RSC Advances

Nopinone-based aggregation-induced emission (AIE)-active difluoroboron β-diketonate complex: photophysical, electrochemical and electroluminescence properties†

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Four difluoroboron (BF2) β-diketonate nopinone complexes 3a–3d that exhibited typical aggregation-induced emission (AIE) properties were synthesized using the natural renewable β-pinene derivative nopinone as the starting material. The thermal, photophysical, electrochemical and electroluminescence properties as well as the AIE properties of complexes 3a–3d were analyzed systematically. The data of photophysical and electrochemical demonstrated that compound 3b with a methoxy group exhibited the largest bathochromic shift, the highest absolute photoluminescence quantum yields and narrowest optical bandgap among 3a–3d. Using 3b as the emitter, electroluminescent (EL) device I exhibits blue-green light with CIE coordinates of (0.2774, 0.4531) and showed a better performance with a luminous efficacy (ηL) of 7.09 lm W−1 and correlated color temperature (Tc) of 7028 K. The results demonstrate that new AIE compounds are promising solid-state luminescent materials with practical utility in electroluminescent materials.

1. Introduction

In recent years, organoboron complexes as the most important type of fluorescent dyes,1–3 have caused great interest. Difluoroboron (BF2) complexes based on N- and O-donor ligands are known to show intense fluorescence in solution and solid state.4–6 Besides, they have outstanding fluorescence properties such as high quantum yield, large Stokes shifts, intense emission, thermal and photochemical stability.7–9 These features have been exploited in NIR7,10 and molecular probes,11 optical imaging,12,13 solar cells,14 oxygen15 and mechanical sensors,16,17 laser dyes,18 anion receptors19,20 and organogels.21 For example, some difluoroboron (BF2) β-diketonate complexes showed mechanochromic luminescence.22 In 2015, some new difluoroboron complexes were reported as biological oxygen sensors.23,24

Traditional luminophores generally suffer from the aggregation-caused quenching (ACQ) effect, which reduced the performance of traditional luminophores when used in optoelectronic devices. In 2001, Tang discovered the phenomenon of aggregation-induced emission (AIE): luminophores show non-fluorescent in solutions, but highly emissive in aggregate formation in or in crystalline state.25 The main cause of the AIE effects is restriction of intramolecular motions (RIM), including rotation and vibration along the C–C single bond.26 Many fluorescent organic dyes showing AIE properties are studied, they include tetraphenylethene,27,28 siloles,29–31 BODIPY dyes,32,33 triphenylethene,34,35 tetraphenyl-1,4-butadiene (TPBD),36 pentacenequinone37 and isophorone38,39 based dyes. Recently, the exploration of new AIE fluorophores is still a challenging field to synthetic chemist. In this paper, a simple strategy to synthesize high-performance solid-state light emitters with AIE property is proposed.

As a rich and cheap plant essential oils, the annual output of turpentine is about 100 000 tons or more. Nopinone is a derivative synthesized from β-pinene, which is a main ingredient of turpentine. In recent years, many nopinone derivatives have been synthesized such as 3-cyanopyridine derivatives,40 chiral 1,3-aminoalcohols and 1,3-diols,41 terpenyl diselenides,42 quinazolin-2-amine nopinone derivatives.43 However, there is no work about using the pinane frame to construct some new EL materials.

In this paper, we designed and synthesized four novel nopinone derivatives-containing difluoroboron β-diketonate groups. The synthetic route is illustrated in Scheme 1. The structures of these compounds are characterized with 1H NMR,
A solution of nopinone (2 mol) dissolved in ethylene glycol/C14ogravimetric analysis (TGA) was carried out on a TGA 2050 solidi
stirred su
Devices was fabricated by embedding the luminophores and
transient state
10 mV s
electrode and an Ag/AgCl reference electrode, the scan rate was
using a conventional three-electrode con
electrochemical analyzer. The measurements were determined
weight losses. Cyclic voltammetry was taken on a CHI-600E

2.3. Synthesis

2.3.1. General procedure for synthesis of compounds 2a–2d
A solution of nopinone (2 mol) dissolved in ethylene glycol
dimethyl ether was added to a suspension of NaH (6 mol) in
ethylen glycol dimethyl ether.41 The mixture was refluxed for
0.5 h, whereupon compounds 1a–1d (3 mol) dissolved in ethylene glycol dimethyl ether was added to the reaction mixture under reflux. The reacted mixture was quenched by addition of EtOH (95%) after 7 h, and it was extracted with ethyl acetate, and the organic layers were washed with saturated brine to neutrality. After solvent evaporation, the yellow crude crystals were recrystallized from methanol to give 2a–2d.

Compound 2a was a pale yellow solid, yield: 69.2%, mp:
127.2–128.8 °C.1H NMR (400 MHz, CDCl3) δ: 15.61 (s, 1H), 7.64–
7.57 (m, 2H), 7.24 (d, J = 8.0 Hz, 2H), 2.70 (dd, J = 3.1, 1.2 Hz,
2H), 2.61–2.49 (m, 2H), 2.40 (s, 3H), 2.28 (tt, J = 6.0, 3.1 Hz, 1H),
1.45 (d, J = 9.5 Hz, 1H), 1.34 (s, 3H), 0.96 (s, 3H).13C NMR (100
MHz, CDCl3) δ: 209.07, 173.14, 140.50, 132.45, 128.92, 128.16,
103.54, 54.72, 39.91, 39.50, 28.40, 27.80, 25.84, 21.53, 21.48. HRMS
(m/z): [M + Na] + calculated for C17H20O2Na+, 279.1361; found,
279.1356.

Compound 2b was a yellow solid, yield: 65.7%, mp:
113.2–113.8 °C.1H NMR (400 MHz, CDCl3) δ: 15.79 (s, 1H), 7.77–7.65
(m, 2H), 7.20–7.07 (m, 2H), 2.68 (t, J = 2.8 Hz, 2H), 2.66–
2.51 (m, 2H), 2.30 (tt, J = 6.0, 3.1 Hz, 1H), 1.45 (d, J = 9.5 Hz,
1H), 1.35 (s, 3H), 0.96 (s, 3H).13C NMR (100 MHz, CDCl3) δ:
209.76, 171.84, 161.13, 130.05, 127.72, 113.57, 103.09, 55.35,
54.64, 39.99, 39.47, 28.66, 27.86, 25.82, 21.49. HRMS (m/z): [M +
Na] + calculated for C16H17BrO2Na+, 295.1310; found, 295.1305.

Compound 2c was a pale yellow solid, yield: 45.8%, mp:
114.1–114.5 °C.1H NMR (400 MHz, CDCl3) δ: 15.59 (s, 1H), 7.78–7.65
(m, 2H), 7.20–7.07 (m, 2H), 2.68 (t, J = 2.8 Hz, 2H), 2.66–
2.51 (m, 2H), 2.30 (tt, J = 6.0, 3.1 Hz, 1H), 1.45 (d, J = 9.5 Hz,
1H), 1.35 (s, 3H), 0.96 (s, 3H).13C NMR (100 MHz, CDCl3) δ:
209.24, 171.81, 164.87, 162.38, 130.40, 115.34, 103.72, 54.71,
39.86, 39.54, 28.35, 27.76, 25.80, 21.52. HRMS (m/z): [M + Na] +
calculated for C16H17ClO2Na+, 283.1111; found, 283.1105.

Compound 2d was a yellow solid, yield: 59.1%, mp:
133.3–133.9 °C.1H NMR (400 MHz, CDCl3) δ: 15.51 (s, 1H), 7.60 (s, 4H),
2.69 (t, J = 2.9 Hz, 2H), 2.63–2.53 (m, 2H), 2.31 (tt, J = 6.0, 3.1 Hz,
1H), 1.47 (d, J = 9.6 Hz, 1H), 1.37 (s, 3H), 0.98 (s, 3H).13C NMR
(100 MHz, CDCl3) δ: 209.42, 171.40, 134.07, 131.50, 129.79,
124.66, 104.06, 54.77, 39.80, 39.56, 28.26, 27.73, 25.81, 21.55.
HRMS (m/z): [M + Na] + calculated for C15H15O2Br2Na+, 343.0310; found, 343.0304.

2.3.2. General procedure for synthesis of compounds 3a–3d
BF3·(C2H5)2O (1.0 mol) was added to a solution of compound 2a–2d (0.2 mol) in dry dichloromethane, and the reaction mixture was stirred for 2 h at 45 °C. After removal of the solvent, the yellow crude crystals were recrystallized from methanol to give 3a–3d.

Compound 3a was a pale yellow solid, yield: 92.6%, mp:
139.3–139.6 °C.1H NMR (400 MHz, CDCl3) δ: 7.87–7.80 (m, 2H),
7.30 (d, J = 8.1 Hz, 2H), 2.94–2.83 (m, 2H), 2.84–2.74 (m, 1H),
2.68 (dd, J = 11.0, 5.7 Hz, 1H), 2.44 (s, 3H), 1.49 (d, J = 10.1 Hz,
1H), 1.42 (s, 3H), 1.26 (s, 1H), 0.97 (s, 3H).13C NMR (100 MHz,
CDCl3) δ: 201.83, 179.42, 144.19, 130.60, 129.62, 129.33, 104.19,
51.25, 40.39, 39.79, 28.49, 28.41, 25.49, 21.72, 21.42. HRMS (m/ z): [M + Na] + calculated for C17H18BF2O2Na+, 327.1344; found,
327.1341.

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Compound 3b was a yellow solid, yield: 89.3%, mp: 147.7–148.2 °C. 1H NMR (400 MHz, CDCl3) δ: 8.04–7.96 (m, 2H), 7.04–6.92 (m, 2H), 3.90 (s, 3H), 2.89 (dd, J = 14.6, 3.0 Hz, 2H), 2.77 (t, J = 5.6 Hz, 1H), 2.73–2.60 (m, 1H), 2.42 (tt, J = 5.9, 3.0 Hz, 1H), 1.49 (d, J = 10.0 Hz, 1H), 1.42 (s, 3H), 0.97 (s, 3H). 13C NMR (100 MHz, CDCl3) δ: 200.80, 178.45, 163.72, 132.26, 125.68, 114.05, 103.54, 55.61, 51.17, 40.31, 39.90, 28.80, 28.57, 25.50, 21.39. HRMS (m/z): [M + Na]⁺ calculated for C17H19BF2O3+Na⁺, 391.0293; found, 391.0290.

Compound 3c was a white solid, yield: 81.9%, mp: 160.2–160.8 °C. 1H NMR (400 MHz, CDCl3) δ: 7.83–7.74 (m, 2H), 7.69–7.59 (m, 2H), 2.91–2.75 (m, 3H), 2.71 (dd, J = 10.6, 5.8 Hz, 1H), 2.43 (tt, J = 5.9, 3.1 Hz, 1H), 1.49 (d, J = 10.2 Hz, 1H), 1.43 (s, 3H), 0.97 (s, 3H). 13C NMR (100 MHz, CDCl3) δ: 202.81, 177.96, 166.66, 164.11, 132.13, 129.57, 115.94, 104.22, 51.38, 40.49, 39.75, 28.39, 25.47, 21.42. HRMS (m/z): [M + Na]⁺ calculated for C16H16BF3O2+Na⁺, 331.1093; found, 331.1091.

Compound 3d was a yellow solid, yield: 86.9%, mp: 175.2–175.7 °C. 1H NMR (400 MHz, CDCl3) δ: 7.83–7.74 (m, 2H), 7.69–7.59 (m, 2H), 2.91–2.75 (m, 3H), 2.71 (dd, J = 10.6, 5.8 Hz, 1H), 2.43 (tt, J = 5.9, 3.1 Hz, 1H), 1.49 (d, J = 10.2 Hz, 1H), 1.43 (s, 3H), 0.97 (s, 3H). 13C NMR (100 MHz, CDCl3) δ: 203.26, 178.01, 132.21, 131.97, 130.81, 128.07, 104.57, 51.45, 40.56, 39.71, 28.41, 28.20, 25.50, 21.47. HRMS (m/z): [M + Na]⁺ calculated for C16H16BBF2O2+Na⁺, 391.0293; found, 391.0290.

### 3. Results and discussion

#### 3.1. Synthesis

The synthetic routines of four fluorescent compounds were shown in Scheme 1. The compounds 2a–2d were prepared from nopinone and compounds 1a–1d according to the Claisen condensation. Target compounds 3a–3d were then synthesized by reaction of compounds 2a–2d with BF3·(C2H5)2O with high yields. The chemical structures of the synthesized compounds were confirmed by 1H NMR, 13C NMR, and HRMS. Compounds were readily soluble in common organic solvents like THF, chloroform, ethyl acetate. The structure of 2a was also verified by X-ray crystallography (Fig. S1†). Suitable single crystals of 2a for X-ray structural analysis was obtained by slow evaporation of methanol solution at room temperature.

#### 3.2. Photophysical properties

The photophysical properties of the resultant compounds 3a–3d in neat film were investigated. The UV-vis absorption spectra of 3a–3d at room temperature are shown in Fig. 1. The compounds 3c, 3a, 3d, 3b, exhibited a strong absorption maximum in neat film at 366 nm to 368 nm, 374 nm, and 388 nm, respectively. The photoluminescence (PL) spectra of 3a–3d at room temperature are shown in Fig. 1. All obtained compounds showed obvious fluorescence emission (emission maxima λem = 496 nm for 3b vs. 480 nm for 3d, 463 nm for 3a, and 441 nm for 3c, Table 1), which can be ascribed to the different electron density dispersed on the molecules. Obviously, compound 3c showed bathochromic shift due to the presence of electron-donating methoxy, which enhanced intramolecular charge transfer (ICT) process between the electron-donating methoxy and the electron-accepting BF4 unit, and led to shift the λmax to the long wavelength. The ICT process of these compounds were further studied in both experimental investigation (Fig. S2†) and theoretical calculation (Fig. 2).

The absolute photoluminescence quantum yields for compounds 3a–3d in solid state are summarized in Table 1, and the values of compounds 3a–3d were 1.99%, 47.16%, 4.94% and 21.03%, respectively. It was found that introduction of methyl, fluorine, bromine moiety did not make an obvious difference in

| Compound | λabs (nm) | λem (nm) | Φp (%) | τp (ns) | Kq (10⁹ s⁻¹) | Knr (10⁹ s⁻¹) |
|----------|----------|----------|--------|--------|--------------|--------------|
| 3a       | 368      | 463      | 1.99%  | 1.52   | 0.01         | 0.64         |
| 3b       | 388      | 496      | 37.16% | 4.52   | 0.08         | 0.14         |
| 3c       | 366      | 441      | 4.94%  | 1.10   | 0.04         | 0.86         |
| 3d       | 374      | 480      | 12.03% | 2.15   | 0.06         | 0.41         |

a Φp is the absolute photoluminescence quantum yields. b Radiative rate constant (kq = Φp/τp). c Non radiative rate constant (knr = (1 − Φp)/τp).
terms of the fluorescence lifetime (3a, $\tau_f = 1.52$ ns; 3c, $\tau_f = 1.10$ ns; 3d, $\tau_f = 2.15$ ns). However, compared with other compounds, the fluorescence lifetime of 3b substituted with methoxy has increased by 2 times (3b, $\tau_f = 4.52$ ns). Based on fluorescence lifetimes of these compounds, radiative and non-radiative rate constants ($k_r$ and $k_{nr}$) were respectively estimated. As shown in Table 1, methoxy group increased the $k_r$ (the radiative rate constant) and decreased the $k_{nr}$ (the non-radiative rate constant) of BF$_2$ complexes. Thus, the introduction of different substituent functional groups can significantly affect the photoluminescence properties of BF$_2$ complexes.

3.3. Electrochemical properties and theoretical calculations

The electrochemical properties of 3a–3d were examined using cyclic voltammetry. The cyclic voltammograms of the 3a–3d are shown in Fig. S2,† the onset oxidation potentials ($E_{\text{on}}$) were found to be 1.30, 1.26, 1.34 and 1.35 V for compounds 3a–3d. According to the equation [HOMO = $-(4.40 + E_{\text{on}})$], the HOMO energy levels were calculated. The lowest unoccupied molecular orbital energies ($E_{\text{LUMO}}$) is calculated based on the equation of $E_{\text{LUMO}} = E_{\text{HOMO}} + E_g$, in which energy band gap ($E_g = 4.1$ eV for 3a, 3.89 eV for 3b, 4.11 eV for 3c and 4.05 eV for 3d, respectively) were estimated from the UV-vis absorption. HOMO–LUMO gap is usually used to characterize the ICT occurred in chromophore molecules. The HOMO, LUMO and $E_g$ are listed in Table 2. The CV curves of these compounds remained unchanged under multiple successive scans, demonstrating their good stability against electrochemical oxidation.

To further investigate the relationship between the emission and the structure property of the four compounds at the molecular level, the geometrical structures of compounds 3a–3d were analyzed employing DFT calculations. The electron density distributions of target compounds are illustrated in Fig. 2. The electron clouds of the HOMOs and LOMOs for 3a, 3c, 3d were mainly distributed over whole molecule. The electron clouds of the HOMOs in 3b were mainly distributed over the whole molecule, and the electron clouds of the LUMOs were mostly distributed over BF$_2$dbm unit due to electron withdrawing ability of the BF$_2$dbm unit. These results further prove that the ICT process occurs from the donor to the acceptor moiety. The corresponded data are summarized in Table 2. According to the calculations, introduction of methoxy may reduce the HOMO–LUMO energy gap ($4.12$ eV for 3b, $4.24$ eV for 3d, $4.3$ eV for 3a and $4.33$ eV for 3c, respectively) which is consistent with the results of cyclic voltammetry. The HOMO and LUMO gap of compound 3b is lower than that of 3a, 3c, 3d, which could lead to a red-shift in the absorption and fluorescence spectra. The conclusion is coincident with the experimental results.

3.4. Thermal properties

The thermal stabilities of four new compounds were evaluated by thermogravimetric analysis (TGA) under a stream of N$_2$ with a scanning rate of 10 °C min$^{-1}$. Their TGA curves are shown in Fig. S3† and their degradation temperatures ($T_d$) for 5% weight loss are listed in Table 2. The degradation temperatures $T_d$ for compounds 3a–3d were 252.3, 296.6, 232.8 and 285.4 °C, respectively. The data demonstrate that the resulting compounds can possess good thermal properties, which is desirable for the application in electroluminescent materials.

3.5. Aggregation-induced emission performances

The PL emission spectra of resultant compounds 3a–3d in DMF/water mixtures with different water fractions ($f_w$: 0–90%) in Fig. S4–S6,† Fig. 3 reveals that the PL intensity of 3b is slightly weakened upon addition of a small amount of water ($f_w \leq 20\%$) and the dramatic enhancement of luminescence is observed for the water fraction ($f_w$) of 30%. Similar observation is seen for 3c, 3a and 3d. All compounds showed higher emission intensity when water fractions ($f_w$) was 90%.

According to the Fig. S7,† the emission of 3b is weaker in pure DMF solution owing to the twisted intramolecular charge transfer (TICT) emission. The emission spectra remained almost unchanged when the water volume fraction was gradually increased from 0% to 20%. When the water content was further increased from 30% to 90%, the fluorescence intensity was swiftly enhanced, which attributed to the restriction of intramolecular rotation (RIR)45–48 According to the Fig. S7,† the emission of 3b in the water fraction ($f_w$) of 60% is weaker than that of 50%, which is probably due to the difference in aggregate morphology.49,50 It is obvious that the poor solvent water could induce the fluorescence intensity increase, demonstrating the AIE characteristics of the four compounds.

![Table 2 Electrochemical properties and thermostability of 3a–3d](#)

| Compounds | HOMO (eV) | LUMO (eV) | $E_g$ (eV) | T_d (°C) |
|-----------|-----------|-----------|-----------|----------|
| 3a        | 5.70      | -5.94     | 1.60      | 4.10     | 3.40     | 252.3     |
| 3b        | 5.66      | -5.82     | 1.77      | 3.89     | 1.96     | 296.6     |
| 3c        | 5.74      | -5.10     | 1.63      | 4.11     | 4.33     | 232.8     |
| 3d        | 5.75      | -6.12     | 1.70      | 4.05     | 4.24     | 285.4     |

* Estimated from HOMO = $-(4.4 + E_{\text{on}})$; LUMO = HOMO + $E_g$.

* Estimated from the onset of the absorption spectra.
3.6. Electroluminescent devices

Owing to relatively high absolute fluorescence quantum yields of 3b and 3d, EL devices based on 3b and 3d were fabricated. As shown in Fig. 4 and Fig. S8, both of the devices I and II display blueish-green light (peak at 499.2 nm and peak at 500.4 nm, respectively), the Commission Internationale de L’Eclairage (CIE) coordinates of devices I and devices II are located at (0.2774, 0.4531) and (0.3084, 0.4800) respectively, which are close to their solid PL spectra.

As showed in Fig. 5 and Table 3, the EL performances of the luminescent materials substituted with methoxy was better than the luminescent materials substituted with bromine, which is identical to the order of photophysical properties in the solid state. For the device of I, a luminous efficacy ($\eta_p$) of 7.09 lm W$^{-1}$, a color rendering index ($R_a$) of 54.4 and a correlated color temperature ($T_C$) of 7028 K at a current density of 9.9 mA were achieved. Therefore, the nopinone derivative containing difluoroboron is still one effective strategy for new EL materials.

4. Conclusions

In summary, four novel nopinone derivative containing difluoroboron $\beta$-diketone groups 3a-3d were synthesized with a simple method. The photophysical experiments demonstrated that the maximum absorption wavelengths of new compounds were in the range of 360–390 nm and the maximum fluorescence wavelengths of new compounds were in the range of 440–500 nm. These compounds also exhibited emission enhancement in their aggregate state. Besides, four target compounds 3a-3d exhibited high thermal stabilities, which is necessary for fabricating long lifetime devices. Theoretical calculations (DFT) were performed to provide further insights into our experimental results. Furthermore, devices I and II were fabricated which displayed blueish-green EL emission (peak at 499.2 nm and 500.4 nm, respectively). Among the two devices, the device of I exhibited the highest device performance with a luminous efficacy ($\eta_p$) of 7.09 lm W$^{-1}$, a color rendering index ($R_a$) of 54.4 and a correlated color temperature ($T_C$) of 7028 K, which provide guidance for the design and synthesis of new efficient EL materials in the future.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The research was supported by the National Natural Science Foundation of China (No. 31470592), the Natural Science
Foundation of Jiangsu Province (Grants No. BK20151513), Jiangsu Provincial Key Lab for the Chemistry and Utilization of Agro-Forest Biomass, and Priority Academic Program Development of Jiangsu Higher Education Institutions, China.

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