Selective iodinated dipyrrolyldiketone BF_2 complexes as potential building units for oligomeric systems†

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Selective iodination at the α-pyrrole positions of dipyrrolyldiketone BF_2 complexes is a key procedure to afford mono- and bisiodinated derivatives as the starting materials of the coupling reactions for various utility molecules and covalently linked oligomer systems. Iodination can also be applied to the phenylene-bridging receptor dimer to obtain the derivatives selectively iodinated at the terminal α-pyrrole position(s).

Introduction

As 'binding sites' responsive to anions,[1,2] boron complexes (*e.g.* **1a–c**, Fig. 1)[3–6] based on 1,3-dipyrrolyl-1,3-propanediones[7–9] act as efficient acyclic anion receptors by the 'inversion' of pyrrole rings from the most stable conformations. The chemical modification of the periphery of the receptors would control the anion binding properties and behaviours related to the transformation of π-conjugated systems. For example, α-aryl-substitution as observed in **1b** is an efficient strategy for obtaining utility anion-responsive systems by using aryl moieties as the platforms for introducing various substituents to the receptors. In fact, receptors with long aliphatic chains at α-aryl units, such as **1c**, constitute anion-responsive supramolecular organogels based on π–π and van der Waals interactions.[6] However, the receptors **1b**,**c** have been prepared from aryl-substituted pyrroles as starting materials to obtain the corresponding dipyrrolyldiketones as the intermediates for BF_2 complexes. As the use of α-arylpyrroles is limited to the formation of 'monomers' at present, facile modifications of receptor frameworks and the extension of these frameworks to include promising higher oligomers would require other efficient synthetic strategies. β-Ethyl-substituted **2a** (Fig. 1), possessing free and fairly reactive α positions, is considered as a potential building block for oligomeric and polymeric system;[5] however, it is not so easy to afford α–α oxidatively coupled compounds chemically in a single step from **2a**. In this report, the selective iodination of **2a** and its subsequent coupling reaction to aryl-substituted anion receptors are reported.

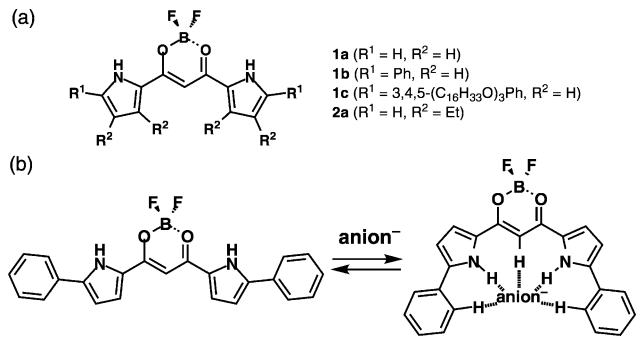

Fig. 1 (a) BF_2 complexes of dipyrrolyldiketones (β-free **1a–c** and β-ethyl-substituted **2a**) and (b) anion binding mode of **1b**.

Results and discussion

The treatment of **2a** with 2.7 and 1.1 equiv. of *N*-iodosuccinimide (NIS) in CH_2Cl_2 afforded diiodo-substituted **2a–I$_2$** and monoiodo-substituted **2a–I$_1$** in 84% and 66% yields, respectively (Fig. 2).[10] Bromination with *N*-bromosuccinimide (NBS) gave complicated mixtures containing species with a bromo-substituent at the fairly reactive 'bridging (*meso*) carbon'. Iodination with other reagents such as I_2 could not be achieved. In the case of the iodination of unsubstituted **1a** using NIS, complicated mixtures were obtained

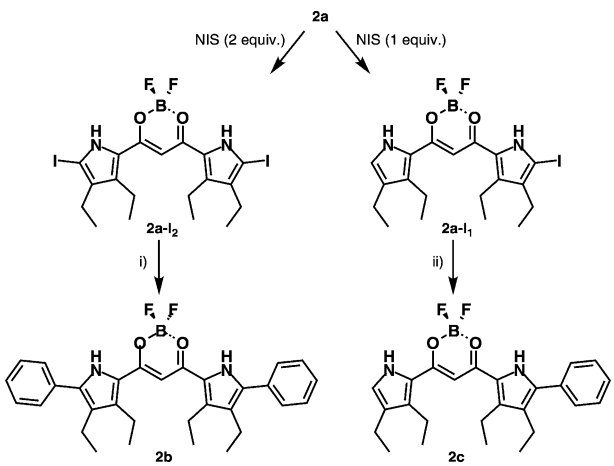

Fig. 2 Synthetic routes of **2b** and **2c** *via* iodinated derivatives **2a–I$_2$** and **2a–I$_1$**, respectively: i) phenylboronic acid (2.2 equiv.), $Pd(PPh_3)_4$ (0.08 equiv.) and Na_2CO_3 (7.2 equiv.) in DME–water and ii) phenylboronic acid (1.2 equiv.), $Pd(PPh_3)_4$ (0.08 equiv.) and Na_2CO_3 (5 equiv.) in toluene–DMF–water.

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† Electronic supplementary information (ESI) available: Complete ^{1}H NMR assignments of BF_2 complexes, optimized structures and anion binding behaviors for **2b**,**c** and X-ray structural analysis of **2a–I$_2$** and **2b**, CCDC reference numbers 680227 and 680228. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b806161k

due to the lack of selectivity for the reaction sites. However, the halogenation of dipyrrolyldiketones as precursors with 1 equiv. of NIS or NBS mainly afforded *meso*-halogenated species. Halogenated pyrroles are known to immediately decompose in solution and are difficult to handle. Although iodinated **2a–I$_2$** and **2a–I$_1$** are light-sensitive and gradually transformed into complicated mixtures such as dimeric species in solution, we can readily isolate and purify them by shielding them from light without significant problems, in order to use them for subsequent reactions. In the next step, Suzuki cross-coupling reactions of **2a–I$_2$** and phenylboronic acid (2.2 equiv.) afforded bisphenyl-substituted **2b** in 35% yield, while a similar procedure using **2a–I$_1$** and phenylboronic acid (1.2 equiv.) afforded monophenyl **2c** in 34% yield.[11–13] Chemical identification of **2a–I$_1$**, **2a–I$_2$** and **2b**,**c** were performed by ^{1}H NMR and MALDI-TOF and ESI-TOF-MS. As compared to the UV–vis absorption spectra of **1a** (432 nm), **1b** (500 nm) and **2a** (452 nm), those of **2b** and **2c** in CH_2Cl_2 were observed at 499 and 476 nm, respectively. This suggested that the factors for the redshifts by phenyl and ethyl moieties were partially cancelled by the distortion of phenyl units due to the sterical effects of β-ethyl substituents. Emissions in the same solvent were observed at, for example, 535 nm (**2b**) and 509 nm (**2c**), excited at each absorption maximum, with high quantum yields of 0.94 (**2b**) and 0.70 (**2c**), respectively. The use of NIS for the iodination of the 'β-alkyl-substituted BF_2 complex' is crucial for activating α-pyrrole positions in order to afford the desired aryl-substituted receptors. In addition, the formation of monoaryl-substituted **2c** from **2a–I$_1$** appears to be a more facile and efficient procedure than the synthetic route *via* the mixture of dipyrrolyldiketones obtained from equivalent amounts of α-unsubstituted and α-aryl-substituted pyrroles.

The solid-state structures of **2a–I$_2$** and **2b** have been determined by single-crystal X-ray analysis (Fig. 3).‡ Similar to other derivatives,[4,5] each molecule has a conformation of two pyrrole NHs facing the carbonyl oxygen. The terminal phenyl rings are tilted to the core plane consisting of 16 atoms at 24.29° and 31.89° for **2b**, which are slightly larger but comparable to those of **1b** (20.0° and 28.6°).[6] This observation suggests that the aryl rings of **2b** may be more canted to the core plane in the solution state than in the solid state, and they partially disrupt the π-conjugation to exhibit a more blue-shifted λ_{max} than expected from the crystal structure. Similar to **1a**,**b**, β-ethyl-substituted derivatives form dimers by N–H···F–B hydrogen bonding: the distances between N(–H)···F are 2.785–2.914 Å for **2a–I$_2$** and 2.905 Å for **2b**. In addition, self-assembled π–π stacking dimers, possibly formed by the sterical effects of the β-substituents, are constructed in the solid state in both cases, and these dimers are contrary to the infinite stacking structures observed in β-free **1a** and **1b**.

The anion binding of aryl-substituted dipyrrolyldiketone BF_2 complexes, as illustrated in Fig. 1b, has been suggested by the

‡ Crystal data for **2a–I$_2$** (from CH_2Cl_2–hexane): $C_{19}H_{23}BF_2N_2O_2I_2$, M_w = 614.00, monoclinic, $P2_1/n$ (no. 14), a = 16.022(5), b = 16.416(5), c = 32.819(10) Å, β = 101.164(5)°, V = 8468(5) Å^3, T = 123(2) K, Z = 16, D_c = 1.926 g cm^{-3}, μ(Mo-Kα) = 3.005 mm^{-1}, 52 127 reflections measured, 19807 unique (R_{int} = 0.0363). R_1 = 0.0658, wR_2 = 0.1524, GOF = 1.253 ($I > 2\sigma(I)$). CCDC 680227. Crystal data for **2b** (from CH_2ClCH_2Cl–hexane): $C_{31}H_{33}BF_2N_2O_2$, M_w = 514.40, triclinic, $P\bar{1}$ (no. 2), a = 10.962(7), b = 11.536(6), c = 12.261(6) Å, α = 77.123(17), β = 75.75(2), γ = 62.248(19)°, V = 1319.3(12) Å^3, T = 123(2) K, Z = 2, D_c = 1.295 g cm^{-3}, μ(Mo-Kα) = 0.090 mm^{-1}, 13 095 reflections measured, 5969 unique (R_{int} = 0.0408). R_1 = 0.0537, wR_2 = 0.1485, GOF = 0.977 ($I > 2\sigma(I)$). CCDC 680228.

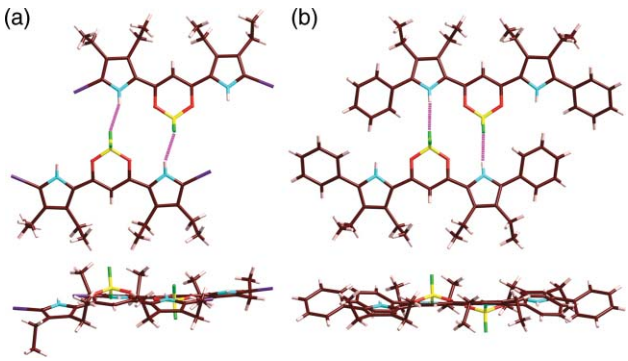

Fig. 3 Single-crystal X-ray structures (top and side views) of (a) **2a–I$_2$** (two of the four independent conformations) and (b) **2b** as dimeric forms by hydrogen bonding. Atom colour code: brown, blue, pink, red, yellow, green and purple represent carbon, nitrogen, hydrogen, oxygen, boron, fluorine and iodine, respectively.

^{1}H NMR spectral changes of, for example, **2b** (1 mM), upon the addition of Cl^- as a tetrabutylammonium (TBA) salt (3 equiv.) in CD_2Cl_2; the signals of NH, bridging CH and *o*-CH of the aryl moieties at 9.49, 6.52 and 7.52 ppm, respectively, vanish and the corresponding signals of the complexes are generated at 11.95, 8.54 and 7.78 ppm, respectively. This result suggests that **2b** forms a pentacoordinated anion complex in solution, as observed in **1b**.[6] The binding constants (K_a) of **2b** and **2c**, summarized in Table 1, have been determined by the UV–vis absorption spectral changes in CH_2Cl_2; the λ_{max} values of **2b** and **2c** at 499 and 476 nm are moderately shifted to 502 and 477 nm, respectively, upon the addition of Cl^- with smaller absorbances. Here, **2b**,**c** exhibit high K_a values for anions, even though they are linear non-'preorganized' receptors. In comparison with α-free **2a**, however, the decreased K_a values of **2b**,**c**, *e.g.* 2700 mol^{-1} dm^3 for **2b**, 4200 mol^{-1} dm^3 for **2c** and 6800 mol^{-1} dm^3 for **2a**, suggest that the introduction of aryl moieties to **2a** is not effective for the binding of anions, particularly large oxoanions for **2b**. This trend of K_a values obtained by aryl-substitutions is more remarkable than that in the β-free receptors, **1a** and **1b**, which have comparable K_a except for oxoanions. These results suggest that the terminal *o*-CH is effective for spherical halide anions but does not work efficiently in **2b**,**c** due to the stercial hindrance by β-ethyl moieties.

Density functional theory (DFT) studies (B3LYP/6-31G** level)[14] have estimated the relative stabilities of preorganized conformations, adequate for anion binding, possessing two 'inverted' pyrrole rings. The preorganized structures of **2b** and

Table 1 Binding constants (K_a, mol^{-1} dm^3) of **2b** and **2c** as well as **1a**,**b** and **2a** as references for anions as TBA salts in CH_2Cl_2, and the ratios of binding constants of **1a**,**b** and **2b**,**c** to that of **2a** (in parentheses)

	1a[a]	**1b**[b]	**2a**[c]	**2b**	**2c**
Cl^-	15 000 (2.2)	30 000 (4.4)	6800	2700 (0.40)	4200 (0.61)
Br^-	2100 (1.8)	2800 (2.3)	1200	300 (0.25)	600 (0.50)
$CH_3CO_2^-$	930 000 (4.4)	210 000 (1.0)	210 000	27 000 (0.13)	98 000 (0.47)
$H_2PO_4^-$	270 000 (3.0)	72 000 (0.79)	91 000	2200 (0.024)	36 000 (0.40)

[a] Ref. 4. [b] Ref. 6. [c] Ref. 5.

2c are estimated to be less stable than structures with two pyrrole NH facing carbonyl oxygens at 4.25 and 4.74 kcal mol^{-1} respectively, which is almost similar to β-ethyl-substituted **2a** (4.98 kcal mol^{-1})[5] and smaller than β-free **1a** (9.08 kcal mol^{-1})[4] and **1b** (8.71 kcal mol^{-1}).[6] These theoretical studies suggest that the relative stabilities of the preorganized states in **2b**,**c** due to β-ethyl moieties may enhance the binding affinities of anions as observed in **2a**; however, the effects of preorganization on **2b**,**c** appear to be cancelled by the sterical effects between β-ethyl and terminal phenyl units.

Examples of desired systems obtained using the procedure mentioned in this report are efficient anion sensors and stimuli-responsive π-conjugated oligomers.[15] In fact, the covalently linked dimer **3a** (Fig. 4) has been synthesized in 46% yield by the coupling reaction of **2a–I$_1$** (2 equiv.) with 1,3-benzenediboronic acid bis(pinacol)ester. By this procedure, α–α directly coupled dimer **3b** is also obtained in trace amount (*ca.* 0.5%). The λ_{max} value of **3a** of 489 nm, due to the incomplete π-conjugation at the *meta*-phenylene linkage, is in sharp contrast to the fairly broad absorption of **3b** observed around 520 nm (λ_{max}). Further iodination of phenylene-bridging dimer **3a** afforded bisiodinated dimer **3a–I$_2$** and monoiodinated **3a–I$_1$** in 84 and 41% using 2.3 and 1.0 equiv. of NIS, respectively. In these cases, iodinations at the bridging phenylene moiety have not been observed. The iodinated **3a–I$_2$** and **3a–I$_1$** are also potential subunits for formation of anion-responsive oligomers.

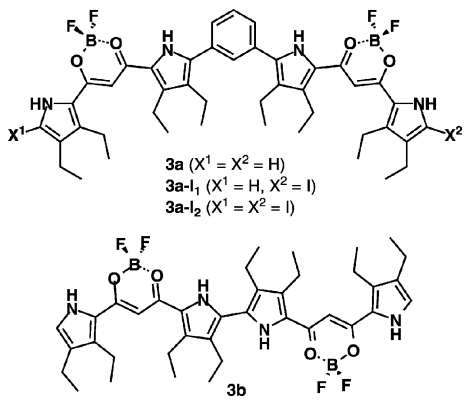

Fig. 4 Phenylene-bridging dimers **3a** and **3a–I$_{1,2}$** and direct-linked dimer **3b** from monoiodinated **2a–I$_1$**.

Conclusions

We have exhibited the selectively iodinated BF_2 complexes of dipyrrolyldiketones for obtaining various aryl-substituted acyclic anion receptors and their oligomers. It is remarkable to perform the extension of π-conjugation using cross coupling reactions at pyrrole α-positions, even though we have shown only low yields (*ca.* 30–50%) at the present moment. These moderate yields possibly originate from the reaction conditions for the dipyrrolyldiketone derivatives being difficult to optimise, the properties of these derivatives, as well as the sterical hindrance at α-positions by β-ethyl substituents. In fact, the coupling reactions in EtOH, which were used by Setsune *et al.* for arylpyrrole derivatives,[13] have afforded too small amounts of the desired compounds in our case, due to the unstable boron unit under the conditions. On the other hand, couplings with π-conjugated pentacycles, not hexacycles as observed in **2b** and **2c**, have been found to give somewhat higher yields due to smaller inner angles of pentacycles. Based on these observations, the protocol in this report can be applied to the formation of higher oligomers, which would exhibit the fascinating properties such as anion-driven folding behaviours.

Experimental

Starting materials were purchased from Wako Chemical Co., Nacalai Chemical Co., and Aldrich Chemical Co. and used without further purification unless otherwise stated. UV–visible spectra were recorded on a Hitachi U-3500 spectrometer. Fluorescence spectra and emission quantum yields were recorded on a Hitachi F-4500 fluorescence spectrometer and a Hamamatsu Quantum Yields Measurements System for Organic LED Materials C9920-02, respectively. NMR spectra used in the characterization of products were recorded on a JEOL ECA-600 600 MHz spectrometer. All NMR spectra were referenced to solvent. Matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI-TOF-MS) was recorded on a Shimadzu Axima-CFRplus using negative mode. Electrospray ionization mass spectrometric studies (ESI-MS) were recorded on a BRUKER microTOF using negative mode ESI-TOF method. TLC analyses were carried out on aluminium sheets coated with silica gel 60 (Merck 5554). Column chromatography was performed on Wakogel C-200, C-300, and Merck silica gel 60 and 60 H.

BF_2 complex of 1,3-bis(3,4-diethyl-5-iodopyrrol-2-yl)-1,3-propanedione, 2a–I$_2$

To a CH_2Cl_2 (50 mL) solution of BF_2 complex of 1,3-bis(3,4-diethylpyrrole-2-yl)-1,3-propanedione (**2a**)[5] (100.0 mg, 0.28 mmol) at room temperature was added *N*-iodosuccinimide (169.0 mg, 0.75 mmol). The mixture was stirred at room temperature for 3 h. After confirming the consumption of the starting material by TLC analysis, the mixture was washed with water and extracted with CH_2Cl_2, dried over anhydrous $MgSO_4$, and evaporated to dryness. The residue was then chromatographed over silica gel flash column (eluent: CH_2Cl_2) and recrystallized from CH_2Cl_2–hexane to afford **2a–I$_2$** (142.2 mg, 84%). $R_f = 0.49$ (CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.45 (s, 2H, NH), 6.35 (s, 1H, CH), 2.78 (q, $J = 7.8$ Hz, 4H, CH_2CH$_3$), 2.42 (q, $J = 7.8$ Hz, 4H, CH_2CH$_3$), 1.25 (t, $J = 7.8$ Hz, 6H, CH$_2$CH_3), 1.10 (t, $J = 7.8$ Hz, 6H, CH$_2$CH_3). MALDI-TOF-MS: m/z (% intensity): 611.99 (15), 612.99 (88), 613.99 (100). HRMS (ESI-TOF): m/z (% intensity): 612.9864. Calcd for $C_{19}H_{22}BF_2I_2N_2O_2$ ([M − H]$^-$): 612.9841. This compound was further characterized by X-ray diffraction analysis.

BF_2 complex of 1-(3,4-diethyl-5-iodopyrrol-2-yl)-3-(3,4-diethylpyrrol-2-yl)-1,3-propanedione, 2a–I$_1$

To a CH_2Cl_2 (70 mL) solution of BF_2 complex of 1,3-bis(3,4-diethylpyrrol-2-yl)-1,3-propanedione (**2a**)[5] (300.1 mg, 0.83 mmol) at room temperature was added *N*-iodosuccinimide (203.3 mg, 0.90 mmol). After stirring at room temperature for 3 h, the mixture was washed with water and extracted with CH_2Cl_2, dried over anhydrous $MgSO_4$, and evaporated to dryness. The residue was then chromatographed over silica gel flash column (eluent: CH_2Cl_2) and recrystallized from CH_2Cl_2–hexane to afford **2a–I$_1$**

(235.2 mg, 58%). $R_f = 0.40$ (CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.42 (s, 1H, NH), 9.34 (s, 1H, NH), 6.92 (d, J = 3.0 Hz, 1H, pyrrole-H), 6.42 (s, 1H, CH), 2.78 (qq, J = 7.8 Hz, 4H, CH_2CH$_3$), 2.48 (q, J = 7.8 Hz, 2H, CH_2CH$_3$), 2.43 (q, J = 7.8 Hz, 2H, CH_2CH$_3$), 1.25 (tt, J = 7.8 Hz, 6H, CH$_2$CH_3), 1.21 (t, J = 7.8 Hz, 3H, CH$_2$CH_3), 1.10 (t, J = 7.8 Hz, 3H, CH$_2$CH_3). MALDI-TOF-MS: m/z (% intensity): 486.09 (24), 487.09 (100), 488.09 (54). HRMS (ESI-TOF): m/z (% intensity): 487.0870. Calcd for $C_{19}H_{23}BF_2IN_2O_2$ ([M − H]$^-$): 487.0874.

BF_2 complex of 1,3-bis-(3,4-diethyl-5-phenylpyrrol-2-yl)-1,3-propanedione, 2b

A Schlenk tube containing **2a–I$_2$** (70.0 mg, 0.114 mmol), phenylboronic acid (30.6 mg, 0.251 mmol), tetrakis-(triphenylphosphine)palladium(0) (24.2 mg, 0.02 mmol), and Na_2CO_3 (87.8 mg, 0.82 mmol) was flushed with nitrogen and charged with a mixture of degassed 1,2-dimethoxyethane (5 mL) and water (0.5 mL). The mixture was heated at 90 °C for 18 h, cooled, then partitioned between water and CH_2Cl_2. The combined extracts were dried over anhydrous $MgSO_4$ and evaporated. The residue was then chromatographed over silica gel flash column (eluent: 10% EtOAc–hexane) to give **2b** (17.3 mg, 35%) as a pink solid. R_f = 0.38 (10% EtOAc–hexane). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.37 (s, 1H, NH), 7.53–7.51 (m, 4H, Ph-*o*-CH), 7.50–7.48 (m, 4H, Ph-*m*-CH), 7.43–7.39 (m, 2H, Ph-*p*-CH), 6.56 (s, 1H, CH), 2.86 (q, J = 7.8 Hz, 4H, CH_2CH$_3$), 2.62 (q, J = 7.8 Hz, 4H, CH_2CH$_3$), 1.35 (t, J = 7.8 Hz, 6H, CH$_2$CH_3), 1.20 (t, J = 7.8 Hz, 6H, CH$_2$CH_3). UV–vis (CH_2Cl_2, λ_{max}[nm] (ε, 10^5 M^{-1} cm^{-1})): 499.0 (1.21). Fluorescence (CH_2Cl_2, λ_{em}[nm] (λ_{ex}[nm])): 535.0 (499.0). MALDI-TOF-MS: m/z (% intensity): 512.26 (8), 513.25 (44), 514.26 (100). HRMS (ESI-TOF): m/z (% intensity): 513.2536. Calcd for $C_{31}H_{32}BF_2N_2O_2$ ([M − H]$^-$): 513.2536. This compound was further characterized by X-ray diffraction analysis.

BF_2 complex of 1-(3,4-diethyl-5-phenylpyrrol-2-yl)-3-(5-phenylpyrrol-2-yl)-1,3-propanedione, 2c

A Schlenk tube containing **2a–I$_1$** (250.0 mg, 0.512 mmol), phenylboronic acid (74.91 mg, 0.614 mmol), tetrakis-(triphenylphosphine)palladium(0) (57.8 mg, 0.05 mmol), and Na_2CO_3 (325.4 mg, 3.07 mmol) was flushed with nitrogen and charged with a mixture of degassed toluene and DMF (1 : 1, 8 mL) and water (0.2 mL). The mixture was heated at 80 °C for 12 h, cooled, then partitioned between water and CH_2Cl_2. The combined extracts were dried over anhydrous $MgSO_4$ and evaporated. The residue was then chromatographed over silica gel flash column (eluent: 0.5% MeOH–CH_2Cl_2) to give **2c** (75.6 mg, 34%) as a yellow solid. $R_f = 0.46$ (1% MeOH–CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.32 (s, 1H, NH), 9.29 (s, 1H, NH), 7.55–7.51 (m, 2H, Ph-*o*-CH), 7.50–7.47 (m, 2H, Ph-*m*-CH), 7.43–7.40 (m, 1H, Ph-*p*-CH), 6.94 (d, J = 3.0 Hz, 1H, pyrrole-H), 6.52 (s, 1H, CH), 2.85 (q, J = 7.8 Hz, 2H, CH_2CH$_3$), 2.80 (q, J = 7.8 Hz, 2H, CH_2CH$_3$), 2.61 (q, J = 7.8 Hz, 2H, CH_2CH$_3$), 2.49 (q, J = 7.8 Hz, 2H, CH_2CH$_3$), 1.33 (t, J = 7.8 Hz, 3H, CH$_2$CH_3), 1.28 (t, J = 7.8 Hz, 3H, CH$_2$CH_3), 1.22 (t, J = 7.8 Hz, 3H, CH$_2$CH_3), 1.19 (t, J = 7.8 Hz, 3H, CH$_2$CH_3). UV–vis (CH_2Cl_2, λ_{max}[nm] (ε, 10^5 M^{-1} cm^{-1})): 476.0 (1.12). Fluorescence (CH_2Cl_2, λ_{em}[nm] (λ_{ex}[nm])): 509.0 (476.0). MALDI-TOF-MS: m/z (% intensity): 437.21 (35), 438.22 (100), 439.23 (26) HRMS (ESI-TOF): m/z (% intensity): 437.2211. Calcd for $C_{25}H_{28}BF_2N_2O_2$ ([M − H]$^-$): 437.2222.

Phenylene-bridged dimer of 2a, 3a

A Schlenk tube containing **2a–I$_1$** (450.0 mg, 0.92 mmol), 1,3-phenyldiboronic acid 1,3-bis(pinacol)ester[16] (152.0 mg, 0.46 mmol), tetrakis(triphenylphosphine)palladium(0) (106.0 mg, 0.09 mmol), and Cs_2CO_3 (899.3 mg, 2.76 mmol) was flushed with nitrogen and charged with a mixture of degassed DMF (9 mL), toluene (9 mL), and water (0.2 mL). The mixture was heated at 90 °C for 12 h, cooled, then partitioned between water and CH_2Cl_2. The combined extracts were dried over anhydrous $MgSO_4$, and evaporated. The residue was then chromatographed over silica gel flash column (eluent: 0.5% MeOH–CH_2Cl_2) to give the dimer **3a** (167.5 mg, 46%) as a red solid. R_f = 0.30 (1% MeOH–CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.39 (s, 2H, NH), 9.30 (s, 2H, NH), 7.64 (s, 1H, phenylene-CH), 7.59–7.58 (m, 1H, phenylene-CH), 7.53 (m, 2H, phenylene-CH), 6.94 (s, 2H, pyrrole-H), 6.53 (s, 2H, CH), 2.84–2.82 (m, 4H, CH_2CH$_3$), 2.82–2.80 (m, 4H, CH_2CH$_3$), 2.64 (m, 4H, CH_2CH$_3$), 2.48 (m, 4H, CH_2CH$_3$), 1.30 (m, 6H, CH$_2$CH_3), 1.27 (m, 6H, CH$_2$CH_3), 1.20 (m, 12H, CH$_2$CH_3). UV–vis (CH_2Cl_2, λ_{max}[nm] (ε, 10^5 M^{-1} cm^{-1})): 489.0 (2.10). Fluorescence (CH_2Cl_2, λ_{em}[nm] (λ_{ex}[nm])): 511.0 (489.0). MALDI-TOF-MS: m/z (% intensity): 796.38 (47), 797.40 (100), 798.39 (50). HRMS (ESI-TOF): m/z (% intensity): 797.4045. Calcd for $C_{44}H_{51}B_2F_4N_4O_4$ ([M − H]$^-$): 797.4052.

Direct-linked dimer of 2a, 3b

Direct-linked dimer **3b** was obtained in 0.5% yield as a dark purple solid as one of the byproducts of the coupling reaction for **3a**. R_f = 0.33 (1% MeOH–CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.32 (s, 1H, inner NH), 9.27 (s, 1H, outer NH), 6.98 (d, J = 3.0 Hz, 2H, pyrrole-H), 6.54 (s, 1H, CH), 2.87–2.84 (m, 4H, CH_2CH$_3$), 2.83–2.79 (m, 4H, CH_2CH$_3$), 2.61 (q, J = 7.8 Hz, 4H, CH_2CH$_3$), 2.49 (q, J = 7.8 Hz, 4H, CH_2CH$_3$), 1.34 (t, J = 7.8 Hz, 6H, CH$_2$CH_3), 1.28 (t, J = 7.8 Hz, 6H, CH$_2$CH_3), 1.22 (t, J = 7.8 Hz, 6H, CH$_2$CH_3), 1.16 (t, J = 7.8 Hz, 6H, CH$_2$CH_3). UV–vis (CH_2Cl_2, λ_{max}[nm]): 520.0. Fluorescence (CH_2Cl_2, λ_{em}[nm] (λ_{ex}[nm])): 601.0 (520.0). MALDI-TOF-MS: m/z (% intensity): 720.37 (43), 721.37 (100), 722.38 (39). HRMS (ESI-TOF): m/z (% intensity): 721.3736. Calcd for $C_{38}H_{47}B_2F_4N_4O_4$ ([M − H]$^-$): 721.3738.

Bisiodinated derivative of 3a, 3a–I$_2$

To a solution of **3a** (232.4 mg, 0.291 mmol) in CH_2Cl_2 (70 mL) at room temperature was added *N*-iodosuccinimide (150.5 mg, 0.669 mmol). The mixture was stirred at room temperature for 7 h. After confirming the consumption of the starting material by TLC analysis, the mixture was washed with water, extracted with CH_2Cl_2, dried over anhydrous $MgSO_4$, and evaporated to dryness. The residue was then chromatographed over silica gel flash column (eluent: 1.2% MeOH–CH_2Cl_2) to afford **3a–I$_2$** (248.6 mg, 84%). $R_f = 0.25$ (CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.42 (s, 2H, NH), 9.41 (s, 2H, NH), 7.64 (s, 1H, phenylene-CH), 7.63–7.60 (m, 1H, phenylene-CH), 7.56–7.54 (m, 2H,

phenylene-CH), 6.48 (s, 2H, CH), 2.84 (q, $J = 7.8$ Hz, 8H, CH_2CH_3), 2.65 (q, $J = 7.8$ Hz, 4H, CH_2CH_3), 2.43 (q, $J = 7.8$ Hz, 4H, CH_2CH_3), 1.34 (t, $J = 7.8$ Hz, 6H, CH_2CH_3), 1.29 (t, $J = 7.8$ Hz, 6H, CH_2CH_3), 1.20 (t, $J = 7.8$ Hz, 6H, CH_2CH_3), 1.11 (t, $J = 7.8$ Hz, 6H, CH_2CH_3). MALDI-TOF-MS: m/z (% intensity): 1048.26 (52), 1049.20 (100), 1050.17 (48). HRMS (ESI-TOF): m/z (% intensity): 1049.1985. Calcd for $C_{44}H_{49}B_2F_4I_2N_4O_4$ ($[M - H]^-$): 1049.1985.

Monoiodinated derivative of 3a, 3a–I_1

To a solution of **3a** (296.4 mg, 0.321 mmol) in CH_2Cl_2 (80 mL) at room temperature was added *N*-iodosuccinimide (72.14 mg, 0.321 mmol). The mixture was stirred at room temperature for 14 h. After confirming the consumption of the starting material by TLC analysis, the mixture was washed with water, extracted with CH_2Cl_2, dried over anhydrous $MgSO_4$, and evaporated to dryness. The residue was then chromatographed over silica gel flash column (eluent: 1% MeOH–CH_2Cl_2) to afford **3a–I_1** (122.0 mg, 41%). $R_f = 0.38$ (3% MeOH–CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$, 20 °C): δ (ppm) 9.39 (s, 3H, NH), 9.29 (s, 1H, NH), 7.64 (s, 1H, phenylene-CH), 7.60 (m, 1H, phenylene-CH), 7.51–7.42 (m, 2H, phenylene-CH), 6.93 (s, 1H, pyrrole-H), 6.51 (s, 1H, CH), 6.45 (s, 1H, CH), 2.82–2.78 (m, 8H, CH_2CH_3), 2.64–2.63 (m, 4H CH_2CH_3), 2.46 (m, 2H, CH_2CH_3), 2.42–2.41 (m, 2H, CH_2CH_3), 1.32 (m, 6H, CH_2CH_3), 1.26 (m, 6H, CH_2CH_3), 1.20–1.17 (m, 9H, CH_2CH_3), 1.09 (t, $J = 7.8$ Hz, 3H, CH_2CH_3). MALDI-TOF-MS: m/z (% intensity): 922.29 (44), 923.31 (100), 924.30 (62). HRMS (ESI-TOF): m/z (% intensity): 923.3019. Calcd for $C_{44}H_{50}B_2F_4IN_4O_4$ ($[M - H]^-$): 923.3019.

Method for X-ray analysis

A single crystal of **2a–I_2** was obtained by vapor diffusion of hexane into a CH_2Cl_2 solution. The data crystal was a reddish purple prism of approximate dimensions 0.50 mm × 0.30 mm × 0.20 mm. A single crystal of **2b** was obtained by vapor diffusion of hexane into a CH_2ClCH_2Cl solution. The data crystal was a red prism of approximate dimensions 0.50 mm × 0.30 mm × 0.20 mm. In each case, data were collected at 123 K on a Rigaku RAXIS-RAPID diffractometer with graphite monochromated Mo-Kα radiation ($\lambda = 0.71075$ Å), and the structure was solved by direct method. The non-hydrogen atoms were refined anisotropically. The calculations were performed using the Crystal Structure crystallographic software package of Molecular Structure Corporation. CIF files (CCDC 680227, 680228) are available online as ESI.†

DFT Calculation

Ab initio calculations of **2b** and **2c** were carried out using Gaussian 03[14] and an HP Compaq dc5100 SFF computer. The structures were optimized, and the total electronic energies were calculated at the B3LYP level using a 6-31G** basis set.

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