-RTP materials.

Doped polymer systems. In the construction of doped polymeric CP-RTP systems, polyvinyl alcohol (PVA) not only provides a rigid microenvironment that effectively suppresses nonradiative decay, but also offers excellent film-forming capability, thereby endowing the system with favorable processability.^{76–79} In 2024, Huang et al. introduced a dynamic hydrogen-bonding network, in which chiral phosphorescent chromophores were doped into a PVA matrix to achieve water- and thermal-responsive blue CP-RTP (Figure 4A).⁸⁰ The resulting material exhibited an impressive CP-RTP lifetime of up to 3.35 s, a PLQY of 25.0%, and a $|g_{lum}|$ of up to 0.05. Moreover, full-color stimuli-responsive CP-RTP was successfully achieved through combined chiral and phosphorescence energy transfer processes (Figure 4B). He et al. synthesized a novel biphenyl[b,d]furan compound, (*R*)-1, and obtained its enantiomerically pure form via NHC-catalyzed kinetic resolution followed by silica gel chromatography.⁸¹ By doping (*R*)-1 into PVA matrix at a mass ratio of 1:600, followed by thermal annealing at 120°C for 30 minutes and subsequent UV irradiation (254 nm) for another 30 minutes, both fluorescent and

phosphorescent intensities were significantly enhanced. The CPL was activated, and the $|g_{lum}|$ was boosted from near 0 to 0.12. Notably, the PLQY increased from 2.5% to 14.8%, accompanied by a prolonged lifetime of up to 564.5 ms. In 2024, Chen et al. developed a hybrid system exhibiting both TADF and RTP by doping acridine yellow (AF) into a PVA network via a doping-drying method.⁸² To further enhance performance, a CNC-PVA-AF composite film was fabricated via evaporation-induced co-assembly of AF, PVA, and CNCs, successfully realizing a dual-emission system with both circularly polarized thermally activated delayed fluorescence (CP-TADF) and CP-RTP characteristics. The $|g_{lum}|$ s, lifetimes and PLQYs for CP-TADF and CP-RTP reached 0.32 and 0.57, 253 and 202 ms, 12.21% and 6.63%, respectively. This work provides a new strategy for the design of multifunctional CPL-active materials. In 2024, Yuan et al. developed co-doped films comprising chiral naphthyl phosphate derivatives (*R/S*-BNDHP) as energy and chirality donors, rhodamine B (RB) as the acceptor, and PVA as the host matrix.⁸³ The resulting materials exhibited efficient green CP-RTP with a high Φ of 14.23%, a prolonged lifetime of 1025.5 ms, and a $|g_{lum}|$ of 8.44×10^{-3} . Moreover, by varying the RB concentration, tunable multicolor CP-RTP emission from green to orange-red was achieved (Figure 4C).

Polystyrene (PS) film, as a host matrix, exhibits sensitivity to both oxygen and temperature,^{84–86} enabling the construction of dynamically responsive CP-RTP systems through environmental modulation of phosphorescent emission. In 2024, Li et al. developed CP-RTP films by doping chiral binaphthol-phenoselenazine derivatives ((*R/S*)-Binol-PSeA) into a PS matrix, achieving a $|g_{lum}|$ of 9.32×10^{-3} , a high emission efficiency of 27.0%, and lifetime of 40.0 ms.⁸⁷ Owing to the oxygen and thermal sensitivity of the PS film, tunable circularly polarized fluorescence (CPF) and CP-RTP emissions were realized. Furthermore, doping (*R/S*)-Binol-PSeA into small-molecule hosts such as TPP and PCZ extended the CP-RTP lifetime to 85.9 ms.

Polymethyl methacrylate (PMMA) is also an excellent polymer host for achieving high-performance CP-RTP. In 2022, Subi J. George et al. designed dual-emissive chiral phosphors by linking heavy-atom-substituted pyromellitic diimide (PmDI) units to a cyclohexanediamine-based chiral core, successfully achieving CP-RTP emission at room temperature.⁸⁸ The resulting (*RR*)/(*SS*)-BrPmDI and (*RR*)/(*SS*)-Br₂PmDI embedded in PMMA films exhibited excellent CP-RTP performance, with PLQYs of ~10–18% in air (~42–46% in vacuum) and $|g_{lum}|$ ranging from 1.3 to 4.0×10^{-3} (Figure 4D). Ma et al. synthesized a chiral copolymer, p(phNA-co-BrNpA), and fabricated a photo-responsive CP-RTP composite film by blending it with PMMA.⁸⁹ Upon UV irradiation, the PMMA matrix consumes molecular oxygen, thereby suppressing triplet excitons quenching and significantly enhancing the phosphorescence emission. As a result, the composite exhibits strong CP-RTP with a $|g_{lum}|$ of up to 0.019, along with excellent stability and reversible photo-responsiveness.

Polyvinylpyrrolidone (PVP) can form vitrified films upon casting, providing a rigid microenvironment that effectively stabilizes triplet excitons and suppresses nonradiative decay,^{90,91} thereby enabling high-performance CP-RTP. In 2024, Huang et al. introduced three aromatic structures (naphthalene, phenanthrene, and pyrene) into chiral amides as guest molecules and doped them into a PVP matrix to construct CP-RTP systems with green, yellow, and red afterglow emissions (Figure 4A).⁹² These systems exhibited Φ_p of 7.3–13.6%, lifetimes of 341–1017 ms, and $|g_{lum}|$ values of 1×10^{-3} – 2.1×10^{-3} . By co-doping all three guests into PVP, they further achieved excitation-wavelength-dependent multicolor CP-RTP. In 2023, Wang et al. selected axially chiral molecules (*R/S*)-1,1'-binaphthyl-2-amine (*R/S*-NA) as chiral guests, and constructed a host-guest doped system with triphenylphosphine (TPP).⁹³ Upon introducing the rigid polymer PVP, charge separation efficiency was enhanced, extending the afterglow duration from 5 to 10 s. Electron paramagnetic resonance (EPR) confirmed the formation of long-lived charge separated states, while CD and CPL spectra demonstrated chirality retention in the ground, singlet, and triplet states.

Energy transfer strategies offer a promising approach for the construction of full-color CP-RTP systems.^{94–96} In 2024, Huang et al. proposed a simple and effective strategy for achieving CP-RTP by incorporating isolated chiral luminophores into a rigid polymer matrix with confined domains (Figure 5A).⁹⁷ The resulting blue CP-RTP polymer exhibited a long lifetime of up to 3.0 s and a $|g_{lum}|$ of 1.02×10^{-2} . Moreover, full-color CP-RTP polymers were successfully

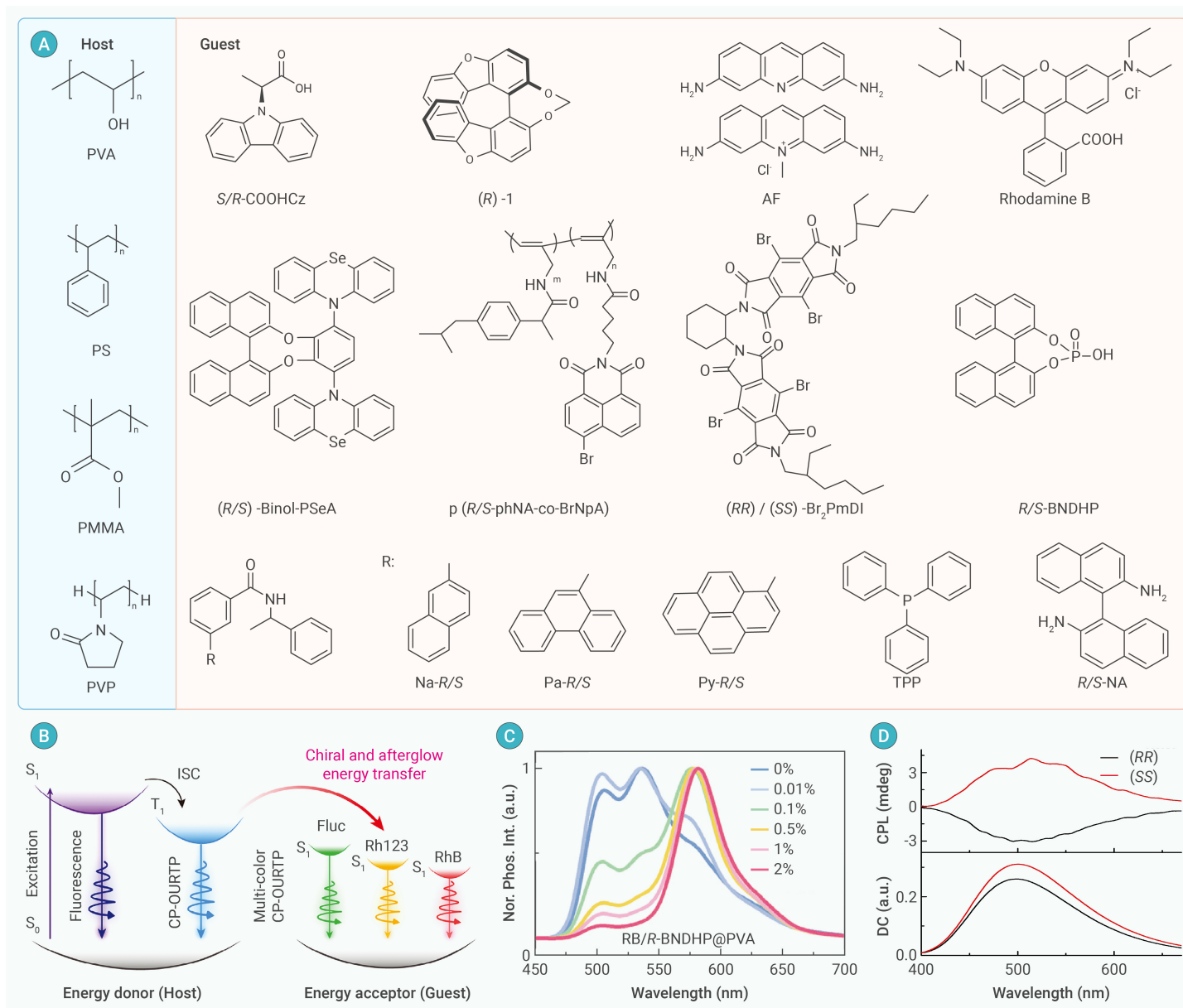


Figure 4. CP-RTP materials based on doped polymer systems (A) Molecular structures of CP-RTP materials based on multi-components host-guest doped polymer systems. (B) Schematic illustration of multi-color CP-RTP. Reproduced with permission. Copyright 2024, Wiley.⁸⁰ (C) Delayed spectra of RB/R-BNDHP@PVA films with varying dopant concentrations. Reproduced with permission. Copyright 2024, Wiley.⁸³ (D) CPL spectra of (RR)/(SS)-BrPmDI/PMMA films. Reproduced with permission. Copyright 2022, Wiley.⁸⁵

achieved *via* synergistic phosphorescence and chiral energy transfer by doping the system with commercially available water-soluble fluorescent dyes (Figures 5B–C). Deng et al. proposed a general strategy by integrating circularly polarized phosphorescence energy transfer (CPP-ET) with chiral selective absorption to construct a series of full-color and white CP-RTP materials.⁹⁸ Using chiral helical polyacetylene as the chiral source and blue long-persistent inorganic phosphor as the emissive donor, they first realized blue CP-RTP films with a high $|g_{lum}|$ of up to 3×10^{-2} *via* the chirality-selective absorption effect. Subsequently, by introducing various fluorescent acceptors through CPP-ET, they achieved full-color tunable CP-RTP films with $|g_{lum}|$ values up to 10^{-3} and significantly prolonged lifetimes from nanoseconds to several minutes. In 2024, Sun et al. proposed a novel strategy for synthesizing carbonized polymer dots (CPDs) with intrinsic CP-RTP characteristics, using sodium alginate and *L/D*-arginine as precursors *via* a hydrothermal method.⁹⁹ Under relatively mild reaction conditions, the resulting CPDs exhibited green CP-RTP in the solid state and enabled the construction of a chiral light-harvesting system based on CPL resonance energy transfer, achieving color-tunable CP-RTP.

Crosslinked polymer networks provide rigid microenvironments that can

effectively stabilize triplet excitons and suppress nonradiative decay,^{100–102} making them excellent matrices for realizing CP-RTP. Yang et al. synthesized a novel chiral phosphorescent molecule and incorporated it into a dynamically cross-linked vitrimer film to construct CP-RTP materials.¹⁰³ The optimal performance was achieved at a BAD:DGEBA molar ratio of 1:200, yielding green phosphorescence with a lifetime of 895 ms, a PLQY of 9.70%, and a high $|g_{lum}|$ value of up to 0.014. The material demonstrated remarkable thermal responsiveness, with reversible afterglow quenching at 75°C and robust stability across multiple thermal cycles. CP-RTP materials hold great promise for diverse applications, yet current strategies often suffer from synthetic complexity, limited versatility, and energy loss. Zhang et al. developed a series of full-color CP-RTP materials by combining anionic cellulose derivatives (CBTCOONa and CMCNa) with achiral chromophores.¹⁰⁴ By tuning the chromophores, the system exhibited color-tunable CP-RTP from blue to red, with notable features including excitation wavelength-, concentration-, and time-dependent phosphorescence under visible-light excitation, and a high $|g_{lum}|$ of up to 1.16×10^{-2} (Figure 5D).

Polymer can serve as rigid matrices to effectively suppress non-radiative decay, enhancing both chiral emission intensity and RTP lifetime, ultimately

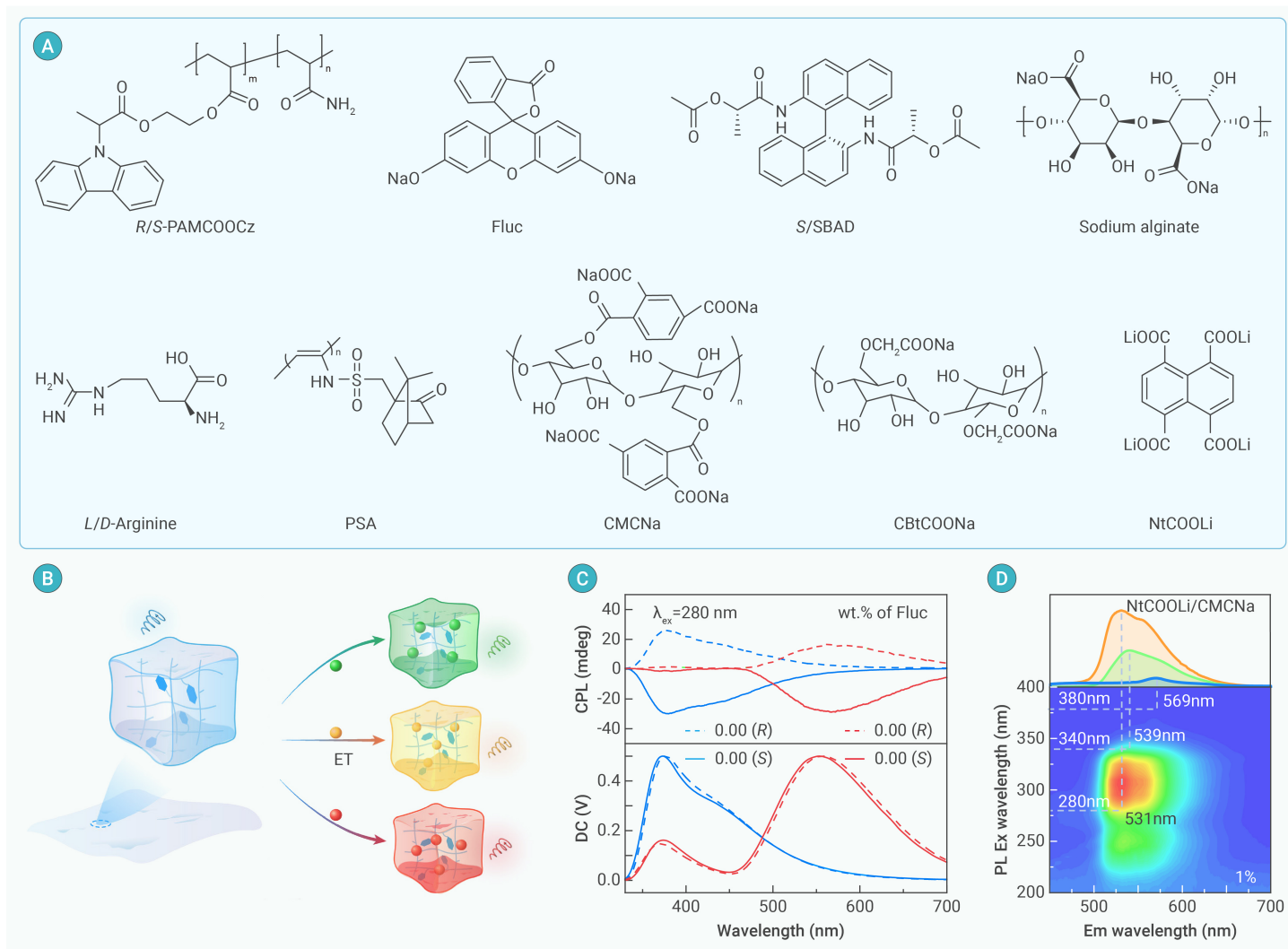


Figure 5. CP-RTP materials developed from doped polymer systems (A) Molecular structures of CP-RTP materials based on copolymer systems. (B) Schematic illustration of multicolor CP-RTP through synergistic phosphorescence and chiral energy transfer from CP-RTP polymer to varied fluorescent emitters. (C) CPL spectra of Fluc doped *R*-PAMCOOCz films with varying doping concentrations. Reproduced with permission. Copyright 2024, Nature Publishing Group.³⁷ (D) Phosphorescence excitation and emission spectra of 1% NtCOOLi/CMCNa film. Reproduced with permission. Copyright 2024, Nature Publishing Group.¹⁰⁴

promoting efficient CP-RTP. Furthermore, the construction of doping systems and energy-transfer architectures can significantly improve emission efficiency and lifetime, amplify chiral signals, and enable multifunctional CP-RTP features such as color tunability and stimuli responsiveness.

Host-guest doping systems

The host-guest doping strategy is a widely adopted approach for constructing RTP materials.^{90,105–110} It disperses guest chromophore within a rigid host matrix to regulate intermolecular interactions and triplet excitons dynamics, facilitating RTP emission. This strategy is also crucial for the development of CP-RTP materials (Figure 6A).

Encapsulating chiral chromophores within a solid matrix is a proven strategy to realize CP-RTP. In 2016, Hirata et al. reported the first metal- and heavy-atom-free CP-RTP in air by doping enantiomers of *N*, *N'*-dimethyl-1, 1'-binaphthylidamine (DMBDA) into a β -estradiol matrix (Figure 6B).¹¹¹ The doped enantiomeric material exhibited blue CPF and yellow CP-RTP, with corresponding $|g_{\text{lum}}|$ values of 4.5×10^{-4} and 2.3×10^{-3} , respectively. The CP-RTP emission exhibited a lifetime of 0.67 s and Φ_p of 2.3%. In this study, β -estradiol functioned as an effective rigid matrix for enabling CP-RTP emission, underscoring its potential as a high-performance host material. Subsequently, Hideki Fujiwara and colleagues investigated a class of novel double heterohelicene materials, namely compounds 1 and 2, which exhibited strong phosphorescence at 77 K.¹¹² Upon doping into a β -estradiol matrix, these compounds exhibited red and orange CP-RTP, respectively. The enantiomers

of compound 2 were successfully separated by chiral high-performance liquid chromatography (HPLC) employing a chiral silica column, and exhibited mirror-image CPL signals in the β -estradiol host. The resulting CP-RTP demonstrated a lifetime of up to 0.16 s and a $|g_{\text{lum}}|$ of up to 5×10^{-3} .

Embedding achiral chromophores into chiral host matrices also represents an effective and versatile strategy for constructing CP-RTP materials. Xing et al. successfully developed a series of host-guest CP-RTP complexes by employing the steroid compound progesterone (Pg) as the chiral host and various aromatic molecules as guests, through a combination of grinding and slow solvent evaporation.¹¹³ In these systems, Pg provides a rigid chiral microenvironment engages in CH- π interactions and hydrogen bonding with the guest molecules, resulting in either channel-type or cavity-type inclusion complexes. The intrinsic chirality of Pg is transferred to the aromatic guests via chiral induction, thereby enabling full-color photoluminescence and CP-RTP.

The construction of supramolecular helical architectures through molecular self-assembly provides an effective strategy for realizing CP-RTP. In 2021, Xing et al. covalently linked a naphthalimide moiety to chiral fragments via amine substitution of bromine atoms, leading to the formation of supramolecular helical assemblies from initially achiral monomers and inducing solid-state CPL emission (Figure 6A).¹¹⁴ Under excitation wavelengths below 320 nm, efficient ISC was induced, resulting in red CP-RTP with a lifetime of up to 5.38 ms, a PLQY of 8.98%, and a $|g_{\text{lum}}|$ value in the range of 1×10^{-3} to 5×10^{-3} . At excitation wavelengths above 320 nm, blue fluo-

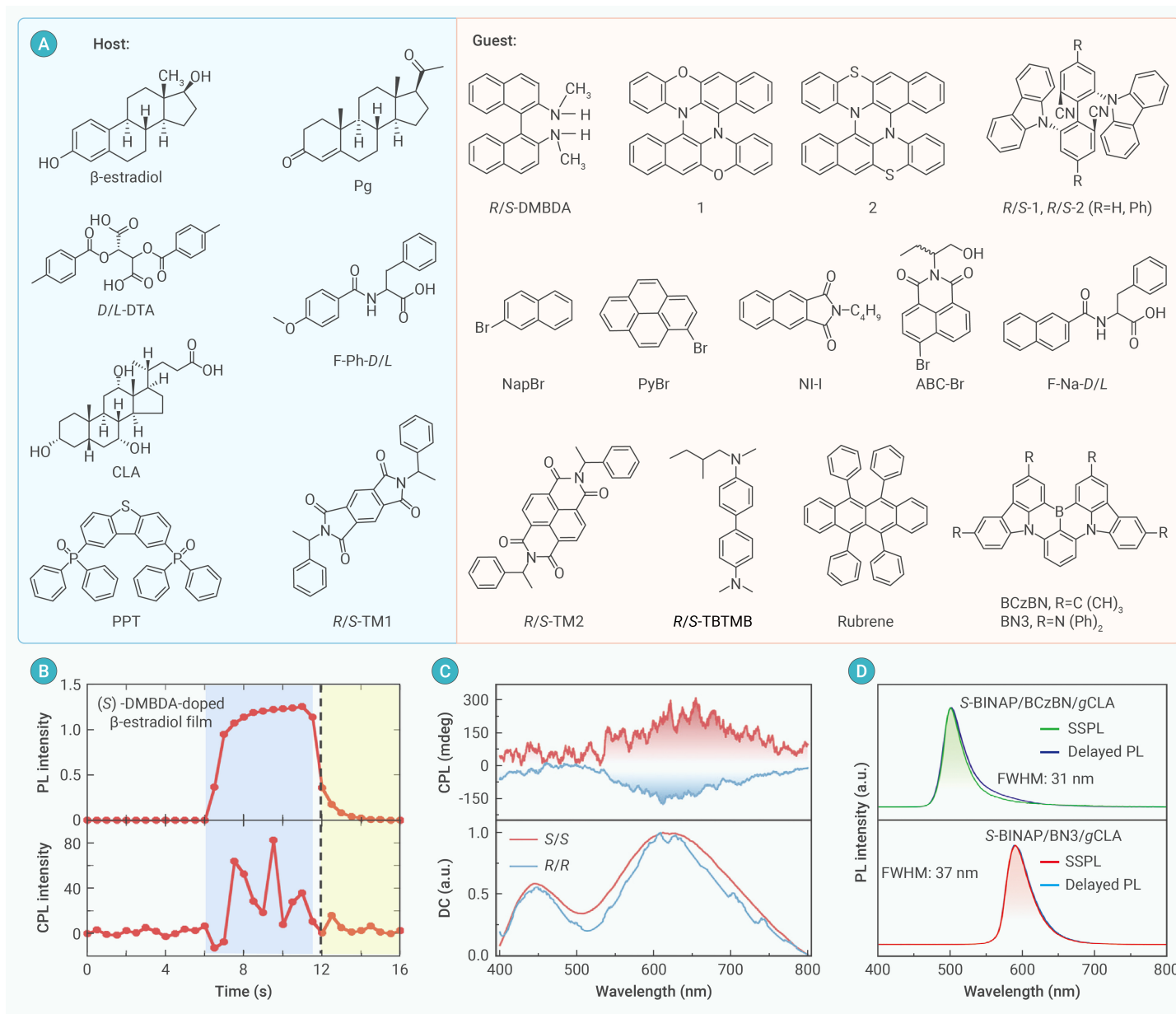


Figure 6. CP-RTP materials constructed from host-guest doping systems (A) Molecular structures of CP-RTP materials based on host-guest doped small-molecule systems. (B) CPL spectra of (S)-DMBDA-doped β -estradiol film. Reproduced with permission. Copyright 2016, American Chemical Society.¹¹¹ (C) CPL spectra of S-TM1/S-TM2 and R-TM1/R-TM2. Reproduced with permission. Copyright 2024, Wiley.¹²¹ (D) Delayed PL spectra of S-BINAP/BCzBN/gCLA and S-BINAP/BN3/gCLA. Reproduced with permission. Copyright 2025, Wiley.¹²⁴

rescence became dominant, while RTP and CPL emissions were completely suppressed, enabling reversible modulation of photophysical properties as a function of excitation wavelength. This study provides an effective strategy for constructing color-tunable CP-RTP materials with UV-detectable switching behavior.

Chen and co-workers proposed an "exciton hourglass" model and developed a series of axially chiral CP-RTP materials (Figure 6A), which exhibited ultralong-lived blue RTP accompanied by CPL characteristics.¹¹⁵ The enantiomers displayed nearly ideal mirror-image symmetry in their CPL spectra, with maximum $|g_{\text{lum}}|$ values reaching 4.4×10^{-3} . Remarkably, when these chiral molecules were doped into nematic liquid crystal (NLC) matrices as chiral inducers, the $|g_{\text{lum}}|$ values significantly increased, reaching up to ± 0.34 . Cai et al. reported a series of near-infrared (NIR) CP-RTP materials featuring tunable emission colors and prolonged lifetimes, achieved by doping achiral NIR-phosphorescent guest molecules into chiral host matrices with high crystallinity.¹¹⁶ (-)-di-p-toluoyl-L/D-tartaric acid (L/D-DTA) were employed as chiral hosts, providing robust chirality and rigid crystalline environments that stabilize triplet excitons and induce chiral phosphorescence. The resulting

materials exhibited color-tunable CP-RTP ranging from green to yellow and red, with emission wavelengths extending up to 720 nm in the NIR region, $|g_{\text{lum}}|$ values up to 1.14×10^{-2} , and lifetimes of up to 2.14 s.

Due to the conformation-dependent modulation of RTP properties, RTP materials are well-suited for chiral recognition.^{117–119} Zhang and co-workers proposed a more broadly applicable strategy for CP-RTP-based chiral recognition.¹²⁰ Using a benzamide derivative of L-phenylalanine as a single-molecule solid-state sensor and employing a host-guest doping approach, they successfully distinguished natural L-amino acids from their D-enantiomers based on the distinct CP-RTP signals observed in the doped systems. In another attempt, Chen et al. designed and synthesized a pair of structurally similar enantiomeric chiral blue hosts (R/S-TM1) and red guests (R/S-TM2).¹²¹ When the host and guest shared the same chiral configuration, the system exhibited strong red CP-RTP emission; in contrast, blue CP-RTP emission was observed when the chiral configurations are mismatched. The system was further applied to chiral recognition by doping R-TM2 with varying enantiomeric excess (ee) into S-TM1. A linear increase in RTP intensity at 612 nm was observed with decreasing ee of R-TM2, providing an effective and highly

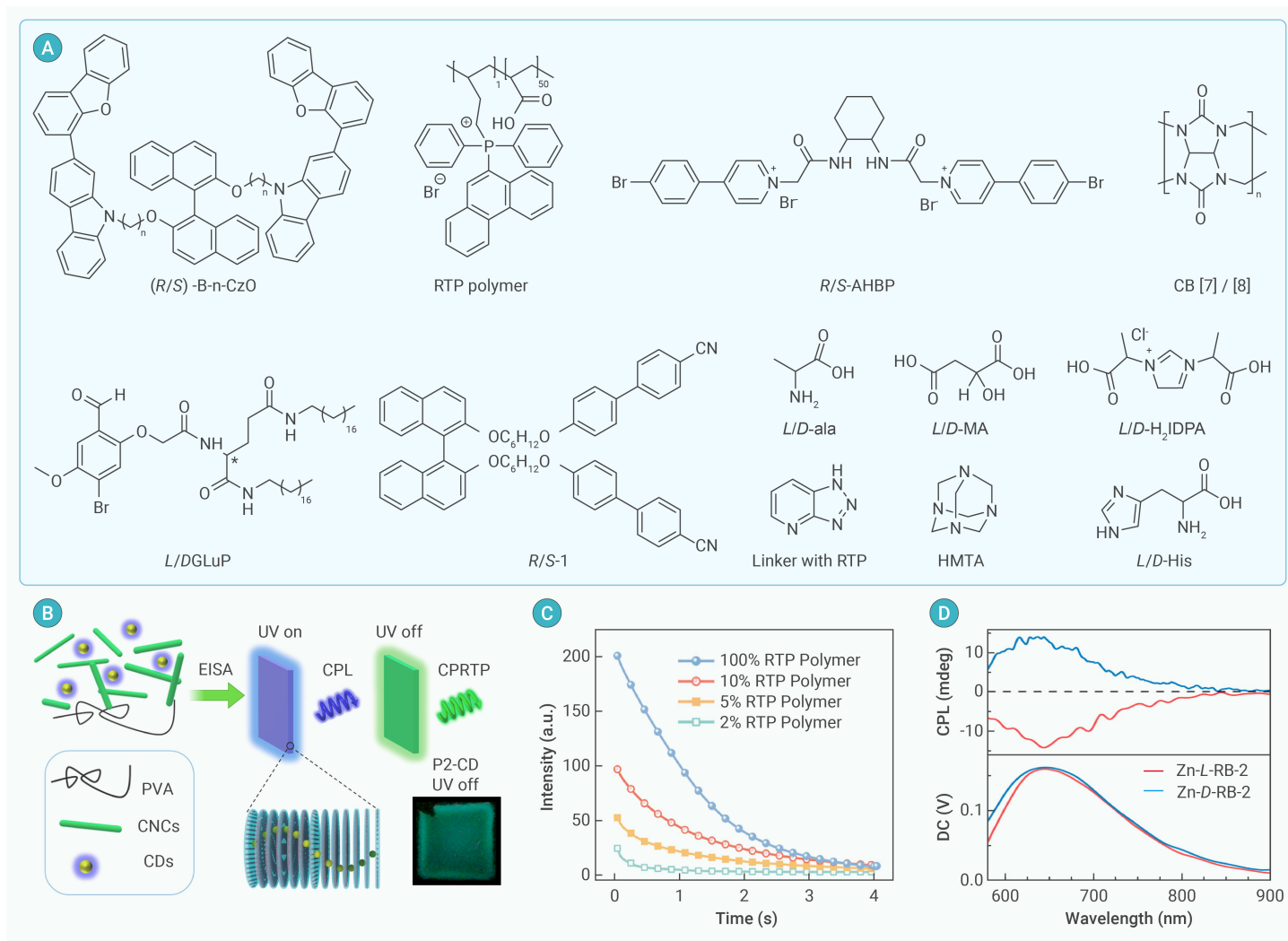


Figure 7. CP-RTP materials assembled from supramolecular systems (A) Molecular structures of CP-RTP materials based on supramolecular assembly systems. (B) Preparation of hybrid chiral photonic films through evaporation-induced self-assembly (EISA). Reproduced with permission. Copyright 2020, American Chemical Society.¹³⁹ (C) Time-dependent afterglow intensity of room-temperature phosphorescent-chiral helical superstructure films with varying RTP polymer contents. Reproduced with permission. Copyright 2024, Wiley.¹³³ (D) CPL spectra of Zn-L/D-RB-2 supramolecular glasses. Reproduced with permission. Copyright 2023, Nature Publishing Group.¹⁴⁵

sensitive approach for enantiomeric discrimination (Figure 6C).

In 2025, Huang et al. proposed an effective strategy by integrating chiral chains with the well-known donor N,N,N',N'-tetramethylbenzidine (TMB) to construct chiral donors, thereby generating chiral exciplex materials with ultralong-lived and color-tunable circularly polarized organic long persistent luminescence (CP-OLPL) properties.¹²² The resulting chiral exciplex exhibited intense green CP-OLPL with a duration of up to 1.5 hours and a $|g_{\text{lum}}|$ value of 4.5×10^{-3} . Furthermore, by introducing rubrene fluorophore and employing synergistic singlet-singlet and chiral energy transfer processes, orange-red CP-OLPL with a duration exceeding 1 hour was achieved. These multicolor CP-OLPL materials were successfully applied in chiral afterglow display, multi-level information encryption, and afterglow lighting.¹²³ Chen et al. proposed a strategy for designing bright, efficient, and narrowband organic circularly polarized hyperafterglow (CP-hyperafterglow) materials by incorporating conjugated energy donors with CPL and multi-resonance energy acceptors within a rigid host matrix.¹²⁴ Cholic acid (CLA) was utilized as a rigid host matrix, while chiral phosphine-containing BINAP derivatives and multi-resonance thermally activated delayed fluorescence (MR-TADF) molecules served as guest emitters. This host-guest system enabled multicolor CP-hyperafterglow with long lifetimes (120–770 ms), high PLQY ($\approx 90\%$), small full-width at half-maximum (31–39 nm) (Figure 6D), and notable $|g_{\text{lum}}|$ ($\approx 10^{-3}$) via Förster resonance energy transfer (FRET) and chiral transfer. In host-guest doping systems, the CP-RTP performance relies on the synergistic interaction between rigid host matrices and emissive guest molecules. Rigid hosts and well-matched host-guest interactions can effectively suppress non-radiative

decay and stabilize triplet excitons, thereby prolonging phosphorescence lifetime and enhancing Φ_p and $|g_{\text{lum}}|$. Furthermore, by precisely tuning the intermolecular distance and interactions between host and guest components, multifunctional CP-RTP properties can be achieved.

Supramolecular assembly systems

Supramolecular assembly has demonstrated unique advantages in the construction of CP-RTP materials (Figure 7A).^{125–129} In 2020, Liu et al. reported the fabrication of hybrid chiral photonic films with CP-RTP properties via an evaporation-induced self-assembly (EISA) strategy (Figure 7B).¹³⁰ A prolonged CP-RTP lifetime of up to 103 ms and a maximum phosphorescence $|g_{\text{lum}}|$ of 0.47. In 2022, Xu et al. developed an ultralong CP-RTP material based on left-handed chiral nematic nanoporous silica films via EISA.¹³¹ By tuning the overlap between the PBG and the phosphorescence band, the handedness of CP-RTP was controlled: right-handed emission ($g_{\text{lum}} = -0.130$, $\tau = 1.094$ s) was achieved with overlap, while left-handed emission ($g_{\text{lum}} = 0.093$, $\tau = 0.949$ s) was obtained near the PBG blue edge. This approach, based on natural templates and defect luminescence, provides a low-cost route to tunable, ultralong CP-RTP materials.

The assembly of liquid crystal materials is often an effective approach for achieving high g_{lum} values in chiral systems. In 2023, Xie et al. designed and synthesized a series of compounds, (R/S)-B-n-CzO, which incorporate chiral binaphthol and a carbazole-dibenzofuran emissive unit.¹³² These compounds were doped into the liquid crystalline monomer LC-242 to construct liquid crystalline polymer networks via self-assembly and UV-induced photopoly-

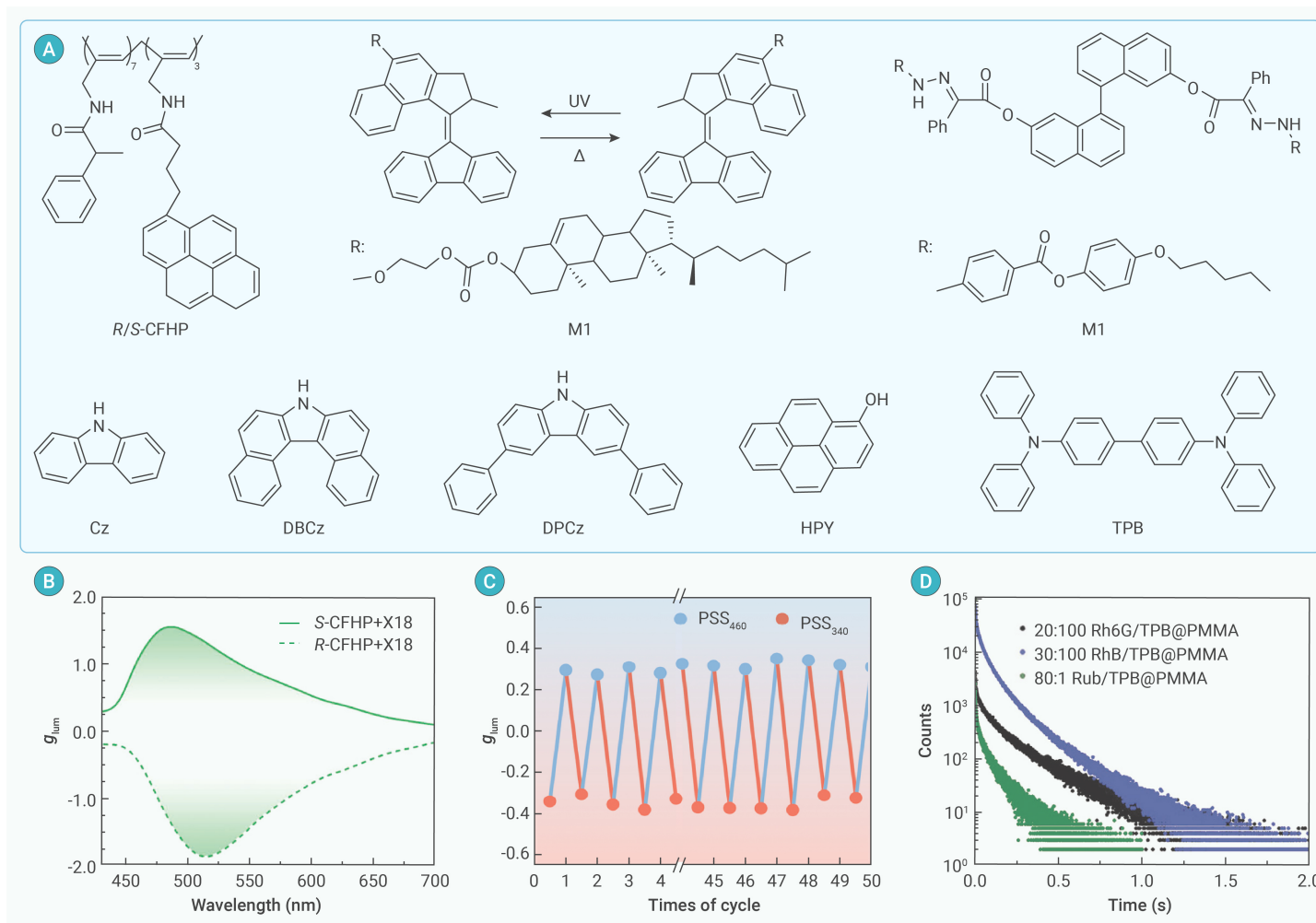


Figure 8. CP-RTP materials integrated in multilayer systems (A) Molecular structures of CP-RTP materials based on multilayer systems. (B) The g_{lum} of N⁺-LCs doped with R/S-CFHP and X18. Reproduced with permission. Copyright 2023, Wiley.¹⁴⁶ (C) Cycling test of g_{lum} values under 460 nm and 340 nm excitation.¹⁵⁴ (D) Lifetime decay profiles of multi-color CP-RTP films. Reproduced with permission. Copyright 2025, Wiley.¹⁵⁵

merization. The resulting crosslinked networks provided structural rigidity that stabilized triplet excitons, enabling RTP with lifetimes ranging from 0.77 to 1.08 s. Moreover, the networks exhibited CP-RTP behavior with $|g_{lum}|$ ranging from 0.013 to 0.098. In 2024, Zhao et al. proposed an effective strategy by integrating RTP polymers with chiral helical superstructures to construct room-temperature phosphorescent-chiral helical superstructure (RTP-CHS) system (Figure 7C).¹³³ The resulting material exhibited ultralong CP-RTP with a phosphorescence lifetime of 735 ms and a remarkably high $|g_{lum}|$ of up to 1.49. Thermo-responsive studies revealed optimal afterglow intensity at 45°C with reversible behavior.

Ma et al. proposed a straightforward host-guest strategy to construct water-soluble, helical supramolecular polymers exhibiting CP-RTP (Figure 7A).¹³⁴ A two-branched chiral monomer, AHBP, was designed, whose terminal groups can thread into the cavity of cucurbit[8]uril (CB[8]) to form head-to-tail helical supramolecular polymers (SPs). Optical studies revealed that upon addition of CB[8] to the AHBP solution, the system transitioned from pure fluorescence to predominantly RTP emission, characterized by a new phosphorescence peak at 510 nm with a lifetime of 0.489 ms, and a Φ_p of 4.0%. Enantiomeric monomers (S)-AHBP and (R)-AHBP were assembled separately with CB[8] to afford (S)-SP and (R)-SP, which exhibited opposite helical handedness. The resulting supramolecular polymers displayed mirror-image CD and CPL signals with a high $|g_{lum}|$ of 2.2×10^{-3} . In 2024, Kim et al. designed and synthesized two purely organic phosphors, L/GluP, featuring chiral centers, long alkyl chains, and amide linkages in their side chains.¹³⁵ In a solvent-induced self-assembly process, gradual addition of distilled water into dimethyl sulfoxide solutions of L/GluP or D/GluP led to a hierarchical transition from disordered aggregates to nanofibers (NFs), then helical

nanofibers, and finally to nanobundles (NBs), accompanied by a photophysical evolution from blue fluorescence to green CP-RTP. CPL spectra further confirmed that the helical NFs and NBs of L/GluP and D/GluP exhibited both fluorescent and phosphorescent CPL signals with $|g_{lum}|$ on the order of 10^{-3} . This study demonstrates a successful strategy for constructing self-assembled supramolecular nanostructures with tailored photophysical properties. In 2024, Cheng et al. introduced a design strategy for CP-RTP materials based on chiral co-assembled liquid crystalline copolymers incorporating photoinduced radicals.¹³⁶ Co-assembling three achiral copolymers (P1, P2, P3) with a chiral inducer (R/S-I) yielded (R/S-I)_m-(P1/P2/P3)_n systems, in which P2 and P3 formed a nematic liquid crystalline phase, while P1 remained amorphous. Remarkably, the chiral co-assembled thin film (R-I)_{0.23}-(P2)_{0.77} exhibited excellent CP-RTP performance under UV irradiation, featuring an emission peak at 592 nm, a $|g_{lum}|$ of 7.89×10^{-2} , and a Φ_p of 12.00%. These results are attributed to the formation of helical nanofiber structures and the stabilization of photoinduced radical ion pairs through photothermal synergy.

A series of CP-RTP materials based on chiral coordination assembly polymers has been reported. In 2022, Ma et al. designed a nitrogen-containing small molecule, 1H-1,2,3-triazolopyridine (Trzpy), and constructed a pair of chiral coordination polymers, L/DCF-10, via reticular chemistry by co-assembling Trzpy with L/D-alanine and Zn²⁺ (Figure 7A).¹³⁷ L/DCF-10 exhibited unique photophysical properties, including excitation-dependent RTP. As the excitation wavelength varied from 290 to 420 nm, the afterglow color gradually shifted from blue-green to orange. Moreover, these materials demonstrated CPL transitioning from fluorescence to phosphorescence, with significant excitation-dependent CPL characteristics. Under 340 nm excitation, the $|g_{lum}|$ of L/DCF-10 reached 1.8×10^{-3} and 2.4×10^{-3} , respectively. In 2024, Ding et al.

Table 1. Photophysical properties of organic CP-RTP materials.

Strategy	Samples	λ/nm	$\Phi/\%$	τ	$ g_{\text{lum}} $	Ref.
Organic crystals	TPA-(<i>R/S</i>)-PEA	500	9.35	862 ms	1.5×10^{-2}	47
	<i>R/S</i> -DNP	495	43.2	22.81 ms	0.13	48
	<i>R/S</i> -1-nea/TCNB	508	31	28.48 ms	0.065	49
	(<i>R/S</i>)-SEGPPOS	505	-	303 ms	2.1×10^{-3}	50
	<i>R/S</i> -COOCz	550	-	0.6 s	2.3×10^{-3}	51
	(<i>R,R</i>)/(<i>S,S</i>)-DAACH	470	-	587 ms	2.3×10^{-3}	52
	<i>R/S</i> -CzCOPEA	528	12.8	908.7 ms	5.6×10^{-3}	53
	SPCzT	539	-	419.8 ms	-	54
	<i>R/S</i> -BINAP	650	0.09	12 ms	1.6×10^{-3}	55
	(<i>R,R</i>)/(<i>S,S</i>)-Cy(F ₂ Pht) ₂	530	6	0.3 s	-	56
	<i>R/S</i> -An-NH	550	14.71	155 ms	-	57
	<i>R_p/S_p</i> -PCP-PyCNCz	550	1.24	528 ms	1.2×10^{-2}	58
	Chol-C6-DF	390	20.2	1.11 s	0.11	62
	(<i>R/S</i>)-PNA	540	30.6	0.68 s	9.4×10^{-3}	68
	<i>R/S</i> -BPNAP	574	14.8	109.1 ms	0.84×10^{-3}	70
	<i>R/S</i> -PAMBNA200	545	26.61	1078 ms	1.06×10^{-2}	71
	PAMCD/CN	500	6.32	665 ms	3.54×10^{-3}	69
	CNSF	520	1.54	331 ms	0.34	72
	Poly(MDFM6C(0.13)-co-M6Chol(0.87))	520	-	104 ms	1.3×10^{-3}	74
	DFM(0.8)-Chol(0.2)	554	11.4	309 ms	5.4×10^{-3}	75
Polymers	<i>R/S</i> -COOHCz@PVA	416	25	3.35 s	0.05	80
	(<i>R</i>)-1/PVA	500	14.8	564.5 ms	0.12	81
	CNC-PVA-AF	507	12.23	824 ms	0.32	82
	<i>R/S</i> -BNDHP/PVA	501	14.23	1026 ms	8.44×10^{-3}	83
	(<i>R/S</i>)-Binol-PSeA/PS	210	27	40 ms	9.32×10^{-3}	87
	(<i>RR</i>)/(<i>SS</i>)-BrPmDI/PMMA	500	18	31.5 ms	4×10^{-3}	88
	p(phNA-co-BrNpA)-PMMA	586	-	4.53 ms	1.86×10^{-2}	89
	Pa-R/PVP	530	13.6	1017 ms	2.1×10^{-3}	92
	<i>R/S</i> -VP	530	-	780.5 ms	0.8×10^{-3}	92
	<i>R/S</i> -PAMCOOCz	414	28.6	3 s	1.02×10^{-2}	97
	S-BP ₆₀	488	-	199 s	3×10^{-2}	98
	CPDs _{D-0.8} @PVA	490	-	57.54 ms	2.43×10^{-4}	99
	S/SBAD	548	9.7	895 ms	0.014	103
	NtCOOLi/CBtCOONa	500-700	-	936 ms	1.93×10^{-2}	104
	(<i>R/S</i>)-DMBDA/ β -estradiol	506	2.3	0.67 s	2.3×10^{-3}	111
	2/ β -estradiol	594	30	0.16 s	5×10^{-3}	112
	PyBr@Pg	620	-	2.7 ms	10^{-3}	113
	MB-Br/TCNB	430, 560	-	5.38 ms	5×10^{-3}	114
	1, 2-NLCs	500	-	5.5 s	0.34	115
Host-guest doping systems	NI-I@DTA	500	7.58	2.14 s	8.4×10^{-3}	116
	<i>L@L</i> , <i>D@D</i>	526	-	637 ms	-	120
	<i>R/R</i> , <i>S/S</i>	612	-	32.68 ms	4.47×10^{-2}	121
	<i>R/S</i> -TBTMB/PPT	525	-	1.5 h	4.5×10^{-3}	122
	BINAP/BCzBN/gCLA	503	~90	770 ms	3.5×10^{-3}	124

(Continued)

Table 1. Photophysical properties of organic CP-RTP materials.

Strategy	Samples	λ /nm	Φ /%	τ	$ g_{lum} $	Ref.
Supramolecular assembly systems	P2-CD	480	0.16	103 ms	0.47	130
	CNS-PBG	440	-	1.094 s	0.13	131
	(<i>R/S</i>)-B-n-CzO/LC-242	545	52.97	1.08 s	0.098	132
	RTP-CHS	490	24.08	735 ms	1.49	133
	(<i>R/S</i>)-AHBP/CB[8]	510	4	0.489 s	2.2×10^{-3}	134
	<i>L</i> /DGLuP	407	4.1	14 ms	1.4×10^{-3}	135
	(<i>R</i>)-I _{0.23} -(P2) _{0.77}	592	12	1.16 ms	7.89×10^{-2}	136
	<i>L</i> /DCF-10	550	9.88	153 ms	2.4×10^{-3}	137
	<i>L</i> /DCF-13	450	7.35	137.4 ms	5×10^{-3}	138
	<i>L</i> /D-1	520	8.66	0.17 s	2.68×10^{-3}	139
	<i>L</i> /D-H-M-AC	606	-	141.2 ms	8.7×10^{-3}	144
	Zn- <i>L</i> /D	465-555	-	356.7 ms	8.5×10^{-3}	145
	DPCz-PVA/N ⁺ -LC-CFHP	482	-	8 s	1.57	146
Multi-layer systems	DPCz-PVA/CLC	482	1.13	2431 ms	1.43	147
	C-dots-PVA/PSA	520	5	1.23 s	1.2×10^{-2}	148
	NP-CPDs-PVA/LC	523	9.74	1.25 s	1.09	152
	P1-PVA/SHS-M1	500-700	24	805 ms	1.38	153
	P1-PVA/5CB-M1	518	9.72	823 ms	0.39	154
	<i>R/S</i> -CLC-TPB	520-578	66.42	125 ms	1.6	155

employed *L/D*-malic acid as a chiral source and 2,6-bis(1-imidazolyl)pyridine (BIP) as the phosphorescent ligand to construct a pair of chiral coordination polymers, *L*/DCF-13.¹³⁸ Upon UV excitation, both materials emit blue light, followed by green afterglow after the light was turned off. The phosphorescence lifetimes of *L*/DCF-13 reached 132.45 ms and 137.36 ms, respectively, along with improved quantum yields. Their CPL spectra showed near-mirror-image symmetry, with $|g_{lum}|$ around 5×10^{-3} at 450 nm. In 2025, Zhang et al. further advanced this strategy by designing a pair of 3D CMOF enantiomers, *L*/D-1, through self-assembly of Zn(II) with 2,2'-biimidazole as a phosphorescent ligand and carboxyl-functionalized chiral imidazolium salts as chiral sources.¹³⁹ Under daylight, the materials appear pale yellow, while under UV irradiation they emit nearly white light, with yellow afterglow lasting up to 6 s after the excitation is turned off. Strong RTP emission was observed under 375 nm excitation, with phosphorescence lifetimes of 0.17 s at room temperature and 0.40 s at low temperature. CPL measurements revealed mirror-image circularly polarized emission, and excitation-wavelength-dependent switching between CPF and CP-RTP was achieved, with $|g_{lum}|$ of 7.57×10^{-3} and 2.68×10^{-3} , respectively.

Yan et al. have made notable progress in developing supramolecular glasses (SMGs)¹⁴⁰⁻¹⁴³ with CP-RTP properties. In 2023, they reported the preparation of a metal-free SMG at room temperature via hydrogen-bond-driven self-assembly from *L*-Histidine (*L*-His) and hexamethylenetetramine in solution.¹⁴⁴ The resulting macroscale SMG exhibited color-tunable RTP with a decay lifetime of up to 141.2 ms and displayed CPL with a high $|g_{lum}|$ of up to 8.7×10^{-3} . The phosphorescence emission was both excitation-wavelength- and temperature-dependent. Subsequently, they developed a series of Zn-*L*-His-based SMGs using an EISA approach. Optical characterization revealed that the SMGs exhibited triple-mode ultralong RTP that was highly dependent on solute concentration, temperature, and excitation wavelength.¹⁴⁵ Through doped with RB, multicolor CP-RTP emission from blue to red was achieved (Figure 7D), with a maximum $|g_{lum}|$ factor of 9.5×10^{-3} and a prolonged lifetime of up to 356.7 ms. Therefore, CP-RTP in supramolecular assembly systems depends on the ordered structures guided by intra/intermolecular non-covalent interactions. Ordered architectures constructed by hydrogen bonding, metal coordination, and liquid crystal-induced alignment precisely suppress

non-radiative decay, which enable the modulation of excited-state dynamics, concurrently and amplification of chiral perturbations, thereby enabling enhanced RTP efficiency, extended emission lifetimes, and significantly improved CPL properties.

Multi-layer systems

Significant progress has also been achieved in CP-RTP materials based on multilayer architectures (Figure 8A). CP-RTP materials have been widely applied across diverse fields; however, achieving high g_{lum} values remains a major challenge. To overcome this limitation, Deng and colleagues developed a series of multilayer CP-RTP materials.¹⁴⁶ They doped chiral fluorescent helical polymers (CFHPs) into a nematic liquid crystal (5CB) to create emissive N⁺-LCs. Owing to the high helical twisting power of CFHPs, the selective reflection band of the N⁺-LCs was precisely tuned to overlap with their emission band, resulting in nearly pure CPL with an outstanding g_{lum} of 1.87 at 9 wt% doping (Figure 8B). Furthermore, by incorporating achiral luminophores, multicolor CPL-active N⁺-LCs were successfully achieved. Using a bilayer architecture, they further achieved CP-RTP emission lasting nearly 20 s with a $|g_{lum}|$ as high as 1.57. In 2024, the group fabricated cholesteric liquid crystal (CLC) films via photopolymerizing of a mixture containing polymerizable nematic liquid crystal monomers (C6M, RM105, and RM23), a photoinitiator (Irg651), and a chiral dopant (CHP).¹⁴⁷ By integrating the CLC films with RTP films into a bilayer structure, green CP-RTP emission with a $|g_{lum}|$ of 1.39 was achieved. Subsequently, multicolor RTP films (based on Cz-, DBCz-, and HPY-doped PVA) were combined with CLC films to construct full-color bilayer CP-RTP systems. In addition, the group advanced their work by constructing a CP-RTP bilayer composite film composed of carbon dots (C-dots) and chiral helical polymers.¹⁴⁸ RTP-active C-dots with a lifetime of 1.23 s were synthesized via a microwave-assisted method, showing blue fluorescence at 445 nm and green RTP at 520 nm. By spin-coating chiral polyacetylene (PSA) on a C-dots/PVA layer, the composite films exhibited both high-efficiency CPF ($|g_{lum}|=0.14$) and CP-RTP ($|g_{lum}|=0.012$) emissions, owing to the chiral filtering effect of PSA.

CLC polymer films represent highly effective media for enhancing the g_{lum} values of CP-RTP materials.¹⁴⁹⁻¹⁵¹ Guo et al. prepared nitrogen- and phospho-

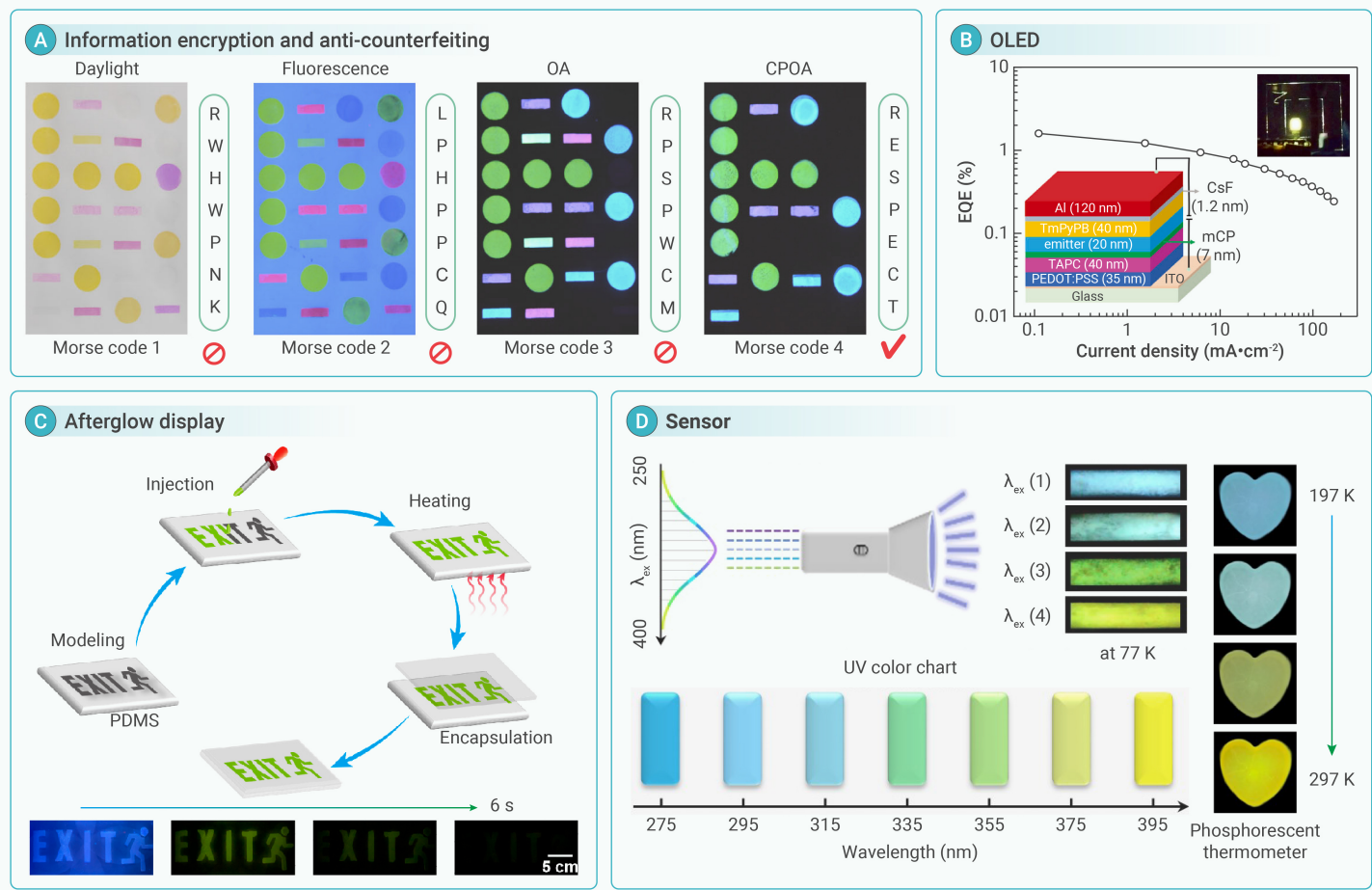


Figure 9. Applications of CP-RTP materials (A) Schematic and photographic representation of multiplex Morse code generation *via* screen-printing. Reproduced with permission. Copyright 2024, Nature Publishing Group.³⁷ (B) The performance of organic light emitting diodes (OLEDs) based on CP-RTP material. Reproduced with permission. Copyright 2020, Nature Publishing Group.⁵⁵ (C) Fabrication process and afterglow photographs of the emergency route signage. Reproduced with permission. Copyright 2021, American Chemical Society.⁵⁸ (D) The L-H-M glass-based phosphorescent thermometer. Reproduced with permission. Copyright 2023, Wiley.¹⁴⁴

rus-doped carbonized polymer dots (NP-CPDs) *via* a one-pot hydrothermal reaction.¹⁵² A bilayer CP-RTP photonic composite film was constructed by dispersing NP-CPDs into a PVA matrix to form the RTP emissive layer, which was then coupled with a CLC polymer film. Through fine-tuning the helical pitch of the cholesteric polymer, the reflection band was modulated to overlap with the RTP emission band of the NP-CPDs, resulting in CP-RTP emission with a high $|g_{\text{lum}}|$ of 1.09. Moreover, the green afterglow persisted for over 8.0 s, achieving visually perceptible CP-RTP emission with both a high g_{lum} and prolonged lifetime.

Zhao's group has also conducted a series of studies on the development of multilayer-structured CP-RTP materials. In 2024, they constructed an innovative bilayer film consisting of a soft helical superstructure (SHS) layer embedded with light-driven molecular motors (M1) and an RTP polymer layer.¹⁵³ Under 405 nm UV irradiation, the M1 molecules undergo photoisomerization, thereby altering the helical twisting power of the SHS and inducing a redshift in the reflection band. Consequently, the $|g_{\text{lum}}|$ values decreased from 1.38 to 0.6. Remarkably, this process was fully reversible and could be cycled over 20 times without performance loss, offering a new strategy for multidimensional optical signal modulation. Subsequently, the team constructed a chiral-switchable CP-RTP system composed of an SHS layer doped with a photo-switchable hydrazone molecule and an RTP polymer layer.¹⁵⁴ Under alternating irradiation at 460 nm and 340 nm, photo-switchable hydrazone molecule effectively controlled reversible chirality inversion (Figure 8C). This photoinduced conformational change triggered a helical inversion in the SHS, enabling reversible modulation of the CP-RTP g_{lum} between +0.30 and -0.35. Impressively, this switching behavior remained fatigue-resistant over 50 cycles. Furthermore, the team developed a bilayer-assembled material (R/S-CLC-TPB) by integrating TPB@PMMA RTP films with CLCs possessing selective reflection properties.¹⁵⁵ This material not only exhibited ultralong CP-

RTP emission with a lifetime of up to 125 ms and a remarkably high $|g_{\text{lum}}|$ value of 1.6, but also enabled tunable afterglow emission through the introduction of a triplet-sensitized FRET strategy (Figure 8D), achieving a color shift from green to orange while maintaining high $|g_{\text{lum}}|$ and brightness.

Therefore, in multilayer systems, precise regulation and synergistic integration of the phosphorescent and chiral layers enable high-performance CP-RTP. The phosphorescent layer enhances RTP efficiency and lifetime by incorporating rigid matrices that suppress non-radiative decay, while the chiral layer modulates chiral emission through tuning helical pitch or incorporating photo-responsive molecules. These features collectively confer multidimensional and controllable optical responses to CP-RTP systems.

A summary of the reported CP-RTP materials and their performance characteristics is provided in Table 1. As shown in the Table 1, high-performance CP-RTP materials should simultaneously exhibit long τ , high Φ_p , and large g_{lum} . Extended τ and high Φ_p are typically achieved through efficient ISC to generate a substantial population of triplet excitons, along with the construction of rigid molecular environments to suppress non-radiative decay. g_{lum} enhancement can generally be realized by introducing CLCs or constructing supramolecular helical architectures to amplify chiral optical signals. Overall, the integration of multiple design strategies to synergistically improve τ , Φ_p , and g_{lum} represents an effective approach toward the development of high-performance CP-RTP materials.

Applications of CP-RTP

CP-RTP materials uniquely combine long-lived emission with chiral luminescence, alongside advantages such as photostability, biocompatibility, and structural tunability. These features make them ideal candidates for diverse applications, including dual-mode information encryption, anti-counterfeiting, afterglow displays, organic light-emitting diodes (OLEDs), and sensors. In the

following sections, representative CP-RTP-based optoelectronic applications are discussed to highlight their functional potential.

Information encryption and anti-counterfeiting. With the rapid advancement of the digital era, massive volumes of data are transmitted and stored on a daily basis. Ensuring data confidentiality and authenticity through encryption and anti-counterfeiting has become increasingly critical. CP-RTP materials, featuring unique chiral luminescence and persistent afterglow, have demonstrated great potential for multilevel information encryption and anti-counterfeiting through rational molecular design and encoding strategies, thereby offering a promising avenue for future information security technologies. Huang et al. exploited the ultralong chiral lifetime, full-color tunability, and water-processability of the CP-RTP materials they developed to fabricate multilevel Morse codes with three-dimensional encryption features-based on CPL, emission color, and lifetime (Figure 9A).⁹⁷ By selecting various emissive materials as water-soluble anti-counterfeiting inks, and applying screen printing techniques, they prepared complex CPL-active patterns. Under daylight, 254 nm UV irradiation, and after UV light is switched off, distinct Morse code signals appear at each stage. With CPL analysis, the authentic three-dimensional encrypted CP-RTP Morse code can be decoded, enabling advanced multilevel information encryption and anti-counterfeiting applications.

OLEDs. CP-RTP materials intrinsically combine CPL and RTP, enabling the direct emission of CP-RTP without the need for external optical components such as polarizers and quarter-wave plates typically required in conventional circularly polarized OLEDs. This unique feature simplifies device architecture and reduces energy consumption, offering distinct advantages in OLED applications. Moreover, the phosphorescence mechanism allows for the utilization of both singlet and triplet excitons, thereby achieving higher exciton utilization and internal quantum efficiency. CP-RTP materials thus present a promising pathway toward high-performance, low-power-consumption, and structurally simplified OLED devices, particularly suitable for applications in flexible displays, information encryption, and high-contrast visual outputs. For example, Zhu et al. developed phosphorescent OLEDs based on *R*-BINAP, *S*-BINAP, and *rac*-BINAP, in which voltage-dependent tunable emission intensities of both fluorescence and phosphorescence were observed in the electroluminescence spectra.⁵⁵ Following optimization, the device exhibited white-light emission with a CIE coordinate of (0.37, 0.37), indicating balanced color output, and demonstrated promising performance with an external quantum efficiency of 1.59% (Figure 9B).

Afterglow display. With the growing demand for advanced optical materials in next-generation display technologies, the development of afterglow display devices with long-persistent luminescence has attracted considerable attention. Among them, CP-RTP materials, owing to their intrinsic chirality and ultralong afterglow emission, offer an ideal platform for the construction of rewritable and intelligent visual display systems.^{156,157} In 2021, Zhao et al. investigated the potential of the synthesized copolymers (*R*)-PNA and (*S*)-PNA for flexible afterglow display systems, leveraging their mechanical flexibility, optical transparency, and prolonged organic phosphorescence.⁶⁸ As shown in Figure 9C, an emergency route sign was fabricated by injecting the copolymer aqueous solution into a PDMS mold, followed by in situ solidification and encapsulation. Upon 254 nm UV irradiation, the sign emitted bright blue light, and after the UV source was turned off, a yellow afterglow lasting about 6 s remained clearly visible to the naked eye at room temperature. These results demonstrate promising potential for flexible afterglow display applications, especially in emergency signage and low-power visual indicators.

Sensor. CP-RTP materials exhibit distinct advantages in the field of optical sensing. On the one hand, their persistent luminescence is highly sensitive to external stimuli such as temperature, oxygen, humidity, and excitation wavelength, enabling real-time visual monitoring of environmental changes. On the other hand, their inherent CPL allows for multidimensional information output, enhancing both detection accuracy and security. The supramolecular glass L-H-M developed by Yan et al. features both excitation- and temperature-dependent persistent luminescence, offering a new strategy for UV sensing visualization and showing great promise as a novel smart phosphorescent thermometer (Figure 9D).¹⁴⁴ Upon increasing the temperature from 197 to 297 K under 365 nm excitation, the afterglow color of L-H-M

shifted sequentially from blue to sky blue, yellow-green, and finally to yellow, enabling intuitive temperature sensing through visible color changes.

CONCLUSIONS AND PERSPECTIVES

With the increasing awareness of the application potential of CP-RTP materials in advanced optoelectronics, information security, and related emerging technologies, this field has witnessed remarkable growth in recent years, accompanied by the development of diverse and innovative molecular design and material engineering strategies. This Review systematically summarizes recent progress in CP-RTP materials, categorized by representative material platforms including host-guest doping systems, organic crystals, polymers, supramolecular assemblies, and multilayer systems. Looking forward, continued advances in understanding the synergistic interplay between chiral structure engineering and phosphorescence mechanisms are expected to drive breakthroughs in mechanism elucidation, performance optimization, intelligent material development, and device integration, further propelling the evolution of organic optoelectronics and interdisciplinary research.

Although much progress has been made, the fundamental mechanisms of CP-RTP remain unclear, particularly the coupling between energy transfer and chirality transfer. The influence of chiral perturbations on excited-state dynamics also requires further clarification. Advanced spectroscopic techniques and theoretical modeling will be essential for revealing these complex processes and developing efficient, tunable systems. Most current materials exhibit low circular polarization values, often insufficient for practical use. While liquid crystalline matrices have achieved higher polarization, they require precise molecular alignment and face compatibility challenges. The development of stable, scalable CP-RTP systems with long lifetimes, high PLQY, and enhanced polarization remains a critical goal. Stimuli-responsive CP-RTP systems are an emerging focus, offering dynamic control over luminescence properties in response to external triggers such as light, heat, pH, or mechanical force. These materials enable multifunctional integration, benefiting applications in sensing, encryption, and flexible electronics. Looking forward, CP-RTP materials hold significant promise in OLEDs, bioimaging, and advanced sensing. Their long-lived emission, environmental sensitivity, and intrinsic circular polarization can contribute to high-performance 3D displays, background-free imaging, and multidimensional information storage. Continued innovation in material design and mechanistic understanding will drive broader adoption in next-generation photonic and electronic technologies.

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H. Li, S. Guo, F. Zhao and C. Tan collected the data and revised the literature necessary for this work. H. Li, S. Guo and H. Li co-wrote the manuscript. H. Li, S. Xu and Y. Tao conceptualize, review and edit the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

No new data and code were created or analyzed in this review.