Circularly polarized electroluminescence from a single-crystal organic microcavity light-emitting diode based on photonic spin-orbit interactions

Jichao Jia1,5, Xue Cao1,5, Xuekai Ma2, Jianbo De3, Jiannian Yao3, Stefan Schumacher2,4, Qing Liao1✉ & Hongbing Fu1✉

Circularly polarized (CP) electroluminescence from organic light-emitting diodes (OLEDs) has aroused considerable attention for their potential in future display and photonic technologies. The development of CP-OLEDs relies largely on chiral-emitters, which not only remain rare owing to difficulties in design and synthesis but also limit the performance of electroluminescence. When the polarization (pseudospin) degrees of freedom of a photon interact with its orbital angular momentum, photonic spin-orbit interaction (SOI) emerges such as Rashba-Dresselhaus (RD) effect. Here, we demonstrate a chiral-emitter-free microcavity CP-OLED with a high dissymmetry factor ($g_{EL}$) and high luminance by embedding a thin two-dimensional organic single crystal (2D-OSC) between two silver layers which serve as two metallic mirrors forming a microcavity and meanwhile also as two electrodes in an OLED architecture. In the presence of the RD effect, the SOIs in the birefringent 2D-OSC microcavity result in a controllable spin-splitting with CP dispersions.

Thanks to the high emission efficiency and high carrier mobility of the OSC, chiral-emitter-free CP-OLEDs have been demonstrated exhibiting a high $g_{EL}$ of 1.1 and a maximum luminance of about 60000 cd/m², which places our device among the best performing CP-OLEDs. This strategy opens an avenue for practical applications towards on-chip microcavity CP-OLEDs.
the active layer for CP EL, including chiral molecules and metal-organic complexes, as well as achiral conjugated polymers with chiral sidechains and chiral dopants. Nevertheless, high-performance CP-OLEDs remain a great challenge hindered by three stumbling blocks: (1) the CP EL materials are rare, limited by difficult molecular design and synthesis; (2) the key parameter, dissymmetry factor \( \eta \), of the CP-OLEDs, is still relatively low, in the range of \( 10^{-2} \) to \( 10^{-3} \), except for a few examples which exhibit high \( \eta \) up to 1.0 by using chiral transition metal complexes and polymers; (3) the CP-OLEDs still show lower device performance than conventional OLEDs, for example, the relatively low luminance, inevitably hindering their practical applications. Therefore, the development of CP-OLEDs with high \( g_{\text{EL}} \), high luminance and of those that are chiral-emitter free is a key issue to be addressed.

The polarization degree of freedom is intrinsic to the nature of light and it can interact with the light field’s orbital angular momentum. This is called photonic spin-orbit interaction (SOI) and is reminiscent of SOI in electronic systems with the photon’s pseudospin mimicking the electron’s spin. Photonic SOI has been widely investigated in inorganic systems, such as graphene, transition-metal dichalcogenides, and metasurface materials, and brings about abundant applications in optoelectronics ranging from classical information processing to the quantum optical regime. The realization of photonic SOI requires the breaking of inversion symmetries in solid-state systems. Contrary to inorganic materials, organic molecular assemblies, especially organic single crystals (OSCs), have highly ordered and anisotropic molecular packing arrangement and therefore anisotropic refractive index and show birefringence. Recently, the tunability of both energy and polarization of the confined photonic modes have been reported in liquid-crystal-filled and OSC-filled birefringent organic cavities. In particular, when two photonic modes with orthogonal linear-polarization and opposite parity are close to resonance, Rashba-Dresselhaus (RD) SOI emerges with the characteristic feature of left- and right-handed CP dispersions. Regrettably, the CP-splitting phenomenon due to RD-SOI is demonstrated in most cases in passive reflection mode. We anticipate that combining a birefringent OSC cavity with OLED architecture might lead to the realization of artificial RD SOI, producing CP EL without the need of chiral emitters.

In the present work, we demonstrate a chiral-emitter free CP-OLED with high \( g_{\text{EL}} \) and high luminance by embedding a thin two-dimensional OSC (2D-OSC) of 1,1-bis((E)-2,4-dimethylstyryl)-2,5-dimethylbenzene (6M-DSB) sandwiched between two silver layers. 6M-DSB are inserted, the anisotropy of its refractive index leads to a strong anisotropy of the refractive index along Y (2.40) because of its giant anisotropy of the refractive index along Y (2.40) and X (1.95) directions (see Fig. 1a and also text below). Furthermore, its semiconducting feature and high solid-state photoluminescence (PL) quantum yield (PLQY = 0.9931, see details in Supplementary Fig. S6) assure efficient electron and hole injection for high-performance EL.

Thin 2D-OSCs of 6M-DSB were prepared by the physical vapor transport method, with the lateral size in a millimeter scale and a thickness of about 990 nm (Supplementary Fig. S7). The uniform and smooth surface of 6M-DSB 2D-OSCs with a roughness less than 1.5 nm pave the way for fabricating microcavity CP-OLEDs. As-prepared 2D-thin-OSCs of 6M-DSB were then transferred on the 200-nm Ag film pre-deposited on silicon wafer. Finally, CsF/Ag films were vacuum deposited sequentially through a mesh-mask, giving rise to an array of microcavity CP-OLEDs on the surface of thin 2D-OSCs. Figure 1a also presents the top-view bright-field photograph of patterned microcavity CP-OLEDs. It can be seen that subunits of CP-OLED array are in 40 \( \times \) 40 \( \mu \text{m}^2 \) and separated by 20 \( \mu \text{m} \) to avoid cross-talk and short circuit. The thin 2D-OSCs of 6M-DSB adopt a lamellar structure with the crystal (O) plane parallel to the substrate (Fig. 1b and Supplementary Fig. S8). Within (O01) plane, nearly planar 6M-DSB molecules stack in a brickwork arrangement among their short-axis with the nearest \( \pi-\pi \) distance ca. 3.6 Å. Their molecule long-axis is tilted at an angle of 63° respect to the substrate. It can be seen from Fig. 1b that this brickwork arrangement brings about significant anisotropic molecular packing arrangements (molecular packing density) along parallel and perpendicular to the \( \pi-\pi \) interaction (defined as Y- and X-direction, respectively), thus leading to a strong anisotropy of the refractive index. We associate the linear polarizations of the cavity modes along X- and Y-direction as X- and Y-polarization, respectively.

### Principle of SOI and experimental realization

In theory, such a birefringent microcavity can be approximately described by an effective Hamiltonian

\[
H(k) = H_{\text{TEM}} + H_{\text{RD}} + H_{\text{XY}},
\]

where \( H_{\text{TEM}} \) describes the intrinsic transverse-electric-transverse-magnetic (TE-TM) splitting of the cavity modes, \( H_{\text{RD}} = -2\alpha\kappa_0 \), \( \kappa_0 \) is the RD Hamiltonian, \( \phi \) giving rise to a spin-splitting along \( \kappa_0 \) direction with the strength \( \alpha \), and \( H_{\text{XY}} = \beta_0 \kappa_0 \) is the Hamiltonian representing the XY splitting, i.e., the energy splitting \( \beta_0 \) at \( \kappa_0 = 0 \) of the perpendicularly linearly polarized modes (X- and Y-polarizations) with opposite parity (here, we define it as \( \beta_0 = E_X - E_Y \), where \( E_X \) and \( E_Y \) are the ground state energies of X and Y modes of opposite parity). The above effective Hamiltonian in the circular polarization basis can be written in the form of a 2 \( \times \) 2 matrix:

\[
H(k) = \begin{pmatrix}
E_0 + \frac{\beta_1^2}{\Delta m} k_x^2 - 2\alpha k_y & \beta_0 + \beta_1^2 e^{-2\pi p} \\
\beta_0 + \beta_1^2 e^{2\pi p} & E_0 + \frac{\beta_1^2}{\Delta m} k_x^2 + 2\alpha k_y
\end{pmatrix},
\]

where \( E_0 \) is the energy of the ground state, \( m \) is the effective mass of cavity photons, \( \beta_1 \) is the strength of the TE-TM splitting, and \( p = \phi \) (0, 2\pi) is the polar angle.

The left panel of Fig. 1c depicts the energy (E) vs. momentum (k) dispersion in an isotropic microcavity. Here, two orthogonally polarized cavity modes with the same parity (X\(_1\), Y\(_1\)) degenerate at \( k_x = 0 \), with \( \beta_0 > 0 \) (\( \beta_0 = 0 \) means two orthogonally polarized cavity modes with different parity at \( k_x = 0 \) to be resonant). Once 2D-OSCs of 6M-DSB were inserted, the anisotropy of its refractive index leads to a birefringent microcavity, in which the splitting between X- and Y-polarized modes at \( k_x = 0 \) occurs, leading to a reduction of \( \beta_0 \) (see the middle panel of Fig. 1c). By carefully tuning the cavity length, i.e., the thickness of the 2D-OSCs, two orthogonally linearly polarized
cavity modes with opposite parity (X<sub>n</sub>, Y<sub>n-1</sub>) approach each other at \( k_y = 0 \), that is, \( \beta_n \sim 0 \). In the resonant case (\( \beta_0 = 0 \)), a clear spin-splitting appears along \( k_y \) direction due to RD SOI with \( \alpha \neq 0 \) (see right panel of Fig. 1c) as predicted by Eq. (1) and therefore linear polarizations change to circular polarizations. That is, at resonance of X<sub>n</sub> and Y<sub>n-1</sub>, the phase difference between the X- and Y-polarized modes across the intra-cavity anisotropic 2D-OSC rotate by \( \pi \), such that the anisotropic 2D-OSC act as a half-wave plate and a linear polarizer along the detection optical path (Supplementary Fig. S5), which allows us to distinguish the polarization of the relevant optical modes. The modes with larger (red dashed lines) and smaller (black dashed lines) curvatures are X- and Y-polarization corresponding to X- and Y-direction, respectively, of the 2D-OSCs of 6M-DSB, which are both well consistent with the calculated results of the cavity modes by using the 2D cavity photon dispersion relations\(^{34}\).

The energy splitting values \( \beta_0 \) between the X- and Y-polarized modes present wavelength-dependent characteristics, for example, \( \beta_0 \) is about 23, 0, and –21 meV for near 448, 497, and 558 nm, respectively, as shown in Fig. 2a, b. Different from other successive dispersion branches (such as at 448 and 558 nm), the crossing point appears at 497 nm and \( k_x = 0 \) originated from X<sub>0</sub> and Y<sub>0</sub> branches (black dotted circle in Fig. 2a), which suggests that the RD SOI emerges in this device. To investigate the polarization property of these cavity modes, we further measured the Stokes vector components\(^4\) to analyze the pseudospin behaviors. The \( S_3 \) components of the Stokes vector of X<sub>n</sub> and Y<sub>n</sub> branches show strongly linearly polarized PL emission (Fig. 2e), while their corresponding \( S_1 \) components exhibit relatively weak (Fig. 2f). As X- and Y-polarized modes approach, the near resonant X<sub>0</sub> and Y<sub>0</sub> branches at \( k_x = 0 \) enhances the RD SOI, leading to the clear splitting of the paraboloids in \( k_y \) direction (Fig. 2b). The \( S_3 \) components present two separate circles with opposite signs and they are highly CP with much higher polarization degree (Fig. 2d), while the \( S_1 \) components become very weak (Fig. 2c).

Therefore, the PL-active CP

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**Fig. 1** | Sample architecture and principle of SOI. a Schematic diagram of the microcavity CP-OLED device structure. The bottom Ag (200 nm) and the top Ag (35 nm)/CsF (10 nm) films serve as the hole and electron injection layers for the OLED and meanwhile function as two mirrors forming a Fabry-Pérot planar microcavity. The 6M-DSB OSCs serve as the emitting layer of the OLED and as birefringent optical medium necessary for the realization of SOI in the microcavity. Right panel: the top-view bright-field of patterned microcavity CP-OLEDs. b Left: Molecular structure of 6M-DSB from single-crystal data, showing the enhanced planarity. Right: brickwork molecular packing arrangement within the (001) crystal plane, viewed perpendicular to the microribbon top-facet. The nearest intermolecular distance is around 3.6 Å. c Left: two orthogonally linearly polarized modes with the same parity in an isotropic microcavity. Middle: the dispersion of two orthogonally linearly polarized modes in an anisotropic microcavity. Right: RD SOI emerges when two orthogonally linearly polarized modes with opposite parity are resonant. d The resonant X- and Y-polarized cavity modes of opposite parity. The 6M-DSB crystal in the microcavity hence acts as a half-wave plate, and the intrinsic mode polarization of the light-emitting side of the mirror turns into a circle, corresponding to left-handed and right-handed circular polarizations, respectively.
emission due to the RD SOI has been clearly demonstrated in our microcavity OLEDs.

**EL performances of the CP-OLED**

The EL performances of our microcavity CP-OLED were then investigated. Figure 3a shows the energy level diagram of the OLED architecture. Ag and Ag/CSF are used as the upper and lower electrodes to inject holes and electrons, respectively. Under a certain voltage, a device achieves uniform and bright EL and edge waveguide (Fig. 3b and Supplementary Fig. S10). We collect the EL emissions from the upper electrode and the crystal edge and compare them with the PL spectrum of 6M-DSB OSCs (Fig. 3c).

The waveguided EL light emitted from the OLED is trapped in single crystals in the form of a whisper gallery mode and then propagates out of the crystal edge. So, this EL spectrum (middle panel of Fig. 3c) is coincident with the PL spectrum of the OSCs (upper panel of Fig. 3c). Notably, the EL spectrum from the upper electrode and the crystal edge and compare them with the PL spectrum of the OSCs. This indicates that the EL emission comes from the OSC active layer of the OLED and is regulated by the active CP emission due to the spin splitting. Correspondingly, the EL emission spectra of unpolarized, \( \sigma^+ \) and \( \sigma^- \) are shown in Fig. 4c.

The left- and right-handed CP emissions are exactly coincident with the above analysis of the cavity modes.

We calculate the RD spin-splitting parameters (\( \alpha = 2E/k_0 \)) as a typical value for the feature of RD SOI, at different photonic modes and show in Fig. 4f (blue triangles). Two modes with different polarizations and opposite parity are brought into resonance and give rise to wavelength-dependent values of the RD effect (Supplementary Figs. S12–S14). In the vicinity of the resonance (X9 and Y8 modes), we obtain a giant RD parameter of \( \alpha \approx 52 \) eV A, which is much larger than that reported in liquid-crystal optical cavities. The key parameters of circular polarization asymmetry factors (\( g_{EL} \) for EL and \( g_{Lum} \) for PL) are usually employed to characterize the performance of CP-OLEDs and can be defined as \( g_{EL} \) (or \( g_{Lum} \)) = \( 2 \times (\beta_1 - \beta_2)/(\beta_1 + \beta_2) \), where \( \beta_1 \) and \( \beta_2 \) correspond to the intensities of left- and right-handed polarization, respectively. The obtained \( g_{EL} \) and \( g_{Lum} \) on the different photonic modes are presented in Fig. 4f. At the resonance wavelength, \( g_{EL} \) and \( g_{Lum} \) reach the maximum values of about 1.4 and 1.1, respectively, which are both the best performances of CP-OLEDs (Supplementary Table S1).

**Discussion**

In summary, we propose a strategy for designing chiral-emitter-free single-crystal CP-OLEDs with high luminescence and large \( g_{EL} \) value through introducing artificial RD SOI into optical microcavities. Thanks to high emission efficiency and high carrier mobility of the 6M-DSB OSC, our microcavity CP-OLEDs exhibit a maximum luminescence of exceeding 60,000 cd/m² and a large \( g_{EL} \) value of 1.1, which are among the best performances of single-crystal CP-OLEDs. The introduction of OSC to such EL devices brings about two advantages: (1) the highly ordered molecular stacking arrangement in single crystals can result in anisotropic refractive index in different directions, which benefit the occurrence of the RD effect. (2) The high current density in single-crystal OLEDs (e.g., 69.25 A cm⁻²) in our case, which is three orders of magnitude higher than that of thin-film OLEDs) also makes them potential candidates also for the future realization of organic electrically pumped solid-state lasers. Our strategy provides a promising design for efficient single-crystal CP-OLEDs, which may greatly promote the development of CP-OLEDs with use in future 3D display applications.
**Fig. 3 | EL architecture and performances.**

*Figure 3 details the energy level diagram of the device (a), a photomicrograph of the 6M-DSB single-crystal OLED array under EL (b), the PL spectrum of the 6M-DSB crystal (c), the upper PL spectrum of the crystal edge waveguide under EL as shown in (b), the middle spectrum of light emanating from the microcavity under EL as shown in (b), and the lower spectrum of light emanating from the microcavity under EL as shown in (b).* 

*Dependence of the current density (black line) and the current efficiency (red line) on the voltage (d). Dependence of the luminescence (black line) and the EQE (red line) on the current density (e).*

**Fig. 4 | Angle-resolved EL measurements.**

*Figures 4 (a, b, c, d) show polarized angle-resolved spectra of EL and PL. The units of the color bars are arbitrary. Spectra of unpolarized, σ+ and σ− components are shown. (f) Wavelength-dependent spin-splitting coefficient α of the RD effect and circularly polarized luminescence dissymmetry factor g of PL and EL with standard deviation error bars.*
Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

References
1. Chen, Y., Gao, J. & Yang, X. Chiral grayscale imaging with plasmonic metasurfaces of stepped nanoapertures. Adv. Opt. Mater. 7, 1801467 (2019).
2. Li, H. et al. Stimuli-responsive circularly polarized organic ultralong room temperature phosphorescence. Angew. Chem. Int. Ed. 59, 4756–4762 (2020).
3. Zinna, F., Giovanella, U. & Di Bari, L. Highly circularly polarized electroluminescence from a chiral europium complex. Adv. Mater. 27, 1791–1795 (2015).
4. Lee, D. M., Song, J. W., Lee, Y. J., Yu, C. J. & Kim, J. H. Control of circularly polarized electroluminescence in induced twist structure of conjugate polymer. Adv. Mater. 29, 1700907 (2017).
5. Li, M., Wang, Y. F., Zhang, D., Duan, L. & Chen, C. F. Axially chiral TADF-active enantiomers designed for efficient blue circularly polarized electroluminescence. Angew. Chem. Int. Ed. 59, 3500–3504 (2020).
6. Zhang, D. W., Li, M. & Chen, C. F. Recent advances in circularly polarized electroluminescence based on organic light-emitting diodes. Chem. Soc. Rev. 49, 1331–1343 (2020).
7. Zhang, Y. P. et al. Chiral spiro-axis induced blue thermally activated delayed fluorescence material for efficient circularly polarized OLEDs with low efficiency roll-off. Angew. Chem. Int. Ed. 60, 8435–8440 (2021).
8. Imai, Y., Nakano, Y., Kawai, T. & Yuasa, J. A smart sensing method for object identification using circularly polarized luminescence from coordination-driven self-assembly. Angew. Chem. Int. Ed. 57, 8973–8978 (2018).
9. Han, Z. et al. Cation-induced chirality in a bifunctional metal-organic framework for quantitative enantioselective recognition. Nat. Commun. 10, 5117 (2019).
10. Takaishi, K., Yasui, M. & Ema, T. Binaphthyl-bipyridyl cyclic dyads as achiral light-emitting polymer via a chiral small-molecule dopant. Adv. Mater. 25, 2624–2629 (2013).
11. David, A. H. G., Casares, R., Cuerva, J. M., Campana, A. G. & Blanco, M. W. Li, M. W. A rotaxane-based circularly polarized luminescence switch. J. Am. Chem. Soc. 130, 1199–1201 (2014).
12. Geng, Y. et al. Origin of strong chiroptical activities in organic framework for quantitative enantioselective recognition. J. Am. Chem. Soc. 140, 11990–11993 (2018).
13. Gong, Z. L. et al. Frontiers in circularly polarized luminescence: molecular design, self-assembly, nanomaterials, and applications. Sci. China Chem. 64, 2060–2104 (2021).
14. Wan, L. et al. Inverting the handedness of circularly polarized luminescence from light-emitting polymers using film thickness. ACS Nano 13, 8099–8105 (2019).
15. Pierre, B., Thierry, L., Thibault, B. & Véronique, C. P. Multispectral polarization viewing angle analysis of circular polarized stereoscopic 3D displays. Proceedings of the SPIE 7524, Stereoscopic Displays and Applications XXI, 75240R (2010).
16. Peeters, E. et al. Circularly polarized electroluminescence from a polymer light-emitting diode. J. Am. Chem. Soc. 119, 9909–9910 (1997).
17. Jeong, S. M. et al. Highly circularly polarized electroluminescence from organic light-emitting diodes with wide-band reflective polymeric cholesteric liquid crystal films. Appl. Phys. Lett. 90, 211106 (2007).
18. Sakai, H. et al. Highly fluorescent carbazolecicene fused by asymmetric 1,2-dialkyl-substituted quinoxaline for circularly polarized luminescence and electroluminescence. J. Phys. Chem. C 119, 13937–13947 (2015).
19. Brandt, R. J., Wang, X., Yang, Y., Campbell, A. J. & Fuchter, M. J. Circularly polarized phosphorescent electroluminescence with a high dissymmetry factor from PHOLEDs based on a planinahelicene. J. Am. Chem. Soc. 138, 9743–9746 (2016).
20. Zinna, F. et al. Design of lanthanide-based OLEDs with remarkable circularly polarized electroluminescence. Adv. Funct. Mater. 27, 1603719 (2017).
21. Di Nuzzo, D. et al. High circular polarization of electroluminescence achieved via self-assembly of a light-emitting chiral conjugated polymer into multidomain cholesteric films. ACS Nano 11, 12713–12722 (2017).
22. Oda, M. et al. Circularly polarized electroluminescence from liquid-crystalline chiral polyfluoroenes. Adv. Mater. 12, 362–365 (2000).
23. Geng, Y. et al. Origin of strong chiroptical activities in films of nonfluorenes with a varying extent of pendant chirality. J. Am. Chem. Soc. 125, 14032–14038 (2003).
24. Yang, Y., da Costa, R. C., Smilgies, D. M., Campbell, A. J. & Fuchter, M. J. Induction of circularly polarized electroluminescence from an achiral light-emitting polymer via a chiral small-molecule dopant. Adv. Mater. 25, 1219–1229 (2012).
25. Jung, J. H., Lee, D. M., Kim, J. H. & Yu, C. J. Circularly polarized electroluminescence by controlling the emission zone in a twisted mesogenic conjugate polymer. J. Mater. Chem. C 6, 726–730 (2018).
26. Whittaker, C. E. et al. Optical analogue of Dresselhaus spin–orbit interaction in phononic graphene. Nat. Photon. 15, 193–196 (2021).
27. Varsano, D., Palummo, M., Molinari, E. & Rontani, M. A monolayer transition-metal dichalcogenide as a topological excitonic insulator. Nat. Nanotechnol. 15, 367–372 (2020).
28. Dorrah, A. H., Rubim, N. A., Zaidim, A., Tamagnonem, M. & Capassom, F. Metasurface optics for on-demand polarization transformations along the optical path. Nat. Photon. 15, 287–296 (2021).
29. Vahala, K. J. Optical microcavities. Nature 424, 839–846 (2003).
30. Aiello, A., Lindlein, N., Marquardt, C. & Leuchs, G. Transverse angular momentum and geometrical spin hemall effect of light. Phys. Rev. Lett. 103, 100401 (2009).
31. Bliokh, K. Y., Prajapati, C., Samlan, C. T., Viswanathan, N. K. & Nori, F. Spin-Hall effect of light at a tilted polarizer. Opt. Lett. 44, 4781–4784 (2019).
32. Rechcifska, K. et al. Engineering spin-orbit synthetic Hamiltonians in liquid-crystal optical cavities. Science 366, 727–730 (2019).
33. Ren, J. H. et al. Realization of exciton-mediated optical spin-orbit interaction in organic microcrystalline resonators. Laser Photon. Rev. 16, 2100252 (2022).
34. Bisi, S. Z., Riecke, C., Gao, J. & Loi, M. A. Outlook and emerging semiconducting materials for ambipolar transistors. Adv. Mater. 26, 1176–1199 (2014).
35. Liao, Q. et al. The effect of 1D- and 2D-porphorns on organic single-crystal optoelectronic devices: lasers and field effect transistors. J. Mater. Chem. C 6, 7994–8002 (2018).
36. Jeon, Y. et al. Sandwich-structure transferable free-form OLEDs for wearable and disposable skin wound photomedicine. Light Sci. Appl. 8, 114 (2019).
37. Ding, R., An, M. H., Feng, J. & Sun, H. B. Organic single-crystalline semiconductors for light-emitting applications: recent advances and developments. Laser Photon. Rev. 13, 1900009 (2019).
38. Yin, F. et al. High performance single-crystalline organic field-effect transistors based on molecular-modified dibenz[a,e]pentalenes derivatives. J. N. Chem. 44, 17552–17557 (2020).
39. Liu, D. et al. Organic laser molecule with high mobility, high photosensitivity quantum yield, and deep-blue lasing characteristics. J. Am. Chem. Soc. 142, 6332–6339 (2020).
41. Liu, D. et al. High mobility organic lasing semiconductor with crystallization-enhanced emission for light-emitting transistors. Angew. Chem. Int. Ed. **60**, 20274–20279 (2021).
42. Zhao, Y. S., Peng, A. D., Fu, H. B., Ma, Y. & Yao, J. N. Nanowire waveguides and ultraviolet lasers based on small organic molecules. Adv. Mater. **20**, 1661–1665 (2008).
43. Liao, Q., Fu, H. B. & Yao, J. Waveguide modulator by energy remote relay from binary organic crystalline microtubes. Adv. Mater. **21**, 4153–4157 (2009).
44. Jin, Y. et al. Control of molecular packing toward a lateral microresonator for microlaser array. J. Mater. Chem. C. **8**, 8531–8537 (2020).
45. Panzarini, G. et al. Exciton-light coupling in single and coupled semiconductor microcavities; polaron dispersion and polarization splitting. Phys. Rev. B **59**, 5082–5089 (1999).
46. Bernevig, B. A., Orenstein, J. & Zhang, S. S. Exact SU(2) symmetry and persistent spin helix in a spin-orbit coupled system. Phys. Rev. Lett. **97**, 236601 (2006).
47. Dufferwiel, S. et al. Spin textures of exciton-polaritons in a tunable microcavity with large TE-TM splitting. Phys. Rev. Lett. **115**, 246401 (2015).
48. Niesner, D. et al. Giant Rashba splitting in CH3NH3PbBr3 organic-inorganic perovskite. Phys. Rev. Lett. **117**, 126401 (2016).
49. Sun, C. L. et al. Lasing from an organic micro-helix. Angew. Chem. Int. Ed. **59**, 11080–11086 (2020).

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Author contributions
J.J., X.C., J.D. and Q.L. designed the experiments and performed experimental measurements. X.M. and S.S. performed the theoretical calculation and analysis. X.M., Q.L. and H.F. wrote the manuscript with contributions from all authors. Q.L., J.Y. and H.F. supervised the project. All authors analyzed the data and discussed the results.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Qing Liao or Hongbing Fu.

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