Efficient selenium-integrated TADF OLEDs with reduced roll-off

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Organic light emitters based on multiresonance-induced thermally activated delayed fluorescent materials have great potential for realizing efficient, narrowband organic light-emitting diodes (OLEDs). However, at high brightness operation, efficiency roll-off attributed to the slow reverse intersystem crossing (RISC) process hinders the use of multiresonance-induced thermally activated delayed fluorescent materials in practical applications. Here we report a heavy-atom incorporating emitter, BNSeSe, which is based on a selenium-integrated boron–nitrogen skeleton and exhibits 100% photoluminescence quantum yield and a high RISC rate ($k_{\text{RISC}}$) of $2.0 \times 10^6$ s$^{-1}$. The corresponding green OLEDs exhibit excellent external quantum efficiencies of up to 36.8% and ultra-low roll-off character at high brightnesses (with very small roll-off values of 2.8% and 14.9% at 1,000 cd m$^{-2}$ and 10,000 cd m$^{-2}$, respectively). Furthermore, the outstanding capability to harvest triplet excitons also enables BNSeSe to be a superior sensitizer for a hyperfluorescence OLED, which shows state-of-the-art performance with a high external quantum efficiency of 40.5%, power efficiency beyond 200 lm W$^{-1}$, and luminance close to 20,000 cd m$^{-2}$.

Organic light-emitting diodes (OLEDs) with simultaneously high efficiency and narrowband emission become increasingly important to the demand for energy-saving and high-quality displays. Thanks to the pioneering work by Hatakeyama and colleagues1,2, multiresonance thermally activated delayed fluorescent (TADF) emitters have emerged with a narrowband emission that could fulfill such requirements. A high external quantum efficiency (EQE) of up to 34% and an electroluminescence with a full-width at half-maximum (FWHM) of 18 nm demonstrated their great potential towards practical applications3. However, multiresonance-induced thermally activated delayed fluorescence (MR-TADF) emitters usually possess long delay lifetimes of several tens of microseconds, which usually lead to high efficiency roll-off at high brightnesses, impeding their commercialization4–10.

To reduce efficiency roll-off, both singlet and triplet excitons should be converted expeditiously. The intrinsic large Frank–Condon overlap integral ensures MR-TADF emitters with a fast radiative rate of singlet excitons. Although the recycle of triplet excitons depends on the reverse intersystem crossing (RISC) channel, and thus the rate of reversed intersystem crossing ($k_{\text{RISC}}$) becomes the key factor to realize low efficiency roll-off11–14. According to Fermi’s golden rule, $k_{\text{RISC}}$ between two states is described as15–18

$$k_{\text{RISC}} \propto |\langle \text{S} | \hat{H}_{\text{SOC}} | \text{T} \rangle|^2 \exp \left( -\frac{\Delta E_{\text{ST}}}{k_B T} \right)$$

where $\langle \text{S} | \hat{H}_{\text{SOC}} | \text{T} \rangle$ is the spin–orbit coupling (SOC) matrix element, $\Delta E_{\text{ST}}$ is the energy difference between the corresponding states, $k_B$ is the Boltzmann constant and $T$ is the temperature. To enhance $k_{\text{RISC}}$, one of the practicable strategies is narrowing $\Delta E_{\text{ST}}$ to provide a smaller energy gap, which benefits the up-conversion process from the low-energy

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T₂ state to the high-energy S₁ state. Generally, ΔE₂ can be reduced by minimizing the overlap between the highest-occupied molecular orbital (HOMO) and lowest-unoccupied molecular orbital (LUMO), which are already atomically separated in MR-TADF emitters. Such a characteristic leaves little room to reduce ΔE₂, thus, enhancing SOC could be a more practical strategy to facilitate RISC. The heavy-atom effect has been verified to be an effective method to enhance SOC in phosphorescent emitters. In our previous work, sulfur was introduced into the MR-TADF system, which shortens the lifetime of delayed fluorescence (τₐ) and smooths the efficiency roll-off compared with its oxygen-substituted analogue, but the device performance is still much less than satisfactory. Aside from optimizing from the molecular level, an alternative TADF-sensitizing strategy—also known as hyper-fluorescence—has proven effective to realize OLEDs with excellent performance, where a TADF emitter is used as a sensitizer to recycle the triplet excitons and then transfer the singlet excitons to the terminal emitter. The long-range Förster resonance energy transfer (FRET) interaction benefits fast consumption of triplet excitons to suppress exciton annihilations such as triplet–triplet annihilation, triplet–polaron annihilation and singlet–triplet annihilation. The core of this mechanism lies on the fast harvesting of triplet excitons via the TADF sensitizer, which also demands a fast RISC process. In this context we are driven to develop MR-TADF emitters with fast RISC, which not only facilitates their emissive properties as emitters but also ensures that they are excellent sensitzers for highly efficient hyperfluorescence OLEDs.

Results

Molecular design and theoretical calculations

The molecules designed in this contribution are presented in Fig. 1a. A conventional boron–nitrogen skeleton was chosen for evaluation due to their high photoluminescence quantum yield (ΦPL) and narrowband emission. Selenium (Zₐ = 34) is inserted to enhance SOC in BNSSe and BNSeSe. The asymmetric BNSSe was developed to establish a comparison and comprehend the structure–property relationship. Their oxygen and sulfur counterparts (2PXZBN, 2PTZBN, respectively) were also prepared to fully validate our molecular design.

We first used density functional theory (DFT) under the representative B3LYP/6-31G(d,p) set to optimize the ground-state geometries of the four molecules. All four show well-separated HOMO and LUMO distributions. The more twisted structures (see Supplementary Fig. 1) of BNSSe and BNSeSe (compared with 2PXZBN and 2PTZBN) may induce less dense packing to avoid inter-chromophore interactions. According to the time-dependent DFT analysis, high oscillator strengths beyond 0.2 and relatively small ΔE₂ values are acquired in these four emitters, implying a fast radiative decay and potential TADF activity. To more accurately model the excited-state energies by considering electron correlation in the form of double excitations, we also prepared to fully validate our molecular design.

Crystallographic and photophysical properties

As shown in the crystal structures of BNSSe and BNSeSe, molecules exhibit rigid configurations, which are beneficial for suppressing non-radiative transitions (Supplementary Fig. 12 and 13). Due to the folded configurations of phenothiazine and phenoselenazine units, molecules in BNSSe and BNSeSe crystals are twisted and stacked loosely. The photophysical properties of BNSSe and BNSeSe—including absorption, fluorescence at 298 K and phosphorescence spectra at 77 K—were measured in toluene, as collected in Fig. 2a and Supplementary Table 6. BNSSe and BNSeSe show intense absorption bands at 469 nm and 467 nm, respectively, which refer to intramolecular charge transfer processes. Both compounds exhibit green emission, with fluorescence spectra peaks at 505 nm and 502 nm for BNSSe and BNSeSe, respectively. To evaluate the ΔE₂ values of these materials, the lowest singlet and triplet excited-state energies were estimated from the onset of fluorescence and phosphorescence bands at 77 K. BNSSe and BNSeSe exhibit identical ΔE₂ values at 0.17 eV, in good agreement with the calculated values by SCF-C2 and ADC(2) (see above). These small energy gaps are beneficial for RISC from triplet excited states to the singlet excited state. The prompt fluorescence (τₐ) and delayed fluorescence (τₜ) lifetimes of BNSSe are 1.6 ns and 2.1 μs, respectively, in oxygen-free toluene, which are distinctly smaller than those of 2PXZBN and 2PTZBN. Moreover, BNSSe possesses a further decreased τₜ of 0.76 ns and τₜ of 1.0 μs, which are the shortest of all reported MR-TADF emitters. Such short delayed fluorescence lifetimes are beneficial for utilizing excitons and suppressing efficiency roll-off. To gain a deeper insight into the emission in the solid state, the photophysical properties of 1-wt%-doped films of 2PXZBN, 2PTZBN, BNSSe and BNSeSe were recorded (see Table 1) in 1,3-dihydro-1,1-dimethyl-3-(3-(4,6-diphenyl-1,3,5-triazin-2-yl)phenyl)inden-2-one (DMIC-TRZ), a universal bipolar host with a hole mobility of 1.03 × 10⁻⁵ cm² V⁻¹ s⁻¹ and an electron mobility of 7.35 × 10⁻⁵ cm² V⁻¹ s⁻¹ at an electric field of 1.2 × 10⁶ V cm⁻¹ (ref. 36). As depicted in Fig. 2c, all four doped films exhibit green emission with slight bathochromic shifts with respect to their toluene solution. Photoluminescence decay curves of these films are shown in Fig. 2d. Both τₜ and τₜ drop in the sequence: 2PXZBN > 2PTZBN > BNSSe > BNSeSe. Furthermore, ΦPL values of 2PXZBN, 2PTZBN, BNSSe and BNSeSe were measured to be 71%, 91%, 99% and 100%, respectively, with an obvious escalating trend as τₜ shortened. The improved ΦPL values of the 1-wt%-DMIC-TRZ-doped BNSSe and BNSeSe films are also associated with their large torsional angles to enlarge intermolecular distance and suppress aggregation-caused quenching. The radiative decay rate constants of fluorescence (kₘ), intersystem crossing (kISC) and kISC are further analysed—using a method provided in the literature—on the basis of these lifetimes and quantum yields. With the increasing number of selenium atoms, kISC is greatly enhanced from 6.0 × 10⁵ s⁻¹ for BNSe to 2.0 × 10⁶ s⁻¹ for BNSe, noting that the latter is, to the best of our knowledge, the largest value among all MR-TADF emitters (typically in the order of 10³–10⁴ s⁻¹; see Supplementary Table 10). Such a tremendous enhancement to kISC is in line with the enhanced SOCs.

OLED devices

Given the prominent photoluminescent properties of 2PXZBN, 2PTZBN, BNSSe and BNSeSe, we fabricated and evaluated OLED devices A–D, employing them as emitters, respectively, with the following device configuration: indium tin oxide (ITO)/1,4,5,8,9,11-hexaazatriphenylene hexacarbonitrile (HAT-CN, 5 nm)/1,1-bis[di-(4-tolylamino)phenyl] cyclohexane (TAPC, 30 nm)/tris(4-carbazolyl-9-yl)phenylamine (TCTA, 15 nm)/3,3-di(9H-carbazol-9-yl)biphenyl (mCBP, 10 nm)/EML (1 wt% emitter in DMIC-TRZ, 50 nm)/(1,3,5-triazine-2,4,6-triy)tris(benzene-3,1-diy)tris(diphenylphosphine oxide) (POT2T,

Nature Photonics | Volume 16 | November 2022 | 803–810

https://doi.org/10.1038/s41566-022-01083-y
20 nm)/1-(4-(10-((1,1′-biphenyl)-4-yl)anthracen-9-yl)phenyl)-2-ethyl-1H-benzo[d]imidazole (ANT-BIZ, 30 nm)/8-hydroxyquinolinato lithium (Liq, 2 nm)/alumina (Al, 100 nm). All device data are summarized in Table 2 and Supplementary Table 8, and selectively presented in Fig. 3. Devices A–D all exhibit green electroluminescence peaks at 517, 520, 515 and 512 nm, respectively. Narrowband emission with FWHMs of 50 nm and 48 nm were recorded for devices C and D, respectively. Attributed to the host with dipole charge transport ability, all devices exhibit low turn-on voltages below 2.5 V and extremely high luminances of over 100,000 cd m⁻². All devices exhibit excellent performance, including high maximum EQEs (EQE max), power efficiencies (PE max) and current efficiencies (CE max). As shown in Fig. 3c–f, EQE max values of 30.7%, 34.6%, 35.7% and 36.8% were observed for devices A–D, respectively. The outstanding EQE max of device D is attributed to a concomitant high Φ PL (~100%) of EML and horizontal orientation factor (Θ || = 89%; Supplementary Fig. 21a), and matches well with the theoretically predicted

![Fig. 1 | Molecular design. a, Molecular structures and the SOC constants of 2PXZBN, 2PTZBN, BNSSe and BNSeSe. b, The DFT-calculated HOMO and LUMO distributions, energy levels, energy band gaps and oscillator strengths (f) of 2PXZBN, 2PTZBN, BNSSe and BNSeSe.](https://doi.org/10.1038/s41566-022-01083-y)
efficiency by using optical simulation (Supplementary Fig. 24a and Supplementary Table 9). Devices A–D exhibit \( P_{\text{E,max}} \) values of 123.4, 157.7, 156.2 and 146.3 \( \text{lm} \, \text{W}^{-1} \), respectively, and their \( C_{\text{E,max}} \) values are as high as 108.8, 124.9, 124.2 and 121.0 \( \text{cd} \, \text{A}^{-1} \), respectively. To the best of our knowledge, the \( P_{\text{E}} \) and \( C_{\text{E}} \) values of devices based on 2PTZBN, BNSSe and BNSeSe are higher than almost all reported TADF OLEDs. Moreover, devices C and especially D exhibit distinctly reduced efficiency roll-off compared with devices A and B, which suggests that the stronger SOCs between \( S_1 \) and \( T_n \) (\( n = 1, 2, 3 \)) in BNSSe and BNSeSe suppress exciton annihilation more efficiently under high current densities. It is worth mentioning that the efficiency roll-off of device D is much smaller than those observed in the latest narrowband TADF OLEDs\(^{25,38-40} \); the EQEs of device D remain 34\% at 1,000 \( \text{cd} \, \text{m}^{-2} \), 26.9\% at 5,000 \( \text{cd} \, \text{m}^{-2} \) and 21.9\% at 10,000 \( \text{cd} \, \text{m}^{-2} \). We assume that the very strong SOC and subsequent high \( k_{\text{RISC}} \) value suppress the triplet-involved annihilation processes in the device (see Supplementary Table 10). The operational lifetimes of devices A–D were preliminarily measured at an initial luminance of 1,000 \( \text{cd} \, \text{m}^{-2} \). Device A shows an \( L_{\text{T50}} \) (the time to reach 50\% of the initial luminance) of 158 h, whereas devices B, C and D exhibit shorter \( L_{\text{T50}} \) values of 5.6, 4.8 and 4.1 h, respectively (Supplementary Fig. 25).

Due to the short delayed fluorescence lifetime, high \( \Phi_{\text{PL}} \) and outstanding electroluminescence performance, we anticipate BNSeSe should be a promising TADF sensitizer candidate for a low-energy emitter. To prove it, one yellow emission MR-TADF emitter BN342 was chosen as the terminal emitter, and the device (E) was fabricated with the following device configuration: ITO/HAT-CN (5 nm)/TAPC (30 nm)/TCTA (15 nm)/mCBP (10 nm)/EML (1 wt\% BN3 and 25 wt\% BNSeSe in DMIC-TRZ, 50 nm)/POT2T (20 nm)/ANT-BIZ (30 nm)/Liq (2 nm)/Al (100 nm). For comparison, sensitizer-free device F was also fabricated with 1 wt\% BN3 doped in DMIC-TRZ as EML. Compared with device F, the

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**Table 1 | Physical data and kinetic parameters of 2PXZBN, 2PTZBN, BNSSe and BNSeSe in 1 wt% DMIC-TRZ doped film**

|        | \( \lambda_{\text{PL}} \) (nm) | \( S_1 \) (eV) | \( T_1 \) (eV) | \( \Delta E_{\text{ST}} \) (eV) | \( \Phi_{\text{PL}} \) (%) | \( \Phi_{\text{TADF}} \) (%) | \( \tau_{\text{PL}} \) (ns) | \( \tau_{\text{DF}} \) (\( \mu \text{s} \)) | \( k_{\text{ISC}} \) (10\(^7\) s\(^{-1}\)) | \( k_{\text{RISC}} \) (10\(^6\) s\(^{-1}\)) |
|--------|-------------------------------|----------------|----------------|-----------------------------|---------------------|---------------------|-----------------|-----------------|-----------------|-----------------|
| 2PXZBN | 523                           | 2.54           | 2.39           | 0.15                        | 71                  | 28                  | 5.2             | 38.1            | 8.2             | 3.4             |
| 2PTZBN | 525                           | 2.55           | 2.42           | 0.13                        | 91                  | 68                  | 5.1             | 20.7            | 4.5             | 0.45            |
| BNSSe  | 520                           | 2.56           | 2.44           | 0.12                        | 99                  | 86                  | 3.0             | 12.7            | 4.3             | 0.043           |
| BNSeSe | 514                           | 2.58           | 2.44           | 0.14                        | 100                 | 95                  | 1.9             | 9.9             | 2.6             | 0.0026          |

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**Fig. 2 | Photophysical properties.**

- **a**, Ultraviolet–visible absorption (Abs), fluorescence (FL) (298 K) and phosphorescence (Ph) spectra (77 K) of BNSSe and BNSeSe in toluene solution.
- **b**, Transient photoluminescence decay curves of BNSSe and BNSeSe in toluene solution before and after argon gas bubbling for 30 min.
- **c**, Photoluminescence spectra of 2PXZBN, 2PTZBN, BNSSe and BNSeSe in 1 wt\% DMIC-TRZ-doped film.
- **d**, Transient photoluminescence decay curves of 2PXZBN, 2PTZBN, BNSSe and BNSeSe in 1 wt\% DMIC-TRZ-doped film.
Table 2 | Summary performances for devices A–H

| Devices (emitter) | CE (cd A⁻¹) | PE (lm W⁻¹) | EQE (%) |
|-------------------|-------------|-------------|---------|
| Max (average)     | 1,000 cd m⁻² | 10,000 cd m⁻² | Max (average) |
| A (2PXZBN)        | 108.8 (107.1 ± 1.0) | 75.1 | 40.9 | 123.4 (120.3 ± 1.3) | 55.8 | 20.7 | 30.7 (29.95 ± 0.30) | 24.0 | 15.8 | 11.6 |
| B (2PTZBN)        | 124.9 (121.6 ± 1.7) | 94.4 | 55.1 | 157.7 (154.8 ± 4.1) | 79.1 | 31.9 | 34.6 (33.83 ± 0.83) | 29.5 | 20.1 | 15.4 |
| C (BNSSe)         | 124.2 (121.2 ± 1.8) | 110.8 | 64.5 | 156.2 (152.0 ± 3.1) | 90.2 | 40.4 | 35.7 (35.02 ± 0.44) | 32.0 | 24.0 | 18.9 |
| D (BNSeSe)        | 121.0 (119.7 ± 0.8) | 111.0 | 70.8 | 146.3 (147.6 ± 2.5) | 90.1 | 45.4 | 36.8 (36.40 ± 0.22) | 34.0 | 26.9 | 21.9 |
| E (HF BN3)        | 164.5 (162.4 ± 2.0) | 131.3 | 94.7 | 205.8 (197.7 ± 8.7) | 112.2 | 56.9 | 40.5 (40.03 ± 0.40) | 32.4 | 26.1 | 23.3 |
| F (BN3)           | 152.2 (147.6 ± 3.5) | 82.2 | 38.1 | 170.7 (165.6 ± 3.9) | 63.5 | 18.2 | 38.7 (36.94 ± 1.03) | 20.4 | 11.9 | 9.4 |
| G (HF DtCzB-DPTRZ) | 161.6 (154.4 ± 4.6) | 139.9 | 98.4 | 181.3 (174.2 ± 6.6) | 114.8 | 54.1 | 39.6 (37.85 ± 0.99) | 34.5 | 27.8 | 24.3 |
| H (DtCzB-DPTRZ)   | 119.3 (108.0 ± 8.3) | 31.5 | 24.5 | 156.2 (141.4 ± 10.8) | 24.6 | 12.1 | 30.7 (23.65 ± 3.39) | 8.0 | 6.8 | 6.3 |

The average device parameters in parentheses are based on the measurement of over fifteen independent devices. HF, hyperfluorescence.

Fig. 3 | OLED (devices A–D). a. Device structure with the energy-level diagrams. b. The chemical structures used for the respective layers. c. Normalized electroluminescence spectra at 1,000 cd m⁻² 2PXZBN, 2PTZBN, BNSSe and BNSeSe. The inset shows a photograph of device D. d. Current density and luminance versus driving voltage characteristics. e. EQE versus luminance characteristics. f. Current and power efficiency versus luminance characteristics.
BNSeSe-sensitized device E exhibits lower turn-on voltage below 2.4 V, which should be attributed to the better energy alignment between BNSeSe and DMIC-TRZ. As summarized in Table 2 and depicted in Fig. 4, excellent electroluminescence performance was observed for device F, with an EQE max of 38.7%, CE max of 152.2 cd A⁻¹, PEmax of 170.7 lm W⁻¹, and maximum luminance (Lmax) of 154,424 cd m⁻². However, device F shows obvious efficiency roll-off at high luminance—the EQE suddenly drops to 20.4% at 1,000 cd m⁻² and 11.9% at 5,000 cd m⁻². By sharp contrast, after introducing BNSeSe as a TADF sensitizer in EML, device E exhibits higher EQEs as well as much smaller efficiency roll-off than device F. An enhanced CE max of 164.5 cd A⁻¹, PEmax of 205.8 lm W⁻¹, and Lmax of 191,023 cd m⁻² were observed for device E. Such high values are never reported in TADF OLEDs. Furthermore, the EQEmax of device E is boosted to 40.5%, and the EQEs remain 32.4% at 1,000 cd m⁻² and 26.1% at 5,000 cd m⁻². Even at the very high brightness of 10,000 cd m⁻², device E maintains a high EQE of 23.3%. We attributed the improved roll-off to the higher kFRET between BNSeSe and BN3 compared with the knr + kISC and r of BNSeSe in the hyperfluorescence system (Supplementary Fig. 20), which leads to the singlet excitons upconverted from the triplet excitons in BNSeSe being quickly consumed by BN3 through FRET. The efficient energy transfer from BNSeSe to BN3 hinders the ISC process in BNSeSe, avoiding the triplet excitons stack at high luminance. Furthermore, the emission luminance of device E decreased from 1,000 cd m⁻² to 500 cd m⁻² for 51 h without emission colour change (Supplementary Fig. 25), and the FWHM remains 40 nm at 1,000 cd m⁻² with marginal enlargement compared with device F. To pursue narrower FWHM in hyperfluorescence device, the terminal emitter BN3 was replaced by a green-emissive dopant DtCzB-DPTRZ with narrower FWHM (23 nm in toluene solution with a concentration of 10⁻⁵ mol L⁻¹). The corresponding BNSeSe-sensitized device (G) not only displays a...
FWHM of only 31 nm, but also manifests very high EQEs of up to 39.6%, greatly outperforming those of the sensitizer-free control device (H).

Conclusion
In conclusion we have synthesized two novel MR-TADF emitters (BNSeSe and BNSeSe) containing heavy-atom selenium. Due to ultra-strong SOC caused by selenium, RISC for BNSeSe was promoted to reach a high level (with $k_{\text{RISC}} = 2.0 \times 10^4$ s$^{-1}$) in comparison with all reported MR-TADF materials. Devices based on BNSeSe display excellent electroluminescence performances, including high $\Phi_{\text{PL}}$ values and narrow-band emission. This work sheds new light on MR-TADF emitters and sensitzers towards highly efficient OLEDs.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41566-022-01083-y.

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Methods
Theoretical calculations
Quantum chemical calculations were performed by the Gaussian 09 program package. Density functional theory was performed at the B3LYP/6-31G(d,p) level to attain the optimized molecular geometries. The HOMO and the LUMO were obtained logically on the basis of the optimized geometric configurations. Time-dependent DFT calculations were performed at the B3LYP/6-31G(d,p) level to obtain the vertical transitions, as well as the natural transition orbitals of the singlet and triplet states on the basis of the corresponding S0 geometries. The SDD pseudopotential was used for selenium atoms; SCS-CC2 and ADC(2) calculations were performed using the MRCC program with the cc-pVDZ basis set. The SOC calculations were further evaluated using PySOC. The optical simulation of OLED devices was performed using the SETFOS 5.1 (Fluxim) program. The input parameters include refractive index value, extinction coefficient, thickness of each layer values (all measured by ellipsometry), as well as photoluminescence spectrum of the emitting layer.

Photophysical measurements
Ultraviolet–visible absorption and photoluminescence spectra were measured using a Shimadzu UV-2700 spectrophotometer (Shimadzu) and Hitachi F-7100 fluorescence spectrophotometer (Hitachi), respectively. Phosphorescence spectra were recorded on the Hitachi F-7100 fluorescence spectrophotometer at 77 K. The transient photoluminescence decay curves were obtained by FluTime 300 (PicoQuant GmbH) with a Picosecond Pulsed UV-LASER (LASER375) as the excitation source. The values of $\Phi_{\text{PL}}$ were measured with a Hamamatsu UV-NIR absolute photoluminescence quantum yield spectrometer (C13534, Hamamatsu Photonics) equipped with a calibrated integrating sphere, the integrating sphere was purged with dry argon to maintain an inert atmosphere.

Device fabrication and performance measurements
The ITO-coated glass substrates with a sheet resistance of 15 Ω square$^{-1}$ were consecutively ultrasonicated with acetone/ethanol and dried with nitrogen gas flow, followed by 20 min ultraviolet light–ozone treatment in an ultraviolet–ozone surface processor (PL16 series, Sen Lights Corporation). The sample was then transferred to the deposition system. Both 8-hydroxyquinolinolato-lithium (Liq) and alumina as electron injection and cathode layers, respectively, were deposited by thermal evaporation at 5 × 10$^{-5}$ Pa. Furthermore, the organic layers were deposited at rates of 0.2–3 Å s$^{-1}$. After the organic film deposition, the Liq and alumina layers were deposited at rates of 0.1 and 3 Å s$^{-1}$, respectively. The emitting area of the device is about 0.09 cm$^2$. The current density–voltage–luminance ($J$–$V$–$L$), L–EQE curves and electroluminescence spectra were measured using a Keithley 2400 source meter and an absolute EQE measurement system (C9920-12, Hamamatsu Photonics).

Data availability
The data that support the plots within this paper and other findings of this study are available from the corresponding author on reasonable request. Source Data are provided with this paper.

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Acknowledgements
This work was funded by the National Natural Science Foundation of China (grant no. 52130308 to C.Y.), the Shenzhen Science and Technology Program (grant nos. KQTD20170330110107046 and ZDSYS20210623091813040 to C.Y.) and the China Postdoctoral Science Foundation (grant no. 2021M692183 to Y.X.H.). We thank C. Zhong (Department of Chemistry, Wuhan University) for the assistance with theoretical calculations, as well as Y. Gu and X. Zhou (TCL China Star Optoelectronics Technology) for their assistance with the optical simulation of the devices. We also thank the Instrumental Analysis Center of Shenzhen University for analytical support.

Author contributions
C.Y. supervised the projects, C.Y., Y.X.H., Z.H. and Y.Z. designed the TADF emitters. Y.X.H., T.H. and Y.Qi synthesized emitters. Y.X.H. characterized the emitters and measured the photophysical and electrochemical properties. J.M. and H.X. fabricated the OLED devices, measured the electroluminescence and prepared thin films. Y.X.H. and H.L. performed theoretical calculations. Y.Qiu conducted the transient photoluminescence measurements. Y.X.H., X.C. and C.Y. contributed to the manuscript writing. Y.X.H., H.L., J.M. and C.Y. contributed to discussions. All authors discussed the progress of the research and reviewed the manuscript.

Competing interests
SZU has filed patent applications on materials and devices. C.Y., Y.X.H. and J.M. are the authors of the invention. CN patent application no. 2021113469101 (pending). The other authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41566-022-01083-y.

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Peer review information Nature Nanotechnology thanks Fernando Dias and Hironori Kaji for their contribution to the peer review of this work.

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