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Review

2D chirality in organic thin films: advances in nonreciprocal chiroptical properties

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Nonreciprocal chiroptical properties in thin films of chiral organic materials have gained remarkable attention in recent years. Originating from the presence of two-dimensional (2D) chiral structures, these properties manifest as an inversion of the handedness of circularly polarized light preferentially transmitted or emitted from opposite faces of the same sample. Here, we provide a comprehensive overview of the most recent advances in this area, discussing representative systems based on organic small molecules, organic polymers, and hybrid organic–inorganic composites, with particular emphasis on elucidating structure–property relationships. Finally, we survey emerging technological applications enabled by nonreciprocal chiroptical responses. By outlining current challenges and open questions, this review aims to stimulate further discussion and inspire new investigations in this rapidly emerging field.

Highlights

Thin films with nonreciprocal chiroptical properties involve the preferential absorption or emission of circularly polarized light with opposite handedness upon flipping the sample.

Nonreciprocal electronic circular dichroism and circularly polarized luminescence signals are manifestations of 2D chirality, arising from the coupling of skewed linear birefringence with linear dichroism or linear fluorescence anisotropy, respectively.

Genuine nonreciprocal chiroptical response must be carefully distinguished from artifactual signals through systematic measurements at multiple rotation angles for each thin-film face.

Experimental evidence of these properties has emerged across organic small molecules, organic polymers, and hybrid organic–inorganic composites only in recent years.

Nonreciprocal chiroptical properties enable impactful technological applications, exploiting opposite circular polarization handedness for the two faces of an active layer.

Nonreciprocal chiroptical properties in 2D chiral materials

Since Pasteur's pioneering experiment on the resolution of tartaric acids, the concept of chirality (from the Greek χείρ, 'hand') has always fascinated scientists, thanks also to its existence in Nature at various hierarchical levels, from subatomic particles to macroscopic objects [1]. In particular, its recent application to the field of π-conjugated systems has paved the way for a variety of cutting-edge technologies in optoelectronics, photonics, and spintronics [2–8].

From a geometrical point of view, the manifestation of chirality is closely connected to spatial dimensionality (Figure 1A). Three-dimensional (3D) chirality is by far the most common form, referring to the property of a rigid object being nonsuperimposable on its mirror image through any translation and/or rotation *in the space* (as in the case of a helix). By contrast, less intuitive is the concept of two-dimensional (2D) chirality, which applies to rigid, strictly planar objects that cannot be overlapped with their mirror image by any roto-translation *confined to the plane*, while superimposition is achieved upon their flipping out of the plane (as in the case of a 'p' letter written on a transparent surface, which can be read as its mirror image 'q' when viewed from the opposite face) [9,10].

In the context of chiral organic materials, 3D chirality is definitely the most prevalent. Because every atom occupies a finite volume, both individual molecules and their aggregates across different hierarchical scales inherently possess three spatial dimensions (length, width, and depth), such that all their relevant physico-chemical properties are defined in 3D space. Although there are no 'truly 2D' materials, it is nevertheless meaningful to introduce the concept of 2D chirality, which may acquire physical relevance when the third dimension becomes negligible compared with the other two. This is precisely the case with thin films: 3D chirality at the molecular level can be transferred across length scales to generate not only classical 3D chiral architectures but also nearly 2D flat structures exhibiting 2D chirality, whose handedness is reversed for the two faces of the film. In other words, 2D chirality refers to flat structures where the symmetry breaking occurs along the out-of-plane direction.

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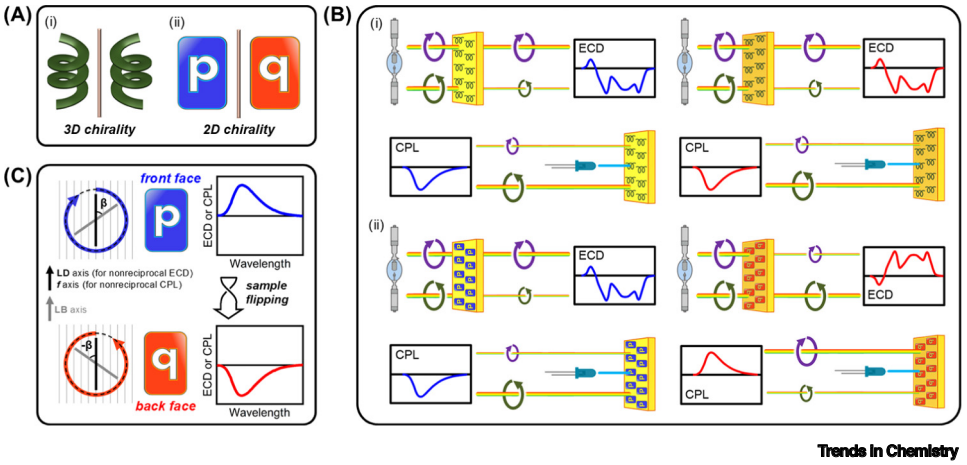


Figure 1. Structural chirality and chiroptical properties in organic thin films. (A) Comparison between 3D and 2D chirality: (i) a helix is a typical example of a 3D chiral object, nonsuperimposable on its mirror image through any roto-translation *in the space*; (ii) a 'p' letter written on a transparent surface is an example of a 2D chiral object, which cannot be overlapped with its mirror image 'q' by any roto-translation *confined to the plane*, while superimposition is achieved upon flipping out of the plane. (B) Manifestation of chiroptical properties in chiral organic thin films: (i) thin films of 3D chiral materials, preserving their helicity irrespective of the observation direction, exhibit *intrinsic* CP absorption and CP emission (i.e., ECD and CPL spectra are invariant for the two faces of the film); (ii) thin films of 2D chiral materials, whose handedness is reversed depending on the side from which they are observed, exhibit *nonreciprocal* CP absorption and CP emission (i.e., ECD and CPL spectra show opposite signs for the two faces of the film). (C) Origin of nonreciprocal chiroptical properties in thin films of 2D chiral materials, according to the Mueller–Stokes formalism. The coupling between LB and LD gives rise to nonreciprocal ECD, while the coupling between LB and *f* generates nonreciprocal CPL. The sign of nonreciprocal signals depends on the skew angle β between the two linear terms: positive if $0° < \beta < 45°$ and negative if $-45° < \beta < 0°$; consequently, it is inverted upon flipping. Abbreviations: CP, circularly polarized; CPL, circularly polarized luminescence; ECD, electronic circular dichroism; LB, linear birefringence; LD, linear dichroism.

The most peculiar functional properties of chiral organic materials for optoelectronic applications are definitely their chiroptical features, that is, the result of different absorption [electronic circular dichroism (ECD)] [11,12] and emission [circularly polarized luminescence (CPL)] [13,14] of circularly polarized (CP) light of opposite handedness. Their manifestation in thin films is closely connected with the structural chirality present. A 3D chiral material, preserving its helicity irrespective of the observer's viewpoint, will have identical chiroptical properties on both faces of the film: these are typically referred to as *intrinsic* (or *true*). For a 2D chiral material, whose handedness is reversed depending on the side from which it is watched, chiroptical properties are opposite upon flipping the film: these have been called *nonreciprocal* (or *apparent*) (Figure 1B) [15,16].

According to the **Mueller–Stokes formalism** (see Glossary) proposed by Shindo (Box 1) [17,18], the emergence of nonreciprocal chiroptical properties in thin films is tied to linear anisotropies. At a given wavelength, the interplay between linear birefringence (LB) and linear dichroism (LD) is responsible for nonreciprocal ECD, while the coupling of LB with linear fluorescence anisotropy (*f*) generates nonreciprocal CPL. Such systems can be considered 2D chiral, as the principal axes of the two interacting linear components are skew (nonparallel and nonorthogonal) to each other. The sign of nonreciprocal signals depends on the skew angle β between the two linear terms: positive if $0° < \beta < 45°$ and negative if $-45° < \beta < 0°$; consequently, it is inverted upon sample flipping (Figure 1C).

Although theoretically well understood, the experimental observation of nonreciprocal chiroptical properties in thin films of chiral organic materials has gained attention only in the last few years.

Glossary

Aggregation pathways: possible routes that a molecular system can follow to self-assemble, in solution and solid state, into supramolecular structures across different hierarchical scales, strongly influenced by experimental conditions.
Anisotropic light scattering: a light-matter interaction phenomenon in which light is scattered nonuniformly (in terms of intensity, polarization, and angular distribution) depending on the direction of interaction with a given material, as a consequence of optical linear anisotropies arising from its structural features.
CP microscopy (CPM): spatially resolved ECD analysis of thin films, achieved by introducing light-polarizing elements (typically, a linear polarizer and a birefringent quarter-wave plate) into the design of an optical microscope and obtaining ECD images of the entire sample at once through charge-coupled device (CCD) cameras.
Dark-field ECD: configuration used to isolate the incoherently scattered contribution present in the crude ECD spectrum, typically achieved by projecting the dichroic light beam exiting from the sample onto a thin needle beam block.
Drop-casting: a thin-film fabrication technique based on the dropwise deposition of the solution of a given material onto a substrate, followed by *slow* solvent evaporation to form the final solid film.
Intramolecular charge-transfer (ICT): a photophysical process where electrons move from an electron-donating group to an electron-withdrawing group within the same molecule, typically upon photoexcitation; it is often stabilized by the decoupling of the donor and acceptor units through an orthogonal twist between them.
Metal halide semiconductors: a class of hybrid organic–inorganic crystalline materials with the general formula $A_iM_jX_k$, where A is an organic cation (typically ammonium derivatives), M is a metal cation (Pb in the case of perovskites, Cu, Bi, etc.), and X is a halide anion. Variations in lattice connectivity give rise to structures of different dimensionalities (0D–3D) with highly tunable optoelectronic properties.
Mueller–Stokes formalism: a mathematical model describing the polarization state of light and its

Box 1. Contributions to crude ECD signals in thin films

Mueller–Stokes formalism has been successfully applied to disentangle the different contributions to experimental ECD spectra of solid-state samples measured using polarization-modulation instrumentation (i.e., conventional spectropolarimeters). For a thin film lying in the x–y plane and perpendicular to the instrumental optical z-axis, the experimental ECD signal can be expressed as the sum of four terms:

$$\begin{aligned} ECD &= CDiso + \tfrac{1}{2}(LD' \cdot LB - LD \cdot LB')\sin 4\theta + (-LD\cos 2\theta + LD'\sin 2\theta)\sin\alpha \\ &+ (P^2_x - P^2_y)\sin 2a\,(-LB\cos 2\theta + LB'\sin 2\theta) \end{aligned} \quad (I)$$

where LD and LB are the linear dichroism and linear birefringence of the sample along the x–y axes; LD′ and LB′ are the corresponding quantities measured along the bisectors of x–y axes; θ is the rotation angle of the sample around the z-axis; α is an instrumental constant associated with the photoelastic modulator (PEM); a is the azimuth angle of the photomultiplier tube (PMT) with respect to the y-axis; P^2_x and P^2_y are proportional to the PMT transmittance along the x- and y-axes.

The first term in Equation I corresponds to the *intrinsic* ECD component, often denoted as CDiso. This contribution originates from the dot product of the electric and magnetic dipoles of a given electronic transition, which is nonzero only in the presence of 3D chirality. As a scalar quantity, CDiso is necessarily isotropic and therefore independent of the thin-film orientation with respect to the optical z-axis.

The second term in Equation I corresponds to the *nonreciprocal* ECD component, often indicated as LDLB. This contribution arises from the coupling between the optical linear anisotropies of the sample, namely LD and LB. A nonzero LDLB can be found when the principal axes of LD and LB are skewed, thus defining a 2D chiral configuration. It is invariant upon sample rotation around the optical z-axis but reverses sign by sample flipping.

The third term in Equation I originates from the residual static birefringence of the PEM, responsible for spurious signals when interacting with samples exhibiting LD. The fourth term is associated with the characteristics of the PMT, which effectively acts as a linear polarizer and can generate spurious signals by interaction with samples exhibiting LB. Both contributions are instrumental artifacts and depend on the sample rotation angle θ. However, averaging the experimental ECD signal over all θ values can, at least in principle, suppress these artifacts.

interaction with polarizing materials; light is represented by a four-component Stokes vector, while the polarizing optical properties of the material are described by a 4 × 4 Mueller matrix.
Selective reflection: a light-matter interaction phenomenon in which a given material preferentially reflects specific wavelengths and/or polarization states of incident light, while others are transmitted or absorbed.
Spin-coating: a thin-film fabrication technique based on the deposition of the solution of a given material onto a substrate under high-speed rotation, where centrifugal force spreads the liquid uniformly on the surface, followed by *rapid* solvent evaporation to form the final solid film.
Synchrotron radiation-ECD imaging (SR-ECD*i*): spatially resolved ECD analysis of thin films using the synchrotron radiation light at Diamond Light Source B23 beamline; it collects local ECD spectra for each pixel in a grid array (spatial resolution ~50 μm) using a motorized XY stage, which can be processed into 2D maps of dichroic signals at specific wavelengths vs. x–y coordinates.

This is not surprising, as for a long time, the straightforward practice of measuring ECD and CPL spectra for the two opposite faces of thin films was rarely reported, leading, in many cases, to the inadvertent neglect of possible nonreciprocal effects. This review provides an overview of the most recent advances in this emerging area, focusing on representative systems based on organic small molecules, polymers, and hybrid organic–inorganic composites. Particular emphasis is placed on elucidating structure–property relationships. We also highlight selected cutting-edge technological applications in chiral organic photonics and electronics that have emerged, or are currently under development, over the past 5 years.

Although beyond the scope of this review, for the sake of completeness, it is worth pointing out that nonreciprocal chiroptical properties have also been described for metal thin films incorporating 2D chiral nanostructures, such as gammadion or fish-scale patterns [9,19,20], fabricated using ion/electron beam lithography, direct laser writing, or other dedicated techniques.

Organic small molecules

In the context of organic small molecules, Di Bari and coworkers have recently reported four π-conjugated chromophores decorated with enantiopure alkyl pendants exhibiting an almost pure nonreciprocal chiroptical response (Figure 2A) [21–24]. Thin films were prepared by **drop-casting** or **spin-coating**, without imparting any preferential molecular orientation; accordingly, they display negligible macroscopic LB, LD, and *f*. To rationalize these observations within the Mueller–Stokes formalism, the authors proposed that, upon solvent evaporation, these molecules can spontaneously assemble into local biaxial domains, each characterized by skewed LD and LB (or *f* and LB). These 2D chiral domains generate local chiroptical signals, whose sign depends on the face exposed to the substrate during film formation; however, their random orientation in the plane results in vanishing macroscopic linear anisotropies upon averaging over

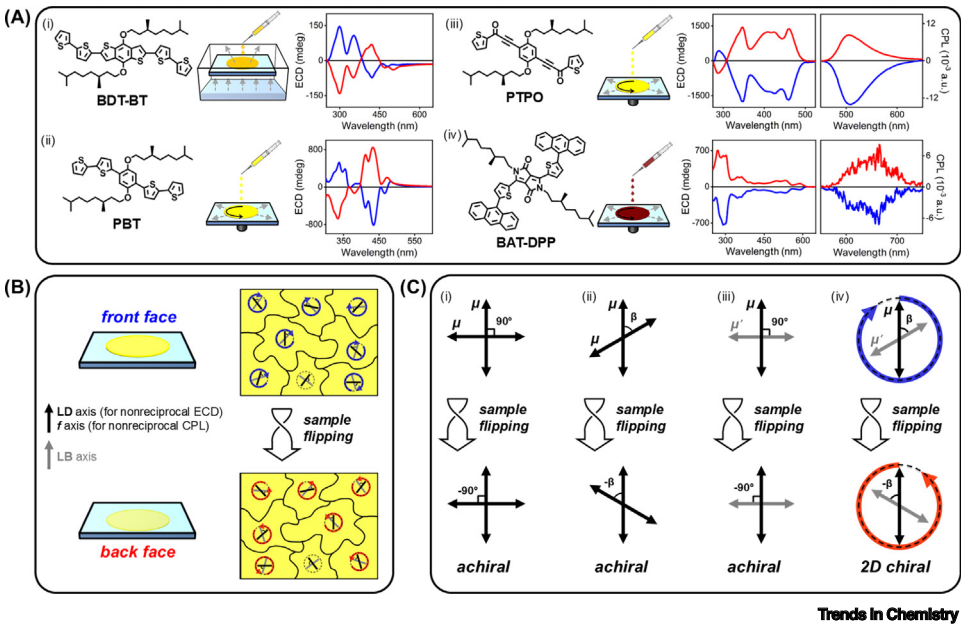


Figure 2. Nonreciprocal chiroptical properties in thin films of chiral organic small molecules. (A) Thin films of π-conjugated chromophores decorated with enantiopure (*S*)-3,7-dimethyl-1-octyl side chains exhibiting nonreciprocal chiroptical response, as reported by Di Bari and coworkers. (i) Drop-casted samples of benzo[1,2-*b*:4,5-*b*′]dithiophene–bis(2,2′-bithiophene) (BDT-BT). Adapted with permission from [21]. Copyright 2017 the Chinese Chemical Society, Institute of Chemistry of Chinese Academy of Sciences and the Royal Society of Chemistry. (ii) Spin-coated samples of 1,4-phenylene–bis(2,2′-bithiophene) (PBT). Adapted with permission from [22]. Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (iii) Spin-coated samples of 1,4-phenylene–bis(thiophenylpropynone) (PTPO). Adapted with permission from [23]. Copyright 2020 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (iv) Spin-coated samples of 3,6-bis(anthracenylthiophenyl)–1,4-diketopyrrolo[3,4-*c*]pyrrole (BAT-DPP). Adapted with permission from [24]. Copyright 2025 the Royal Society of Chemistry. For each panel, blue lines are ECD/CPL spectra measured for the front face, red lines are ECD/CPL spectra measured for the back face. (B) Proposed structural representation for the above-mentioned systems within the Mueller–Stokes formalism. (C) Molecular requirements for the formation of local 2D chiral domains. When the chromophoric unit possesses two (i) degenerate and perpendicular, (ii) degenerate and skewed, or (iii) nondegenerate and perpendicular electronic transition dipoles, it is achiral, as all these configurations preserve in-plane mirror symmetry. When the chromophore exhibits two (iv) nondegenerate and skewed electronic transition dipoles, it exhibits 2D chirality: since this configuration breaks the in-plane mirror symmetry, flipping the sample results in inversion of its helicity. Reproduced with permission from [25]. Copyright 2023 Wiley-VCH GmbH. Abbreviations: CPL, circularly polarized luminescence; ECD, electronic circular dichroism; LB, linear birefringence; LD, linear dichroism.

the whole sample (Figure 2B). Experimental support for this model was provided by **synchrotron radiation-ECD imaging (SR-ECD*i*)** [26,27] and **CP microscopy (CPM)** [28], proving that nonreciprocal features observed in macroscopic ECD/CPL spectra stem from a (usually small) prevalence of local domains adhering with a specific face onto the substrate.

Recently, a semiclassical theory combining Mueller matrix analysis with a Lorentz oscillator model was proposed by Tempelaar *et al.* to identify the molecular requirements for the formation of local 2D chiral domains [29]. According to this model, the chromophoric unit must have two nondegenerate and skewed electronic transition dipoles; under this configuration, the chromophore exhibits 2D chirality, as observation from opposite faces of the chromophoric plane leads to an inversion of its helicity (Figure 2C). Upon crystallization, if molecules assemble through a perfect H-type stack, the resulting aggregate also becomes 2D chiral, which exhibits skewed local LB and LD lying along the H-stacking plane. Unfortunately, this condition is not sufficient to guarantee the formation of 2D chiral domains. Indeed, if the constituent molecules within an H-stack

adopt a consistent tilt, this leads to the formation of a 3D chiral helix, giving rise to intrinsic—rather than nonreciprocal—chiroptical signals. For chromophores with these structural features, it is not possible to predict *a priori* whether self-assembly will lead to 2D or 3D chiral architectures. The final outcome may depend on a variety of factors, including deposition conditions and post-deposition treatments. Moreover, multiple **aggregation pathways** may coexist [30], resulting in systems that exhibit intrinsic and nonreciprocal chiroptical signals in varying proportions, as experimentally observed by Di Bari *et al.* for other similar chiral organic dyes [31–34]. In this context, sporadic examples have also been reported for thin films of enantiopure 1,1′-binaphthyl systems, although only under specific processing conditions [35,36].

Interestingly, a different predictive model was developed by Simpson and coworkers, according to which nonreciprocal chiroptical signals may also arise from the incoherent, scattered component in uniaxial organic thin films, where molecules are oriented along a single axis normal to the film surface [37]. These systems are fundamentally different from those discussed so far, which are instead fully accounted for by the Tempelaar model. Experimental support for Simpson's model was obtained only very recently in uniaxially oriented microcrystalline naproxen thin films, thanks to the implementation of a **dark-field ECD** detection scheme for the selective isolation of low-angle scattered contributions from the crude ECD spectrum [38].

Organic polymers

Compared with small molecules, organic polymers offer intrinsic advantages, including mechanical deformability (e.g., bend, flex, and stretch), thin-film processability, and a strong propensity for hierarchical self-assembly in the solid state, making them suitable materials for the generation of 2D chiral architectures [39–41]. At the same time, the presence of long polymer chains inevitably introduces increased structural variability, especially in blend systems, which may easily generate artifactual chiroptical signals that can be misinterpreted as genuine nonreciprocal ones.

Particularly illustrative in this regard are the studies reported by Deng and coworkers. In an early work, flexible spin-coated thin films of thermoplastic polyurethane blended with chiral helical polyacetylene showed strong nonreciprocal ECD/CPL signals upon mechanical stretching, with dissymmetry factors tunable via the elongation rate [42]. This behavior was attributed to the stretching-induced organization of polymer chains into pinwheel-like 2D chiral structures, displaying opposite handedness on the two film faces (Figure 3A). Similar 2D chiral architectures, indicated as 'kebab-like', were subsequently proposed to rationalize nonreciprocal CPL observed in drop-cast thin films of achiral 1,8-naphthalic anhydride blended with enantiopure polylactic acid (PLA) [43]. However, here an unusual rotation angle dependence of CPL signals was reported, with sign inversion every 90° rotation around the optical axis, tentatively ascribed to **selective reflection** activity of PLA crystallites within 'kebab-like' assemblies (Figure 3B). Such rotation angle dependence became even more pronounced in later studies [44–46], where thin films of many chiral and achiral polymers exhibited ECD signals that appeared nonreciprocal at specific orientations (0°, 90°, 180°, and 270°) but intrinsic at others (45°, 135°, 225°, and 315°). The authors concluded that these signals do not reflect genuine nonreciprocal chiroptical responses associated with 2D chirality, but are instead artifacts, referred to as 'apparent nonreciprocal' (or 'nonreciprocal-like') signals [44], arising primarily from the interaction of pure LD with polarization-modulation instrumentation (Box 1). In these samples, LD originates from the preferential orientation of locally anisotropic, layered sheet-like microstructures formed by aggregation of hard segments of polymer chains (Figure 3C). Additional contributions from **anisotropic light scattering** of such microstructures further modulate the detected intensity and polarization, giving rise to strongly angle-dependent artifactual signals. The authors also reported a trilayer system, made of two external films of oppositely handed chiral polyacetylene

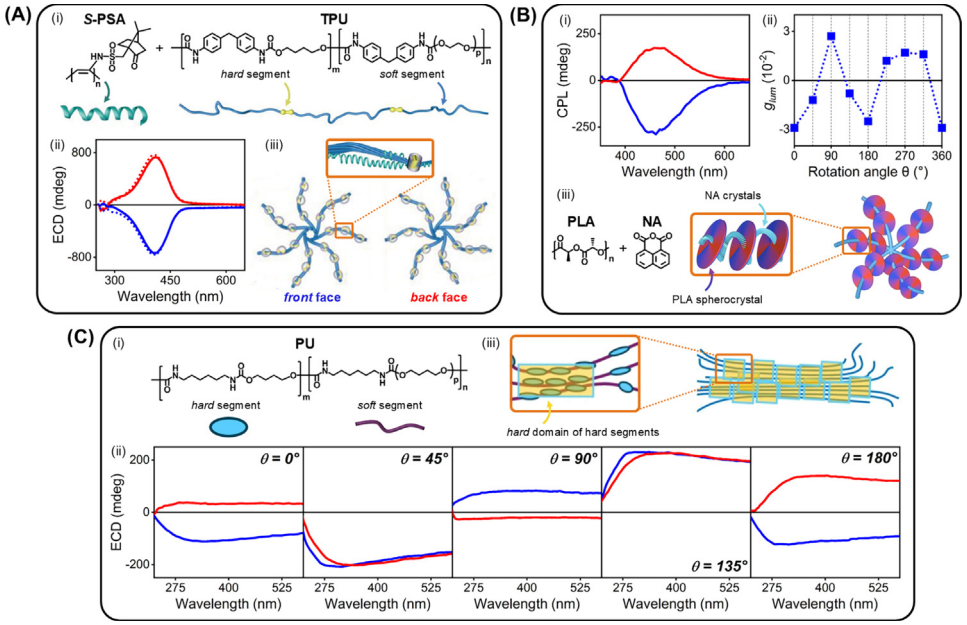


Figure 3. Chiroptical investigation of thin films of organic polymers reported by Deng and coworkers. (A) Flexible spin-coated thin films of thermoplastic polyurethane (TPU) blended with chiral helical polyacetylene (*S*-PSA), exhibiting nonreciprocal chiroptical response upon mechanical stretching: (i) chemical structure of TPU and *S*-PSA; (ii) ECD spectra measured at 50% elongation for the front face (blue lines) and the back face (red lines) at two rotation angles θ: 0° (continuous lines) and 90° (dashed lines); (iii) hypothetical stretching-induced organization of polymer chains into pinwheel-like 2D chiral structures. Adapted with permission from [42]. Copyright 2021 Wiley-VCH GmbH. (B) Drop-casted thin films of achiral 1,8-naphthalic anhydride (NA) blended with enantiopure polylactic acid (PLA): (i) CPL spectra measured for the front face (blue line) and the back face (red line); (ii) maximum luminescence dissymmetry factor g_{lum} values measured for the front face at different rotation angles; (iii) hypothetical organization of NA crystals and PLA spherocrystals into 'kebab-like' 2D chiral structures. Adapted with permission from [43]. Copyright 2022 American Chemical Society. (C) Drop-casted thin films of achiral polyurethane (PU) exhibiting angle-dependent 'apparent nonreciprocal' chiroptical properties: (i) chemical structure of PU; (ii) ECD spectra measured for the front face (blue lines) and the back face (red lines) at different rotation angles θ: 0° (apparent nonreciprocal), 45° (apparent intrinsic), 90° (apparent nonreciprocal), 135° (apparent intrinsic), and 180° (apparent nonreciprocal); (iii) hypothetical organization of hard segments of PU chains into layered sheet-like microstructures responsible for angle-dependent artifactual signals. Adapted with permission from [44]. Copyright 2025 American Chemical Society. Abbreviations: CPL, circularly polarized luminescence; ECD, electronic circular dichroism.

films and a central achiral emissive layer, displaying nonreciprocal CPL [47]; however, here the effect did not originate from 2D chirality, but rather from circular polarization filtering by the outer 3D chiral layers.

In recent years, other research groups have sporadically reported organic polymer-based thin films exhibiting nonreciprocal chiroptical properties [48–50]; however, only in a limited number of cases has their origin been unambiguously attributed to 2D chirality through systematic measurements performed at different rotation angles.

Hybrid organic–inorganic composites

In the realm of hybrid organic–inorganic composites, recent studies have reported chiral **metal halide semiconductors**, particularly perovskites, exhibiting nonreciprocal chiroptical properties in thin films. In these systems, such behavior originates from the 2D chiral configuration of their electronic transition dipoles when projected into the optical polarization plane, which can be induced by lattice distortions or misalignments occurring during thin-film crystallization [51].

Notably, Tempelaar *et al.* have recently provided a rigorous structural basis for the emergence of nonreciprocal ECD in crystalline materials [52]. By reformulating the LDLB term of the Mueller–Stokes formalism (Box 1) in terms of the dielectric tensor and analyzing the tensor forms allowed by different crystallographic space groups, they demonstrated that nonreciprocal ECD can only arise in triclinic, monoclinic, and orthorhombic biaxial crystals.

In these systems, the observed nonreciprocal chiroptical response is governed by the 2D chirality of the optical transition dipoles, manifested through the local LD and LB of individual crystal cells, rather than by the dimensionality of the metal halide semiconductor itself, which ranges from 0D to 3D depending on the connectivity of the crystal lattice [53]. This was first demonstrated in 2022 by Lu and coworkers, who systematically compared the chiroptical response of chiral metal halide semiconductors with different dimensionalities [54]. Strong nonreciprocal ECD signals were found only for 0D (*R*-MBA)$_2$CuCl$_4$ and 1D (*R*-EBA)PbI$_3$ thin films, as confirmed by repeated measurements at different rotation angles for each film face (Figure 4A). However, while dimensionality is not the direct origin of nonreciprocal chiroptical properties, it can play a crucial role in enabling the formation of local 2D chiral structures exhibiting skewed LD and LB. Very recently, it was shown that a 2D perovskite, displaying purely intrinsic ECD signals in pristine spin-coated thin films, developed a strong nonreciprocal chiroptical response after only a partial structural transition from 2D to 1D induced by a wet-treatment strategy [56].

A detailed structural investigation was proposed in 2025 by Beard *et al.* for thin films of (*S*-NEA)$_2$PbBr$_4$ perovskite, characterized by a nonreciprocal chiroptical response strongly

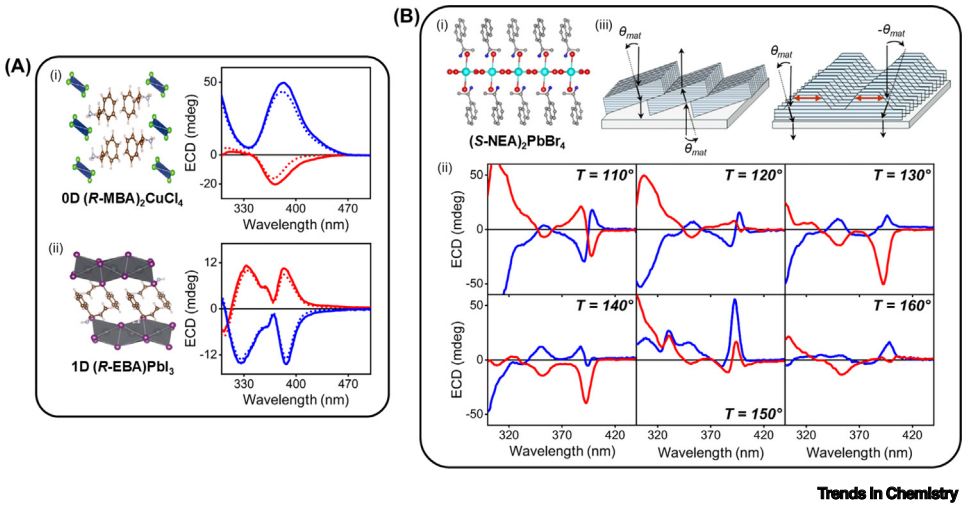


Figure 4. Nonreciprocal chiroptical properties in thin films of chiral hybrid organic–inorganic composites. (A) Thin films of chiral metal halide semiconductors with different dimensionalities exhibiting nonreciprocal chiroptical response, as reported by Lu and coworkers. Crystal structure and ECD spectra, measured for the front face (blue lines) and the back face (red lines) at two different rotation angles θ, for spin-coated thin films of: (i) zero-dimensional (0D) (*R*)-methylbenzylammonium copper chloride ((*R*-MBA)$_2$CuCl$_4$); (ii) one-dimensional (1D) (*R*)-ethylbenzylammonium lead iodide ((*R*-EBA)PbI$_3$). Adapted with permission from [54]. Copyright 2022 American Chemical Society. (B) Thin films of (*S*)-(1-naphthyl)ethylammonium lead iodide ((*S*-NEA)$_2$PbBr$_4$) perovskite exhibiting nonreciprocal chiroptical response dependent on the annealing temperature, as reported by Beard and coworkers: (i) crystal structure of (*S*-NEA)$_2$PbBr$_4$; (ii) ECD spectra of spin-coated thin films of (*S*-NEA)$_2$PbBr$_4$, measured for the front face (blue lines) and the back face (red lines) at different annealing temperature and time (110°C: 20 min; 120°C: 15 min; 130°C: 10 min; 140°C: 5 min; 150°C: 4 min; and 160°C: 3 min); (iii) hypothetical concomitant textures occurring in thin films: ridge-like fibrillar morphologies (left), refracting incident light by a θ_{mat} angle away from the surface normal, and dune-like pattern (right), exhibiting both refraction (by the same θ_{mat} angle) and birefringence. Adapted from [55]. CC-BY 4.0 International License, 2025 American Chemical Society. Abbreviations: ECD, electronic circular dichroism.

dependent on the annealing temperature [55]. The concomitant occurrence of two different textures was hypothesized: (i) ridge-like fibrillar morphologies, which refract incident light away from the surface normal and are responsible for the emergence of the monosignate ECD bands; (ii) a dune-like pattern exhibiting both refraction and birefringence, giving rise to the bisignate ECD bands (Figure 4B).

In recent years, nonreciprocal chiroptical responses have also been reported in thin films of other hybrid organic–inorganic composites [57,58], where careful selection of deposition conditions and post-deposition treatments enabled the achievement of dissymmetry factor values up to 0.1 (with opposite signs for the two faces of the film).

Emerging technological applications

Thin films with nonreciprocal chiroptical properties are particularly appealing: a single 2D chiral material enables the absorption/emission of CP light of opposite handedness simply by flipping the sample, instead of using the two enantiomers of a 3D chiral material. Compared with the mechanism of 3D chirality switching in photoisomeric molecules [59,60] or liquid crystals [61], this capability has opened up new opportunities in organic photonics and electronics, paving the way to technologies scarcely conceivable only a few years ago.

Fabry–Pérot microcavities represent the first technologically relevant application of organic thin films exhibiting nonreciprocal chiroptical features (Box 2). The use of 2D chiral materials as active layers in these optical devices was first proposed in 2021 by Tempelaar *et al.*, who developed a quantum electrodynamical theory describing nonreciprocal ECD under strong light-matter coupling conditions [62]. This model predicted the formation of chiral polaritons upon embedding a layer exhibiting 2D chirality between the reflective mirrors of a Fabry–Pérot microcavity. Experimental validation followed shortly thereafter through the fabrication of Fabry–Pérot microcavities based on spin-coated thin films of enantiopure *p*-phenylene bis-thiophenylpropynone (PTPO) [63], a system previously shown by di Bari *et al.* to spontaneously form local 2D chiral domains responsible for strong nonreciprocal chiroptical responses (Figure 2A) [23]. In these devices, the 2D chiral organic thin film of PTPO and a transparent polymer binding layer (polyvinyl acetate) were embedded between two highly reflective mirrors. Remarkably, the chiroptical signal at the cavity resonance was enhanced by approximately one order of magnitude compared with that of the thin film outside the cavity. This amplification arises from the increased optical path length experienced by CP light within the cavity environment, which selectively reinforces nonreciprocal contributions (Figure 5A). More recently, Delaunay and coworkers reported the emission of chiral polaritons from a Fabry–Pérot microcavity incorporating a 40 nm-thick 2D chiral perovskite film [25]. In this case, the nonreciprocal chiroptical response was enhanced by more than two orders of magnitude compared to that of the bare thin film.

The chiroptical signal amplification principles developed in Fabry–Pérot microcavities incorporating 2D chiral materials have recently been extended to CP lasing technology, where achieving simultaneously high coherence and strong circular polarization remains particularly challenging [66–68]. In this context, Chen *et al.* reported in 2025 an innovative free-space dye laser cavity, consisting of a concave mirror, a Stilbene-420 solution as the gain medium, and a planar high-reflectivity mirror coated with a 2D chiral organic thin film of PTPO [64]. The presence of a layer with nonreciprocal chiroptical features introduces polarization-dependent losses within the cavity, selectively suppressing one circular polarization state and thus enforcing a preferential CP emission. As a result, direct CP laser emission was achieved with a degree of circular polarization exceeding 0.6, corresponding to luminescence dissymmetry factors g_{lum} up to 1.2 (Figure 5B).

Box 2. 2D chiral materials in Fabry–Pérot microcavities

Fabry–Pérot microcavities have recently emerged as a powerful platform for enhancing light-matter interactions. These small optical devices confine light between two highly reflective mirrors, forcing multiple round trips and thus increasing the effective optical path length within the cavity. When a semiconducting layer is embedded between the two mirrors, a strong exciton–photon coupling can be achieved, leading to the formation of hybrid light-matter quasiparticles known as polaritons, with diverse applications in condensed-matter physics, quantum materials, and chemical reaction dynamics.

A major current challenge is the realization of chiral Fabry–Pérot microcavities capable of discriminating between left- and right-handed CP light. Such devices would enable the generation of chiral polaritons, unlocking new opportunities in chiral sensing and CP lasing. However, embedding a thin film of conventional 3D chiral materials (exhibiting intrinsic chiroptical response) inside Fabry–Pérot microcavities is largely ineffective: upon reflection at the cavity mirrors, the handedness of CP light is reversed, so that counter-propagating light in the cavity possesses opposite helicity, leading to cancellation of the chiroptical response (Figure IA), unless circular polarization-preserving mirrors are employed.

Conversely, incorporating a thin film of 2D chiral material (exhibiting nonreciprocal chiroptical response) as the active layer of Fabry–Pérot microcavities offers a unique solution. Since the two faces of the thin film exhibit preferential absorption of CP light with opposite handedness, each inversion of circular polarization upon mirror reflection reinforces, rather than canceling, the discrimination between left- and right-handed CP light (Figure IB). As a result, the chiroptical interaction between CP light and the active layer is strongly amplified within the cavity, enabling efficient chiral polariton formation.

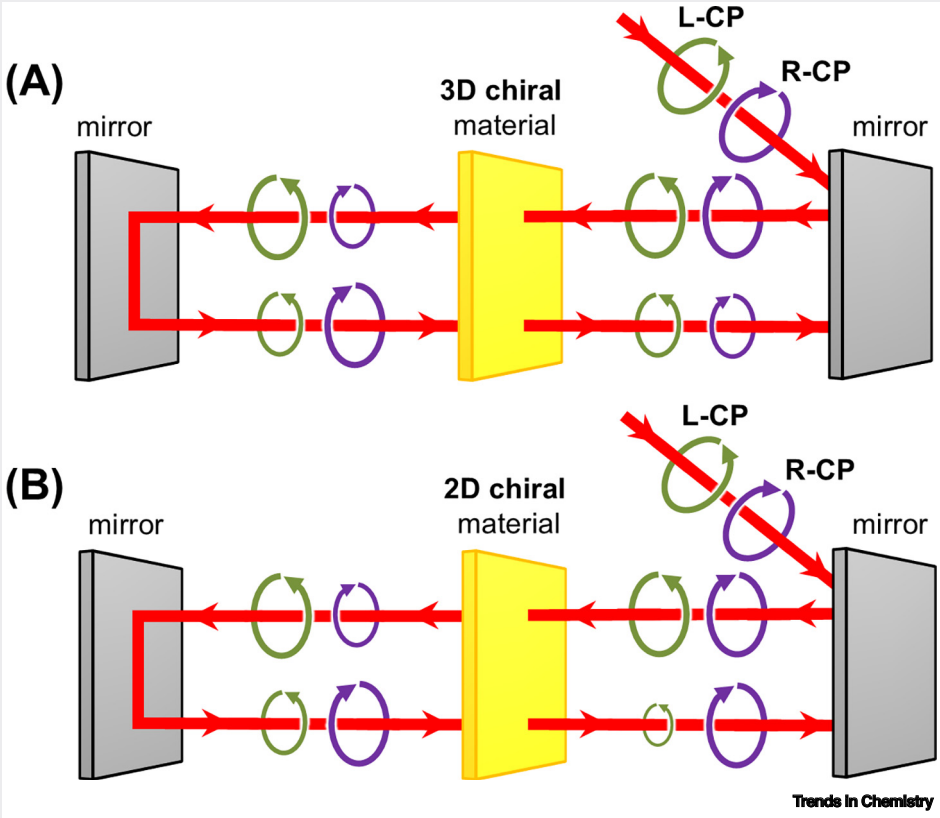


Figure I. Fate of CP light inside a Fabry–Pérot microcavity incorporating a thin film of a (A) 3D chiral material and a (B) 2D chiral material as the active layer.

A distinct strategy in CP lasing technology was proposed in 2024 by Zhao and coworkers, who exploited 2D chiral supramolecular biaxial microcrystals as the gain medium [65]. These were obtained via co-crystallization of an achiral **intramolecular charge-transfer (ICT)** dye within

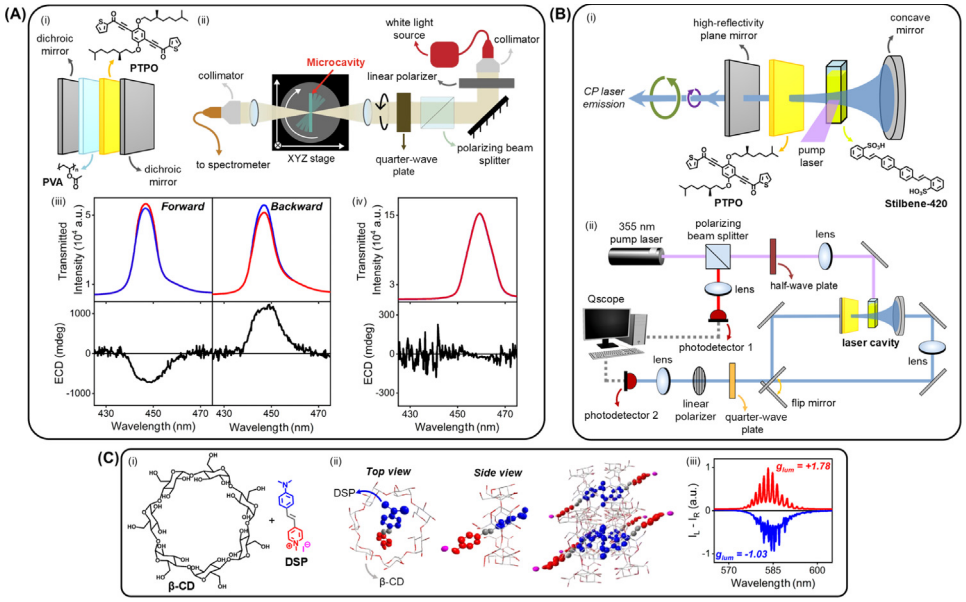


Figure 5. Emerging technological applications of organic thin films with nonreciprocal chiroptical properties. (A) Fabry–Pérot microcavity based on spin-coated thin films of enantiopure *p*-phenylene bis-thiophenylpropynone (PTPO). (i) Schematic illustration of the Fabry–Pérot microcavity architecture and (ii) experimental setup used for the measurement of its chiroptical response. Transmitted intensities of left-handed (blue lines) and right-handed (red lines) CP light and corresponding ECD spectra (black lines) recorded: (iii) for the same PTPO-based Fabry–Pérot microcavity under forward and backward irradiation and (iv) for a Fabry–Pérot microcavity lacking the PTPO thin film. Adapted from [63]. CC-BY 4.0 International License, 2024 Springer Nature. (B) CP lasing technology based on a free-space dye laser cavity, consisting of a concave mirror, a Stilbene-420 solution as the gain medium and a planar high-reflectivity mirror coated with a spin-coated PTPO thin film. (i) Schematic illustration of the CP laser cavity and (ii) experimental setup used for the characterization. Adapted from [64]. CC-BY 4.0 International License, 2025 American Chemical Society. (C) CP lasing technology based on a 2D chiral supramolecular biaxial microcrystal (DSP@β-CD) as the gain medium, obtained via co-crystallization of achiral *trans*-4-[4-(dimethylamino)styryl]-1-methylpyridinium iodide (DSP) dye within a β-cyclodextrin (β-CD) host. (i) Chemical structure of DSP dye and β-CD host. (ii) Crystal structure of DSP@β-CD as a single microcrystal from top and side views (left) and after crystal growth (right). (iii) CP laser emission spectra of DSP@β-CD measured in the forward (blue line) and backward (red line) directions. Adapted with permission from [65]. Copyright 2024 American Chemical Society. Abbreviations: CP, circularly polarized; ECD, electronic circular dichroism; PVA, polyvinyl acetate.

a β-cyclodextrin host, yielding biaxial crystals characterized by skewed LB and *f*, and thus exhibiting strong nonreciprocal CPL. Under stimulated emission conditions, the enhancement of fluorescence linear polarization dramatically amplified the nonreciprocal chiroptical response, enabling high-performance CP lasing with opposite circular polarization handedness depending on the emitting crystal face (Figure 5C). Very recently, the same authors extended this approach to crystals of achiral Coumarin 153 dye, demonstrating that careful control over the crystallization process enables precise tuning of *f*–LB coupling, unlocking nonreciprocal CP lasing in systems that are achiral at the molecular level [69].

Finally, a promising prospective application of 2D chiral materials displaying nonreciprocal CPL lies in their use as active layers in highly efficient circularly polarized-organic light-emitting diodes (CP-OLEDs), where opposite circular polarization emitted from the two faces of the thin film could be beneficial in avoiding depolarization effects upon reflection at the metallic cathode (Box 3). At present, this concept remains largely theoretical [23], although active experimental efforts are currently underway.

Box 3. 2D chiral materials in CP-OLEDs

Organic light-emitting diodes (OLEDs) are a successful and widely adopted technology for efficient energy-saving light sources, offering high color quality and wide viewing angles. In this context, CP light has become crucial for the development of a broad range of applications, including liquid crystal display backlights as well as quantum information processing and communication. As a result, in the recent years, considerable effort has been devoted to the development of circularly polarized OLEDs (CP-OLEDs).

A first strategy to achieve CP emission is based on the integration of broadband circular polarizers as passive components in conventional OLED devices. However, this approach inevitably leads to relatively complex and thick device architectures, thus reducing overall efficiency. A more attractive alternative is the direct generation of CP light from chiral semiconducting emissive layers, which would simplify device architecture, reduce fabrication costs, and facilitate integration with other optoelectronic devices.

When thin films of conventional 3D chiral materials (exhibiting intrinsic chiroptical response) are employed as the emitting layer in CP-OLEDs, a major limitation arises from the device geometry. The back-emitted light is partially reflected by the metal cathode, which reverses the handedness of circular polarization. As a consequence, the reflected emission partially cancels the forward-emitted CP light, resulting in a substantial reduction of the overall circular polarization efficiency, despite the strong intrinsically CP emission of the active layer (Figure IA). Mitigating this effect typically requires the use of semitransparent cathodes, often at the expense of device performance.

This limitation could be effectively overcome by employing thin films of 2D chiral materials as the emissive layer. Owing to the strong nonreciprocal chiroptical response of these materials, forward and backward emission possess opposite circular polarization handedness. Upon reflection at the metal cathode, the back-emitted light recovers the same handedness as the forward emission, thus increasing the total polarization output of the device (Figure IB). However, the application of 2D chiral emitters in CP-OLEDs remains, at the moment, only a theoretical prospect, due to the lack of suitable materials exhibiting strong nonreciprocal CP electroluminescence.

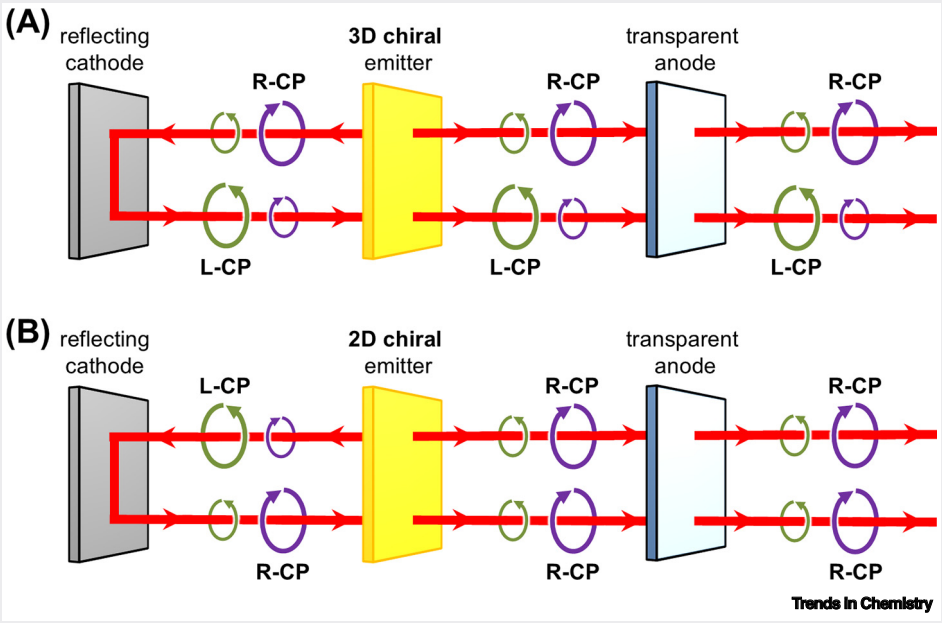


Figure I. Fate of CP emission inside a CP-OLED incorporating a thin film of a (A) 3D chiral material and a (B) 2D chiral material as the active layer.

Outstanding questions

Can the formation of 2D chiral structures in thin films be predicted *a priori* for a given chiral organic material, at least under specific processing conditions?

Under which circumstances do concomitant aggregation pathways coexist in the same organic thin film? Which experimental parameters drive the preferential formation of 2D chiral rather than 3D chiral structures?

How is chiral information transferred from the molecular level to larger-scale 2D chiral architectures in thin films? In particular, what role is played by noncovalent interactions during crystallization at the liquid–solid interface?

For organic materials capable of forming 2D chiral structures in thin films, can the relative population of the two enantiomeric faces adhering to the substrate be controlled? If so, by which strategies?

Are there recurring structural motifs (in terms of molecular symmetry, functional groups, and spatial arrangement) for which the emergence of nonreciprocal chiroptical properties in thin films is more likely?

Concluding remarks and future perspectives

In this review, we have described the most recent advances in the manifestation of nonreciprocal chiroptical properties in organic thin films. Within the Mueller–Stokes formalism [17,18], such phenomena originate from a 2D chiral configuration of linear optical anisotropies: the coupling of

skewed LB and LD gives rise to nonreciprocal ECD, while the interplay of skewed LB and *f* generates nonreciprocal CPL. Representative examples spanning organic small molecules, organic polymers, and hybrid organic–inorganic composites have been discussed, with particular emphasis on elucidating the structural features responsible for nonreciprocal chiroptical signals. At the same time, we have highlighted the critical importance of distinguishing genuine nonreciprocal chiroptical responses associated with 2D chirality from artifacts, which requires systematic ECD/CPL measurements at multiple rotation angles for each thin film face.

However, despite the substantial progress achieved in recent years, several challenges remain (see Outstanding questions). First, it is still not possible to predict *a priori* if a given chiral organic material will form 2D chiral structures in thin films. Many of the systems discussed earlier can be rationalized with the model of Tempelaar *et al.* [29], which requires the chromophoric unit to possess two nondegenerate and skewed electronic transition dipoles. Nevertheless, this condition alone is not sufficient to guarantee the emergence of a nonreciprocal chiroptical response. Even for chromophores fulfilling these criteria, it remains difficult to forecast if the self-assembly will yield 2D chiral or 3D chiral arrangements.

Moreover, competing aggregation pathways can frequently occur in organic thin films [30], leading to the coexistence of various types of aggregates and, consequently, to polymorphism. In this context, purely computational approaches often fail to provide definitive predictions, as many structures corresponding to several energy minima can be found through structure optimization. Therefore, these systems often feature several metastable thermodynamic states in which the molecular assemblies can be trapped, depending on the specific experimental conditions, such as deposition techniques and post-deposition treatments.

Another key point lies in understanding how chiral information is transferred from the molecular level to larger-scale 2D chiral architectures. Noncovalent interactions during the crystallization process at the liquid–solid interface between chiral organic molecules and the substrate surface could play a crucial role here. An even more difficult problem is the lack of control over the relative population of the two enantiomeric faces of 2D chiral structures adhering to the substrate, a parameter that is crucial for the manifestation of strong nonreciprocal chiroptical signals in these materials.

Finally, the occurrence of 2D chirality in organic thin films is extremely sensitive to even minimal variations in the molecular structure, in ways that remain largely unpredictable given the current state of the art. Even empirical rules most often fail to provide clear direction. As a result, the search for new chiral organic materials with nonreciprocal ECD and CPL still largely relies on trial-and-error approaches, which are cost-ineffective and time-consuming.

Addressing these open challenges could dramatically expand the number of chiral organic materials with such exceptional properties, paving the way toward systems tailored for new impactful technological applications in chiral organic photonics and electronics, particularly those exploiting opposite circular polarization handedness for the two faces of the active layers. In this regard, we hope that this review will stimulate further discussion and inspire new investigations in this rapidly emerging field.

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Declaration of interests

The authors declare no competing interests.

References

1. Liu, M. *et al.* (2015) Supramolecular chirality in self-assembled systems. *Chem. Rev.* 115, 7304–7397
2. Shang, X. *et al.* (2022) Emerging materials for circularly polarized light detection. *J. Mater. Chem. C* 10, 2400–2410
3. Liang, Y. *et al.* (2022) Enhancement of electrocatalytic oxygen evolution by chiral molecular functionalization of hybrid 2D electrodes. *Nat. Commun.* 13, 3356
4. Rikken, G.L.J.A. and Avarvari, N. (2022) Dielectric magnetochiral anisotropy. *Nat. Commun.* 13, 3564
5. Crassous, J. *et al.* (2023) Materials for chiral light control. *Nat. Rev. Mater.* 8, 365–371
6. Chiesa, A. *et al.* (2023) Chirality-induced spin selectivity: an enabling technology for quantum applications. *Adv. Mater.* 35, 2300472
7. Yang, Y. *et al.* (2024) Chiral conjugated molecular assemblies interact with substances and light. *Acc. Mater. Res.* 5, 329–346
8. Furlan, F. *et al.* (2024) Chiral materials and mechanisms for circularly polarized light-emitting diodes. *Nat. Photonics* 18, 658–668
9. Arteaga, O. *et al.* (2016) Relation between 2D/3D chirality and the appearance of chiroptical effects in real nanostructures. *Opt. Express* 24, 2242–2252
10. Zhu, H. and Yakobson, B.I. (2024) Creating chirality in the nearly two dimensions. *Nat. Mater.* 23, 316–322
11. Berova, N. *et al.* (2007) Application of electronic circular dichroism in configurational and conformational analysis of organic compounds. *Chem. Soc. Rev.* 36, 914–931
12. Pescitelli, G. (2022) ECD exciton chirality method today: a modern tool for determining absolute configurations. *Chirality* 34, 333–363
13. Arrico, L. *et al.* (2021) Quantifying the overall efficiency of circularly polarized emitters. *Chem. Eur. J.* 27, 2920–2934
14. Guido, C.A. *et al.* (2025) Quantum chemistry calculations of circularly polarized luminescence (CPL): from spectral modeling to molecular design. *Chem. Rev.* 125, 10492–10656
15. Albano, G. *et al.* (2020) Chiroptical properties in thin films of π-conjugated systems. *Chem. Rev.* 120, 10145–10243
16. Albano, G. *et al.* (2022) Reciprocal and non-reciprocal chiroptical features in thin films of organic dyes. *ChemNanoMat* 8, e202200219
17. Shindo, Y. and Nakagawa, M. (1985) Circular dichroism measurements. I. Calibration of a circular dichroism spectrometer. *Rev. Sci. Instrum.* 56, 32–39
18. Shindo, Y. *et al.* (1985) On the problems of CD spectropolarimeters. II: artifacts in CD spectrometers. *Appl. Spectrosc.* 39, 860–868
19. Fedotov, V.A. *et al.* (2007) Asymmetric transmission of light and enantiomerically sensitive plasmon resonance in planar chiral nanostructures. *Nano Lett.* 7, 1996–1999
20. Arteaga, O. *et al.* (2014) Complete polarimetry on the asymmetric transmission through subwavelength hole arrays. *Opt. Express* 22, 13719–13732
21. Albano, G. *et al.* (2017) Chiroptical response inversion upon sample flipping in thin films of a chiral benzo[1,2-*b*:4,5-*b'*]dithiophene-based oligothiophene. *Mater. Chem. Front.* 1, 2047–2056
22. Albano, G. *et al.* (2018) Outstanding chiroptical features of thin films of chiral oligothiophenes. *ChemNanoMat* 4, 1059–1070
23. Zinna, F. *et al.* (2020) Emergent nonreciprocal circularly polarized emission from an organic thin film. *Adv. Mater.* 32, 2002575
24. Albano, G. *et al.* (2025) Unravelling the origin of strong non-reciprocal chiroptical features in thin films of a chiral diketopyrrolo[3,4-c]pyrrole dye. *Nanoscale* 17, 5128–5140
25. Wang, Z. *et al.* (2023) Chiroptical response inversion and enhancement of room-temperature exciton-polaritons using 2D chirality in perovskites. *Adv. Mater.* 35, 2303203
26. Albano, G. *et al.* (2019) Electronic circular dichroism imaging (CDi) maps local aggregation modes in thin films of chiral oligothiophenes. *New J. Chem.* 43, 14584–14593
27. Albano, G. *et al.* (2022) Spatially resolved chiroptical study of thin films of benzo[1,2-*b*:4,5-*b'*]dithiophene-based oligothiophenes by synchrotron radiation electronic circular dichroism imaging (SR-ECDi) technique. *Aggregate* 3, e193
28. Taddeucci, A. *et al.* (2023) Circularly polarized microscopy of thin films of chiral organic dyes. *Chem. Biomed. Imaging* 1, 471–478
29. Salij, A. *et al.* (2021) Theory of apparent circular dichroism reveals the origin of inverted and noninverted chiroptical response under sample flipping. *J. Am. Chem. Soc.* 143, 21519–21531
30. Korevaar, P.A. *et al.* (2014) Pathway complexity in π-conjugated materials. *Chem. Mater.* 26, 576–586
31. Albano, G. *et al.* (2022) Aggregation modes of chiral diketopyrrolo[3,4-*c*]pyrrole dyes in solution and thin films. *Chem. Eur. J.* 28, e202201178
32. Albano, G. *et al.* (2024) Impact of temperature on the chiroptical properties of thin films of chiral thiophene-based oligomers. *Chempluschem* 89, e202300667
33. Albano, G. *et al.* (2024) Systematic investigation of optical and chiroptical properties of chiral π-conjugated oligomers in solution and thin films. *Eur. J. Org. Chem.* 27, e202400294
34. Bertuolo, M. *et al.* (2025) Strong non-reciprocal chiroptical properties in thin films of chiral alkylthio-decorated 1,4-phenylene/thiophene dyes. *Chem. Asian J.* 20, e202401160
35. Von weber, A. *et al.* (2019) Circular dichroism and isotropy – polarity reversal of ellipticity in molecular films of 1,1′-Bi-2-naphtol. *Chemphyschem* 20, 62–69
36. Dini, F. *et al.* (2025) Synthesis and chiroptical properties of bithiophene-functionalized open and methylene-bridged binaphthyl derivatives. *J. Org. Chem.* 90, 14754–14768
37. Turner, G.A. *et al.* (2023) Incoherent nonreciprocal absorbance circular dichroism of uniaxial assemblies. *J. Phys. Chem. B* 127, 8216–8225
38. Turner, G.A. *et al.* (2025) Dark-field absorbance circular dichroism of oriented chiral thin films. *J. Phys. Chem. Lett.* 16, 1403–1408
39. Xie, Y. *et al.* (2022) Flexible, programmable, chiroptical polymer films of twisted stacking layers for circular polarization-based multiplex color display. *Adv. Opt. Mater.* 10, 2102197
40. Wen, L. *et al.* (2024) Amplification and dynamic control of circularly polarized luminescence in poly (vinyl alcohol)/CdSe@CdS nanorod assembly twisted-stacking hetero-structures. *Adv. Opt. Mater.* 12, 2301308
41. Li, J. *et al.* (2025) 2D/3D geometric multiplexing via orthogonal control of circularly polarized transmission and long afterglow imaging. *Small* 21, 2501904
42. Li, P. and Deng, J. (2021) Switchable chiroptical flexible films based on chiral helical superstructure: handedness inversion and dissymmetric adjustability by stretching. *Adv. Funct. Mater.* 31, 2105315
43. Gao, X. *et al.* (2022) Chirality transfer from polylactide to achiral fluorophore in hierarchical crystallization for realizing handedness-tunable and nonreciprocal circularly polarized luminescence. *Macromolecules* 55, 10618–10627
44. Yin, W. *et al.* (2025) Anisotropic artifacts coupled with light-scattering generating 'non-reciprocal-like' CD/CPL signals in polyurethane films. *Macromolecules* 58, 9660–9671
45. Li, P. *et al.* (2023) Synergism between LDLB and true CD to achieve angle-dependent chiroptical inversion and switchable polarized luminescence emission in nonreciprocal nanofibrous films. *Nanoscale* 15, 5345–5359
46. Zhang, R. *et al.* (2025) Generation and modulation of nonreciprocal chirality to realize nonreciprocal CPL emission in polyurethane films. *Sci. China Chem.* 68, 3247–3259
47. Zhao, B. *et al.* (2019) Combining chiral helical polymer with achiral luminophores for generating full-color, on–off, and switchable circularly polarized luminescence. *Macromolecules* 52, 376–384
48. Khorloo, M. *et al.* (2021) Enantiomeric switching of the circularly polarized luminescence processes in a hierarchical biomimetic system by film tilting. *ACS Nano* 15, 1397–1406

49. Yu, Y. *et al.* (2025) Mechanochemically induced circularly polarized luminescence from polymers. *Angew Chem. Int. Ed. Engl.* 64, e202517113
50. Jia, D. *et al.* (2025) Dynamic assembly endows flexible iridescent CNC-based photonic composite film with emergent nonreciprocal chiroptical capability. *Carbohydr. Polym.* 368, 124241
51. Heindl, M.W. *et al.* (2022) Strong induced circular dichroism in a hybrid lead-halide semiconductor using chiral amino acids for crystallite surface functionalization. *Adv. Opt. Mater.* 10, 2200204
52. Parrish, K.A. *et al.* (2025) Differential absorption of circularly polarized light by a centrosymmetric crystal. *Science* 388, 1194–1197
53. Hoye, R.L.Z. *et al.* (2022) The role of dimensionality on the optoelectronic properties of oxide and halide perovskites, and their halide derivatives. *Adv. Energy Mater.* 12, 2100499
54. Zhang, Z. *et al.* (2022) Revealing the intrinsic chiroptical activity in chiral metal-halide semiconductors. *J. Am. Chem. Soc.* 144, 22242–22250
55. Hautzinger, M.P. *et al.* (2025) Control over banded morphologies and circular dichroism in chiral halide perovskites. *ACS Nano* 19, 19141–19148
56. Xiao, Y. *et al.* (2025) 1D–2D composite perovskite films with self-assembled chiral structure for non-reciprocal circularly polarized emission modulation. *Chem. Commun.* 61, 7668–7671
57. Yan, L. *et al.* (2024) Giant apparent optical circular dichroism in thin films of bismuth-based hybrid organic–inorganic metal halide semiconductor through preferred orientation. *Adv. Opt. Mater.* 12, 2302766
58. Fu, H.-R. *et al.* (2024) Hierarchical chiral MOFs with the induced chirality of AIE ligands exhibiting non-reciprocal CPL. *Chem. Commun.* 60, 6182–6185
59. Zhang, L. *et al.* (2020) Supramolecular chiroptical switches. *Chem. Soc. Rev.* 49, 9095–9120
60. Yang, F. *et al.* (2023) Light-triggered modulation of supramolecular chirality. *Chem. Eur. J.* 29, e202203794
61. Zhang, K. and Yu, H. (2023) Chiroptical studies on nanoparticle-liquid crystal composites. *Liq. Cryst.* 50, 572–583
62. Salij, A.H. *et al.* (2024) Theory predicts 2D chiral polaritons based on achiral Fabry–Pérot cavities using apparent circular dichroism. *Nat. Commun.* 15, 340
63. Chen, T.-L. *et al.* (2024) A 2D chiral microcavity based on apparent circular dichroism. *Nat. Commun.* 15, 3072
64. Lin, L.-Z. *et al.* (2025) Circularly polarized stimulated emission from a chiral cavity based on apparent circular dichroism organic thin films. *ACS Photonics* 12, 2557–2565
65. Ji, S. *et al.* (2024) Exceptionally high-g_{lum} circularly polarized lasers empowered by strong 2D-chiroptical response in a host–guest supramolecular microcrystal. *J. Am. Chem. Soc.* 146, 22583–22589
66. Zhan, X. *et al.* (2021) 3D laser displays based on circularly polarized lasing from cholesteric liquid crystal arrays. *Adv. Mater.* 33, 2104418
67. Lu, M. *et al.* (2024) Adaptive helical chirality in supramolecular microcrystals for circularly polarized lasing. *Angew Chem. Int. Ed. Engl.* 63, e202408619
68. Ren, S. *et al.* (2025) Circularly polarized lasing from helical superstructures of chiral organic molecules. *Angew Chem. Int. Ed. Engl.* 64, e202415092
69. Ji, S. *et al.* (2025) Nonreciprocal circularly polarized lasing from organic achiral microcrystals. *J. Am. Chem. Soc.* 147, 16674–16680