Synthesis, Structure, and Properties of β-Vinyl Ketone/Ester Functionalized AzaBODIPYs from FormylazaBODIPYs

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ABSTRACT: Postfunctionalization of azaBODIPY (the BF2 complex of azadipyrromethene) is highly desirable due to the strong tunable absorption bands at wavelengths above 650 nm, and the wide-ranging applications of this class of dyes in biomedicine and materials science. Currently available postfunctionalization methods for this class of dyes have been limited to the Pd-catalyzed coupling reactions on β-halogenated (brominated or iodinated) azaBODIPY platforms. In this work, we report a new strategy for the facile postfunctionalization of the azaBODIPY chromophore with various vinyl ketone and vinyl esters based on a Wittig reaction on our previously developed β-formylazaBODIPYs and our recently developed β-bromo-β′-formylazaBODIPYs. Our strategy uses easily accessible starting materials and mild reaction conditions. It is highly compatible with various common phosphonium ylides (aliphatic, aromatic, and ester substituted ones). These resultant bromo-containing β-vinyl ketone/ester functionalized azaBODIPYs are potential photosensitizers and can be further functionalized via coupling reactions. The ester groups on some of these resultant azaBODIPYs can be further hydrolyzed to achieve the desired water solubility and conjugate with the biomolecule and solid surface.

INTRODUCTION

AzaBODIPY (the BF2 complex of azadipyrromethene, Chart 1) shows a strong absorption band at wavelengths above 650 nm, large molar extinction coefficients, and high photostability. This class of dyes has attracted wide-ranging research interest in biomedicine and materials science, for example, as photosensitizers (for photodynamic therapy), sensors, and near-infrared labeling agents.1–5 BODIPY, as the meso-carbon analogue of azaBODIPY (Chart 1), has been extensively studied.6,7 There are many well-established methods available for the facile postfunctionalization of BODIPY. By contrast, few research efforts have been devoted to the postfunctionalization of azaBODIPY. Recently, some postfunctionalization methods have developed based on Pd-catalyzed coupling (Suzuki,8 Stille,9 and Sonogashira,10 Figure 1) reactions8–11 on β-halogenated (brominated or iodinated) azaBODIPY. These postfunctionalization methods although elegant generally require the use of a transition metal catalyst. In addition, the yields are far from optimal (<50%). In some coupling reactions, a tedious purification process is required due to the partial removal of the BF2 unit under those reaction conditions.

As part of our continuous research efforts in the preparation of functionalized azaBODIPYs, we have recently reported several strategies (thiophene-fusion,12a “push-pull”12b and “conformation-restriction”12c) for the fine-tuning of the optical properties of azaBODIPYs. We have previously reported the regioselective β-formylation of BODIPYs and have successfully extended this reaction to the azaBODIPY system.13 Those resultant β-formylBODIPYs have received wide-ranging research interest in a highly diverse research field.14,15 We rationalized that these resultant β-formylazaBODIPYs may be applied for the Wittig reaction14,16 to achieve the facile postfunctionalization of the azaBODIPY chromophore (Figure 1). With our recent progress in the regioselective β-bromination of β-formylazaBODIPYs, we anticipate that the resultant β-bromo-β′-formylazaBODIPY may be used as a privileged platform in the facile postfunctionalization of the azaBODIPY system. Herein, we report the facile preparation of a series of β-vinyl ketone/ester functionalized azaBODIPYs via a straightforward Wittig reaction on β-formylazaBODIPY, as well as the X-ray structures, the photophysical properties, and the electrochemical properties of these resultant dyes.

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RESULTS AND DISCUSSION

Syntheses. \(\beta\)-FormylazaBODIPYs \(2a\)–\(c\) were prepared in good (75–86%) yields from readily available azaBODIPYs \(1a\)–\(c\) using our previously established formylation procedure (Scheme 1)\(^{13a}\) and were characterized by NMR and HRMS analysis. Their further regioselective bromination smoothly proceeded with liquid bromine \(17\) and generated the corresponding \(\beta\)-bromo-\(\beta\)′-formylazaBODIPYs \(3a\)–\(c\) in excellent (91–95%) isolated yields. These resultant \(\beta\)-formylazaBODIPYs \(2a\)–\(c\) and \(3a\)–\(c\) smoothly reacted with various readily available phosphonium ylide \(5a\)–\(c\)\(^{14d,16}\) under Wittig reaction conditions (80 °C in toluene), from which the desired \(\beta\)-vinyl ketone/ester functionalyzed azaBODIPYs \(4a\)–\(h\) were isolated as the major products (43–83%) isolated yields.

These resultant \(\beta\)-formylazaBODIPYs \(2a\)–\(c\) and \(3a\)–\(c\) smoothly reacted with various readily available phosphonium ylides \(5a\)–\(c\)\(^{13d,13e}\) under Wittig reaction conditions (80 °C in toluene), from which the desired \(\beta\)-vinyl ketone/ester functionalyzed azaBODIPYs \(4a\)–\(h\) were isolated as the major products in 43–83% yields (Scheme 2). These resultant azaBODIPYs \(4a\)–\(h\) were characterized via NMR and HRMS analysis. The structures of azaBODIPYs \(4a\) and \(4b\) and their key synthetic precursors \(2a\) and \(2b\) were further confirmed by X-ray analysis (Figure 2). This Wittig reaction uses readily available starting materials (\(\beta\)-formylazaBODIPYs and phosphonium ylide reagents) and mild reaction conditions and shows good compatibility with various functionalities. It was found that the electron-donating substituents in azaBODIPYs \(1\) increase the reactivity of this formylation and the subsequent Wittig reaction and the yields of these two reactions. The ester moiety may be further hydrolyzed to generate a carboxylic acid group, which provides the desired water solubility and a valuable site for conjugation with the biomolecule and solid surface.

The remaining bromo substituent in azaBODIPYs \(4d\), \(4e\), and \(4f\) provides the desired heavy-atom effect to facilitate their applications as photosensitizers. In addition, this bromo substituent also provides a valuable site for various coupling reactions including the Suzuki coupling reaction demonstrated in this work (Scheme 2). The Suzuki coupling of azaBODIPY \(4d\) with \(4-(\text{diphenylamino})\)phenylboronic acid smoothly proceeded to generate azaBODIPY \(4k\) in 47% isolated yield. The installation of triphenylamine, an important unit in many electronic devices, results in an interesting donor–azaBODIPY–acceptor (D–\(\pi\)–A) structure.

X-ray Structures. Crystals suitable for X-ray analysis of azaBODIPYs \(2a\), \(2b\), \(4a\), and \(4b\) (Figure 2) were obtained via the slow diffusion of petroleum ether into their dichloromethane solutions under ambient conditions. As expected, these azaBODIPYs all show an almost planar structure for the azaBODIPY core (defined by the central six-membered \(\text{C}_2\text{N}_3\text{B}\) ring and two adjacent five-membered pyrrole rings) and a perpendicular arrangement of the plane defined by \(F\)–\(B\)–\(F\) atoms to that of the azaBODIPY core. The \(B\)–\(N\) distances for these azaBODIPYs are within 1.55–1.58 Å, which indicates the usual delocalization of the positive charge. These azaBODIPYs show a characteristic core structure similar to most of the previously reported azaBODIPY systems.\(^{1c,12c}\) The dihedral angles of the four phenyl rings in the dipyrrin core are in the
range of 7.7−81.2° (Table S2), indicating the intramolecular hydrogen bondings between F and the hydrogen atoms on four phenyl moieties. The dihedral angles defined by the two pyrrrole units in azaBODIPYs 2a and 2b are 12.4 and 14.8°, respectively, which were reduced to 3.8 and 1.1°, respectively, for azaBODIPYs 4a and 4b. This indicates that the presence of the β-vinyl ester moiety reduces the distortion of the planar structure of the azaBODIPY chromophore. The average root-mean-square deviation of the 19 atoms (atoms 1−19 labeled in Figures S5 and S7) from the mean plane of the azaBODIPY 4a and 4b cores are 0.0037 and 0.0019 Å, respectively. This indicates that the β-vinyl ester moiety and the C8BN3 central core nearly stay at the same planar structure. Thus, the installation of this β-vinyl ester moiety indeed extends the π-conjugation of the chromophore.

**Photophysical Properties.** The photophysical properties of these resultant azaBODIPYs 4a−k and their key synthetic precursors 2a−c and 3a−c were investigated in chloroform as summarized in Table 1. Each of these dyes, except for 4k, shows an intense absorption band in the range of 650−690 nm with a molar extinction coefficient (57 400−82 600 cm−1 M−1) comparable to that of most azaBODIPYs appearing in the literature. In comparison with azaBODIPYs 2 and 3, each of the azaBODIPYs 4 shows an around 3−30 nm redshift of the absorption spectra. AzaBODIPY 4k shows two absorption bands (a strong absorption band centered at 688 nm and a

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**Scheme 2.** Synthesis of β-Vinyl Ketone/Ester Functionalized azaBODIPYs 4a−h and the Further Functionalization of 4d via Suzuki Coupling Reaction

**Figure 2.** Top and front views of the X-ray structures of (a) 2a, (b) 2b, (c) 4a, and (d) 4b. C, light gray; H, gray; N, blue; B, dark yellow; F, bright green; O, red.
azaBODIPYs may be attributed to the heavy atom effect of the bromo substituent on these azaBODIPYs, which makes azaBODIPYs potential photosensitizers for dye-sensitized solar cells. The weak fluorescence of azaBODIPY may be partially attributed to the extremely broad absorption bands of this dye (Figure 3a).

Each of the azaBODIPYs 4 shows a weak fluorescence emission in the range 690–730 nm (Table 1). The relatively lower fluorescence emission for those bromo-containing azaBODIPYs may be attributed to the heavy atom effect of the bromo substituent on these azaBODIPYs, which makes these azaBODIPYs potential photosensitizers for dye-sensitized solar cells. The weak fluorescence of azaBODIPY 4 may be attributed to the nonradiative decay associated with free rotation of the triphenylamine moiety and the internal charge transfer effect from the triphenylamine moiety to the azaBODIPY core.

The solvatochromic effects of three common organic solvents (toluene, chloroform, and methanol) on the absorption and emission properties of azaBODIPY 4a–k were investigated (Figures S11–S27) as summarized in Table S2. A slight blueshift of the absorption and emission band and a slight decrease in the fluorescence quantum yield were observed with increasing solvent polarity. For example, a slight blueshift of the absorption (from 685 to 672 nm) and emission band (from 719 to 715 nm) and a slight decrease in the fluorescence quantum yield (from 0.10 to 0.04) were observed for azaBODIPY 4a by changing the solvent from toluene to methanol. Similar solvatochromic behavior has been reported previously for the solution of azaBODIPY 1b.1c

**Electrochemical Properties.** The cyclic voltammetry of 1, 2a, 3a, 4d, and 4k were performed in deoxygenated dichloromethane at room temperature with tetrabutylammonium hexafluorophosphate (TBAPF<sub>6</sub>) as the supporting electrolyte (Figure 4). Most of these dyes show two reversible reduction waves and one reversible oxidation wave. AzaBODIPYs 2a and 4d have reduction potentials more negative than 1a. This indicates that the installation of electron-withdrawing substituents (formyl and vinyl ester groups) at the β-position of the chromophore increases the electron-deficiency of the chromophore, and makes azaBODIPY 2a and 4d more susceptible to reduction than 1a. A similar effect was observed for the installation of bromo substituent (3a). AzaBODIPY 4k, containing a strong electron-donating triphenylamine substituent, shows one irreversible reduction at −1.10 V. The highest occupied molecular orbital and lowest unoccupied molecular orbital energy levels for 4d and 4k were estimated based on their onset potential of the first oxidation and reduction waves (−5.59 and −4.08 eV for 4d, −4.95 and −3.51 eV for 4k, respectively). The calculated electrochemical energy band gap for 4k is 1.45 eV, which is in good agreement with its optical band gap.

**CONCLUSIONS**

In conclusion, we have developed a new strategy for the facile postfunctionalization of azaBODIPY based on a classic Wittig reaction on our previously reported β-formylazaBODIPYs and our recently developed β-bromo-β-formylazaBODIPYs. Our strategy uses readily available starting materials, requires mild reaction conditions, and features good yields and good compatibility with various functionalities. The installation of β-vinyl ketone/ester increases the π-conjugation of the system, whereas it has negligible influence on the planar structure of the chromophore. These resultant β-vinyl ketone/ester functionalized azaBODIPY dyes show intense absorption in the NIR range (660–690 nm). The resultant bromo-containing β-vinyl ketone/ester functionalized azaBODIPYs are potential photo-
sensitizers and can be further applied for coupling reactions to generate various $\beta\beta'$-difunctionalized $D-\pi-A$ dyes.

**EXPERIMENTAL SECTION**

**General.** Reagents and solvents were used as received from commercial suppliers unless noted otherwise. All reactions were performed in oven-dried or flame-dried glassware unless otherwise stated and were monitored by thin-layer chromatography (TLC) using 0.25 mm silica gel plates with a UV electrode and the scan rate is 50 mV s$^{-1}$.

**Photophysical Measurements.** UV–visible absorption and fluorescence emission spectra were recorded on commercial spectrophotometers (190–900 nm scan range) at room temperature (10 mm quartz cuvette). Relative fluorescence quantum efficiencies of BODIPY derivatives were obtained by comparing the areas under the corrected emission spectrum of the test sample in various organic solvents with that of Rhodamine B ($\Phi = 0.36$ in chloroform). Nondegassed, spectroscopic grade solvents and a 10 mm quartz cuvette were used. Dilute solutions (0.01 < $A < 0.05$) were used to minimize the reabsorption effects. Quantum yields were determined using eq 1

$$\Phi = \frac{F_r}{F_i} \times \frac{1 - 10^{-A_{ex}(\lambda_e)}}{1 - 10^{-A_{ex}(\lambda_e)}} \times \frac{n_i^2}{n_r^2} \tag{1}$$

where subscripts $x$ and $r$ refer, respectively, to our sample $x$ and a reference (standard) fluorophore $r$ with known quantum yield $\Phi_r$ in a specific solvent; $F$ stands for the spectrally corrected, integrated fluorescence spectra; $A_{ex}(\lambda_e)$ denotes the absorbance at the used excitation wavelength $\lambda_e$; and $n$ represents the refractive index of the solvent (in principle at the average emission wavelength).

**Cyclic Voltammograms.** Cyclic voltammograms of 1 mM 1a, 2a, 3a, 4d, and 4k were measured in dichloromethane solution, containing 0.1 M TBAPF$_6$ as the supporting electrolyte, a glassy carbon electrode as a working electrode, Pt wire as a counter electrode, and a saturated calomel electrode as a reference electrode at 50 mV s$^{-1}$ scanning rate at room temperature (Figure 4).

**Crystallography.** Crystals of 2a, 2b, 4a, and 4b suitable for X-ray analysis were obtained by the slow diffusion of petroleum ether into their dichloromethane solutions under ambient conditions. The vial containing this solution was placed, loosely capped, to promote the crystallization. A suitable crystal was chosen and mounted on a glass fiber using grease. Data were collected using a diffractometer equipped with a graphite crystal monochromator situated in the incident beam for data collection at room temperature. Cell parameters were retrieved using SMART software, which corrects for Lp and decay. The structure was solved by the direct method using the SHELXS-97 program and refined by the least squares method on $F^2$: SHELXL-97, incorporated in SHELXTL V5.10. CCDC-1547895 (2a), CCDC-1547896 (2b), CCDC-1519967 (4a), CCDC-1519968 (4b) contain the supporting crystallographic data for this article. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

**Synthesis.** AzaBODIPYs 1a–c$^{11b,12b}$ and phosphonium ylides 5a–c$^{16}$ were synthesized according to the literature.

**General Procedure for the Preparation of $\beta$-FormylazaBODIPYs 2a–c.** To the anhydrous dimethylformamide (3 mL) was slowly added POCI$_3$ (3 mL) at 0 °C under argon. It was left stirring for 30 min at 0 °C before addition of azaBODIPYs 1a–c (0.3 mmol) in 1,2-dichloroethane (10 mL). The resulting mixture was stirred at 70 °C for 2 h. The reaction mixture was cooled to room temperature and quenched via the slow addition of 10% aqueous solution of K$_2$CO$_3$ (200 mL). The reaction mixture was further stirred for 50 min and extracted with dichloromethane (30 mL × 3). The organic layers were combined, washed with water, and dried over anhydrous MgSO$_4$. The solvent was removed under vacuum. The crude product was further purified with column chromatography using the mixture of petroleum ether and dichloromethane ($\nu$/\nu = 1/2) as eluent to afford the desired $\beta$-formylazaBODIPYs 2a–c as a dark yellow solid in 75–86% isolated yields.

2a was obtained in 86% isolated yield (166 mg) from 1a (185 mg, 0.3 mmol). 1H NMR (300 MHz, CDCl$_3$) $\delta$: 9.73 (s, 1H), 8.10 (t, $J = 9.0$ Hz, 4H), 7.88 (d, $J = 9.0$ Hz, 2H), 7.70 (d, $J = 9.0$ Hz, 2H), 7.11 (s, 1H) 7.05–6.97 (m, 6H), 6.93 (d, $J = 9.0$ Hz, 2H), 3.92 (s, 3H), 3.89 (s, 3H), 3.88 (s, 3H), 3.87 (s, 3H). 13C NMR (75 MHz, CDCl$_3$) $\delta$: 186.7, 164.7, 163.5, 161.8,
General Procedure for the Preparation of azaBODIPYs 4a–j from Wittig Reaction. To freshly distilled toluene (3 mL) in a dry Schlenk tube was added β-formylazaBODIPYs 2a–c and 3a–c (0.14 mmol) and phosphorus ylides 5a–c (1 mmol). The mixture was degassed via three freeze–pump–thaw cycles at –78 °C before purging with argon again. The mixture was then heated to 80 °C. TLC was used to follow the reaction. Upon completion of the reaction, the mixture was cooled to room temperature and washed with brine. The organic layers were combined, dried over anhydrous Na2SO4, and the solvent was removed under vacuum. The residue was purified by column chromatography on silica using the mixture of petroleum ether and dichloromethane (v/v = 2/1) as eluent to afford the desired azaBODIPYs 4a–j as a dark cyan solid in 43–79% isolated yields.

Compound 4a was obtained in 56% isolated yield (202 mg) from 2a (322 mg, 0.5 mmol) and 5a (348 mg, 1 mmol). 1H NMR (300 MHz, CDCl3) δ: 8.04 (d, J = 9.0 Hz, 4H), 7.63–7.57 (m, 5H), 7.03 (t, J = 7.5 Hz, 5H), 6.94–6.87 (m, 4H), 5.78 (d, J = 15.0 Hz, 1H), 4.13 (q, J = 7.0 Hz, 2H), 3.91 (s, 3H), 3.88 (s, 3H), 3.84 (brs, 6H), 1.25 (t, J = 7.5 Hz, 3H). 13C NMR (75 MHz, CDCl3) δ: 167.5, 162.8, 162.3, 162.1, 160.8, 160.3, 155.5, 147.5, 145.0, 142.8, 139.7, 136.3, 132.5, 132.2, 131.8, 131.0, 130.3, 129.2, 124.6, 124.4, 123.4, 123.2, 119.0, 111.2, 114.4, 113.8, 60.3, 55.4, 55.3, 14.3. HRMS (APCI) Calcd for C35H25BF3N3O3 [M + H]+ 716.2738, found 716.2729.

Compound 4b was obtained in 43% isolated yield (141 mg) from 2b (292 mg, 0.5 mmol) and 5a (348 mg, 1 mmol). 1H NMR (300 MHz, CDCl3) δ: 8.08–8.02 (m, 4H), 7.64–7.57 (m, 5H), 7.50 (d, J = 9.0 Hz, 3H), 7.37 (brs, 3H), 7.11 (brs, 1H), 7.04 (d, J = 9.0 Hz, 2H), 6.94 (d, J = 9.0 Hz, 2H), 5.80 (d, J = 15.0 Hz, 1H), 4.14 (q, J = 7.0 Hz, 2H), 3.89 (s, 3H), 3.83 (s, 3H), 1.23 (t, J = 7.5 Hz, 3H). 13C NMR (75 MHz, CDCl3) δ: 167.3, 163.0, 162.4, 160.9, 156.0, 147.5, 145.2, 143.1, 140.2, 135.8, 132.4, 131.8, 131.0, 129.9, 129.3, 128.8, 128.6, 128.2, 127.9, 124.3, 123.0, 122.8, 121.0, 119.7, 114.5, 113.8, 60.3, 55.4, 55.3, 14.3. HRMS (APCI) Calcd for C35H25BF3N3O3 [M + H]+ 716.2738, found 716.2729.

Compound 4c was obtained in 50% isolated yield (163 mg) from 2c (292 mg, 0.5 mmol) and 5a (348 mg, 1 mmol). 1H NMR (300 MHz, CDCl3) δ: 8.06 (d, J = 9.0 Hz, 2H), 7.64–7.60 (m, 4H), 7.54–7.44 (m, 7H), 7.06 (d, J = 6.0 Hz, 2H), 6.96–6.90 (m, 3H), 5.68 (d, J = 15 Hz, 1H), 4.11 (q, J = 6.0 Hz, 2H), 3.92 (s, 3H), 3.87 (s, 3H), 1.21 (brs, 3H). 13C NMR (75 MHz, CDCl3) δ: 167.2, 162.7, 161.4, 160.6, 157.0, 145.6, 135.6, 133.9, 132.5, 131.5, 131.1, 130.8, 130.0, 129.8, 129.7, 128.6, 127.9, 124.5, 124.0, 119.7, 111.8, 114.3, 113.9, 113.3, 60.3, 55.4, 14.2. HRMS (APCI) Calcd for C35H25BF3N3O3 [M + H]+ 716.2727, found 716.2527.

Compound 4d was obtained in 63% isolated yield (249 mg) from 3a (361 mg, 0.5 mmol) and 5a (348 mg, 1 mmol). 1H NMR (300 MHz, CDCl3) δ: 7.87–7.85 (m, 2H), 7.78 (d, J = 9.0 Hz, 2H), 7.79 (d, J = 9.0 Hz, 2H), 7.77 (d, J = 9.0 Hz, 2H), 7.61 (d, J = 9.0 Hz, 2H), 7.50–7.46 (m, 6H), 7.02 (d, J = 9.0 Hz, 2H), 6.99 (d, J = 9.0 Hz, 2H), 3.91 (brs, 6H). 13C NMR (75 MHz, CDCl3) δ: 185.9, 162.2, 162.0, 161.7, 161.5, 146.1, 145.4, 143.8, 143.3, 134.2, 132.7, 131.3, 130.6, 130.2, 130.1, 129.3, 128.0, 128.5, 123.1, 123.0, 113.8, 113.5, 110.5, 55.4. HRMS (APCI) Calcd for C35H25BrBF3N3O3 [M + H]+ 664.1213, found 664.1209.

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142.1, 135.5, 132.5, 132.4, 131.6, 125.0, 123.9, 123.4, 122.4, 121.9, 120.7, 114.6, 113.9, 113.6(0), 113.5(S), 113.1, 109.1, 60.4, 55.4, 55.3, 29.7, 14.3. HRMS (APCI) Calcd for C_{59}H_{49}BF_{2}N_{4}O_{6} [M + H]^+ 788.2894, found 778.2888.

Compound 4h was obtained in 83% isolated yield (355 mg) from 2a (361 mg, 0.5 mmol) and 5b (410 mg, 1 mmol). ^1H NMR (300 MHz, CDCl3) δ: 7.92 (d, J = 9.0 Hz, 2H), 7.38 (d, J = 8.0 Hz, 2H), 7.10 (d, J = 7.8 Hz, 2H), 6.83 (d, J = 7.0 Hz, 2H). 1^3C NMR (75 MHz, CDCl3) δ: 166.6, 160.9, 153.8, 150.0, 146.4, 143.6, 133.0, 132.6, 132.4, 130.6, 130.4, 130.2, 129.5, 128.2, 127.7, 126.0, 122.2, 121.6, 121.3, 114.0, 113.6, 60.4, 55.6, 55.3, 14.2. HRMS (APCI) Calcd for C_{59}H_{49}BF_{2}N_{4}O_{6} [M + H]^+ 734.1632, found 734.1627.

Compound 4f was obtained in 57% isolated yield (209 mg) from 3c (331 mg, 0.5 mmol) and 5a (348 mg, 1 mmol). ^1H NMR (300 MHz, CDCl3) δ: 7.93 (d, J = 9.0 Hz, 2H), 7.71−7.69 (m, 2H), 7.63 (d, J = 9.0 Hz, 2H), 7.56−7.51 (m, 3H), 7.47 (bbr, 6H), 7.00 (d, J = 9.0 Hz, 4H), 6.53 (bbr, 5H), 4.11 (q, J = 7.6 Hz, 2H), 3.89 (bbr, 6H), 2.00 (t, J = 7.5 Hz, 3H). ^13C NMR (75 MHz, CDCl3) δ: 166.8, 160.9, 153.8, 150.0, 143.6, 143.4, 133.0, 132.6, 132.4, 130.6, 130.4, 130.2, 129.5, 128.2, 127.7, 126.0, 122.2, 121.6, 121.3, 114.0, 113.6, 60.4, 55.6, 55.3, 14.2. HRMS (APCI) Calcd for C_{39}H_{31}BBrF_{2}N_{3}O_{4} [M + H]^+ 734.1632, found 734.1618.

Compound 4e was obtained in 52% isolated yield (191 mg) from 3b (331 mg, 0.5 mmol) and 5a (348 mg, 1 mmol). ^1H NMR (300 MHz, CDCl3) δ: 7.88−7.79 (m, 5H), 7.61 (d, J = 8.3 Hz, 4H), 7.54 (s, 1H), 7.47−7.45 (m, 5H), 7.02 (d, J = 8.5 Hz, 4H), 5.74 (d, J = 16.3 Hz, 1H), 4.15 (q, J = 7.0 Hz, 2H), 3.92 (s, 3H), 3.89 (s, 3H), 1.24 (t, J = 7.0 Hz, 3H). ^13C NMR (75 MHz, CDCl3) δ: 198.1, 161.7, 161.4, 160.9, 160.8, 159.5, 158.3, 144.7, 144.5, 143.0, 142.4, 143.4, 132.4(8), 132.4(5), 131.6, 129.2, 124.8, 123.8, 122.4, 121.8, 113.9(4), 113.9(2), 113.6(2), 113.5(7), 109.3, 55.4, 55.3, 27.7. HRMS (APCI) Calcd for C_{57}H_{49}BF_{2}N_{4}O_{6} [M + H]^+ 764.1377, found 764.1370.

Compound 4d: To a dry Schlenk tube containing 4d (79 mg, 0.1 mmol), Pd(PPh)_4 (24 mg, 0.02 mmol), and triphenylamine monoboronic acid (202 mg, 0.7 mmol), were added freshly distilled toluene (2 mL) and the aqueous solution of Na_2CO_3 (1 M, 2 mL). The mixture was then degassed via three freeze−pump−thaw cycles at −78 °C before purging with argon again. The mixture was stirred at 80 °C. TLC was used to follow the reaction. Upon completion of the reaction, the reaction mixture was cooled to room temperature, and the mixture was washed with brine (30 mL × 3). The organic layers were combined, dried over anhydrous Na_2SO_4, and the solvent was removed under vacuum. The residue was purified by column chromatography on silica using the mixture of petroleum ether and dichloromethane (v/v = 1/2) to afford the desired 4d as a dark cyan solid in 47% (45 mg) isolated yield.

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The authors declare no competing financial interest.

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Notes

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ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.7b00393.

Additional photophysical data and spectra, copies of NMR spectra, HRMS and additional computational data for all new compounds (PDF)

Crystal structure data (CIF)

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Notes

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