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Synthesis and Properties of Covalently Linked AzaBODIPY–BODIPY Dyads and AzaBODIPY-(BODIPY)$_2$ Triads

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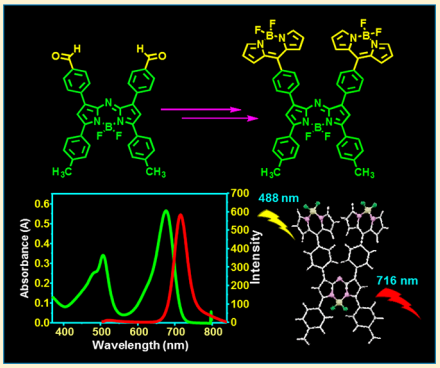
Supporting Information

ABSTRACT: The azaBODIPYs containing one and two formyl functional groups on the 1,7-aryl groups present at the azaBODIPY core were synthesized over sequence of steps and characterized by mass, NMR, absorption, and electrochemical techniques. The monoformylated and diformylated azaBODIPYs are very useful synthons to prepare a wide variety of new fluorescent compounds. The mono- and diformylated azaBODIPYs were treated with pyrrole under mild acidic conditions followed by column chromatographic purification to afford azaBODIPYs appended with one and two dipyrromethanyl groups. The dipyrramethanyl groups of azaBODIPYs were oxidized with DDQ and complexed with $BF_3{\cdot}Et_2O$ to obtain covalently linked azaBODIPY–BODIPY dyads and azaBODIPY-(BODIPY)$_2$ triads. The dyads and triads were characterized in detail by HR-MS, 1D and 2D NMR, absorption, fluorescence, and electrochemical techniques and the structure of one of the triads was deduced by X-ray crystallography. The crystal structure of azaBODIPY-(BODIPY)$_2$ triad revealed that the two BODIPY units were in perpendicular orientation with azaBODIPY unit. The absorption and electrochemical studies indicated a weak interaction among the BODIPY and azaBODIPY moieties and the moieties retain their independent characteristic features in dyads and triads. The preliminary fluorescence studies supported an efficient energy transfer from BODIPY unit(s) to azaBODIPY unit in dyads and triads.



INTRODUCTION

AzaBODIPYs resulted from the replacement of *meso*-carbon of BF_2-dipyrromethene (BODIPY) with nitrogen exhibiting novel absorption and fluorescence properties.[1] The BODIPYs generally absorb and emit in visible region with low to reasonable quantum yields. However, the properties of BODIPYs can be fine-tuned with suitable modifications and the appropriately modified BODIPYs can absorb and emit in visible-NIR region with high quantum yields. On the other hand, the azaBODIPYs show strong absorption and emission in the NIR region with high quantum yields.[2] In recent times, the chemistry of BODIPYs has grown exponentially. This is because of their simple and straightforward synthesis combined with their excellent photophysical properties.[3] BODIPYs can readily undergo different functionalization reactions and the functionalized BODIPYs can be used for the synthesis of complex BODIPYs which can have potential applications in various fields ranging from materials, biology, to medicine.[4] However, the azaBODIPYs were not extensively investigated like BODIPYs which may be partly because of their tedious multistep synthesis and unavailability of suitable and stable precursors.[5] Because of the nature of synthetic procedure and the instability of certain pyrrolic intermediates, azaBODIPYs always have aryl/alkyl groups at the 1-, 3-, 5-, and 7-positions.[6] Thus, the synthesis of azaBODIPYs is not simple and straightforward like BODIPYs. Furthermore, azaBODIPYs containing functional groups at the aryl groups or pyrrole carbons also require several synthetic steps. Thus, very few functionalized azaBODIPYs are available in literature to use them as building blocks to synthesize fluorescent azaBODIPY based systems and test their potential applications in various research fields. A perusal of literature reveals that the few functionalized azaBODIPYs that are available contain functional groups mostly on 3,5-aryl groups and few systems on direct 2,6-positions of azaBODIPY core.[7] However, the functionalized azaBODIPYs containing functional groups at the 1,7-aryl groups of azaBODIPY are very scarce.[8] Herein, we report the first examples of formyl functionalized azaBODIPYs **1a**/**2a** and **1b**/**2b** (Figure 1) where one or two formyl groups were introduced at the 1,7-aryl groups of azaBODIPY over a sequence of synthetic steps. The formyl functional groups are very useful as these functional groups can undergo Knoevenagel, Wittig, Schiff base condensations and are also useful for the synthesis of macrocycles, such as porphyrins, corroles, expanded porphyrins, etc. To show the application of formyl functionalized azaBODIPYs, we prepared azaBODIPY–BODIPY dyads, **3a** and **3b**, and azaBODIPY-(BODIPY)$_2$ triads, **4a** and **4b**, where azaBODIPY is covalently connected with one and two BODIPY units, respectively (Figure 1), and demonstrated an efficient energy transfer at singlet state from

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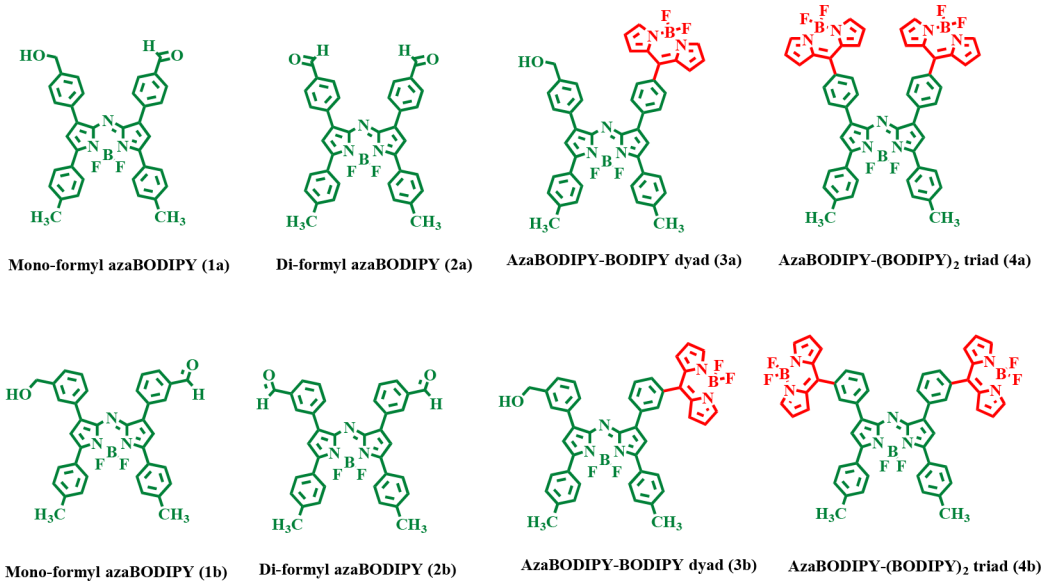
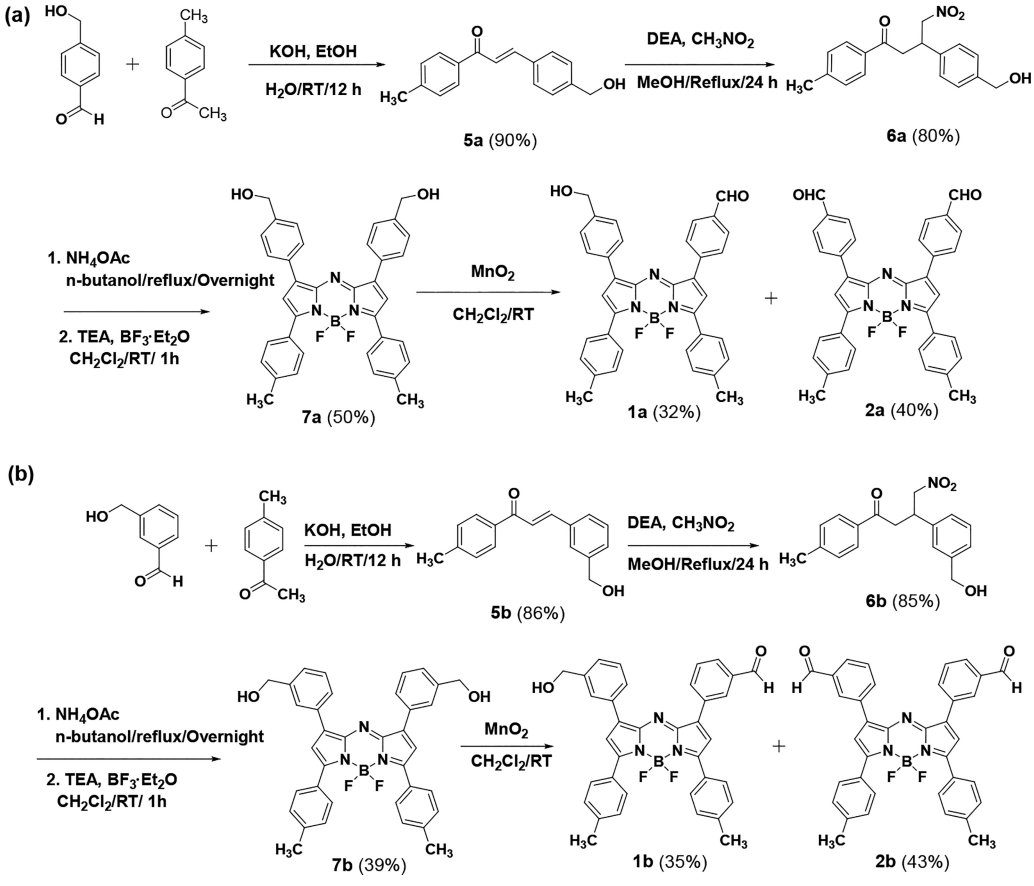


Figure 1. Structures of the newly synthesized mono-(**1a**, **1b**), diformyl azaBODIPYs (**2a**, **2b**), covalently linked azaBODIPY−BODIPY dyads (**3a** and **3b**) and azaBODIPY-(BODIPY)$_2$ triads (**4a** and **4b**).

Scheme 1. (a) Synthesis of Compounds 1a and 2a and (b) Synthesis of Compounds 1b and 2b



BODIPY unit(s) to azaBODIPY unit in dyads (**3a** and **3b**) and triads (**4a** and **4b**).

RESULTS AND DISCUSSION

Synthesis of Mono- and Diformyl Functionalized azaBODIPYs (1a, 1b, 2a, and 2b). The mono- and diformyl functionalized azaBODIPYs **1a**/**1b** and **2a**/**2b**, respectively, were synthesized over a sequence of steps as shown in Scheme 1.

The aldol condensation of corresponding hydroxy methyl benzaldehyde with 4-methylacetophenone results in the formation of chalcone **5a**/**5b**. The compounds **5a**/**5b** were reacted with nitromethane under Michael addition reaction conditions to afford compounds **6a**/**6b**. The compounds **6a**/**6b**

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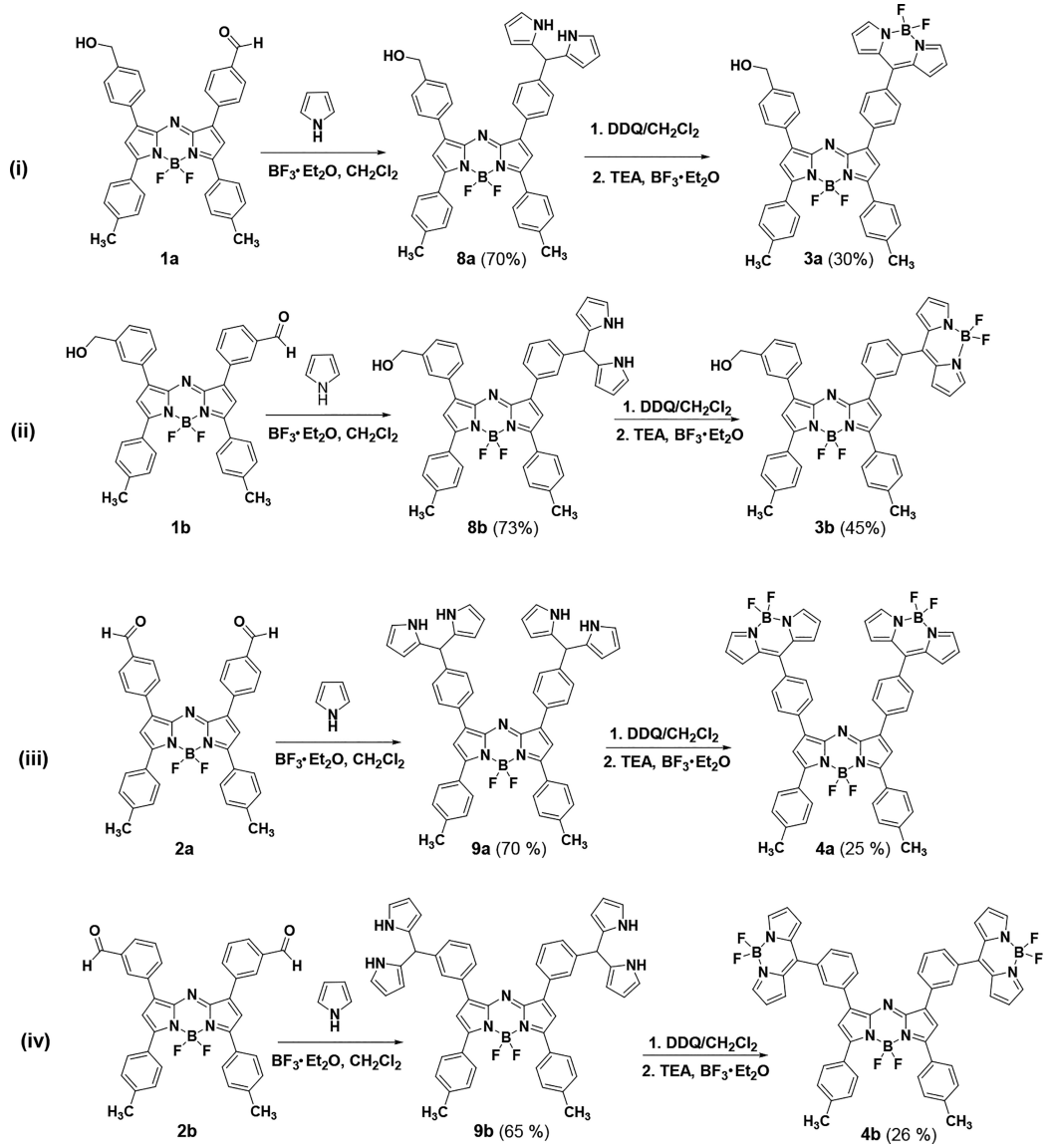
Scheme 2. Synthetic Methodology for azaBODIPY−BODIPY Dyads (3a and 3b) and azaBODIPY-(BODIPY)$_2$ Triads (4a and 4b)



then reacted with ammonium acetate in refluxing *n*-BuOH to afford corresponding azadipyrromethenes. The azadipyrromethene compounds were subsequently treated with $BF_3{\cdot}Et_2O$ in the presence of base followed by column chromatographic purification on silica afforded azaBODIPYs **7a** and **7b** containing 4-hydroxy methyl phenyl groups and 3-hydroxy methyl phenyl groups at the 1,7-positions, respectively. The compounds **7a** and **7b** were confirmed by HR-MS, ^{1}H, ^{13}C, ^{19}F, and ^{11}B NMR techniques (see Supporting Information). The compound **7a**/**7b** was then subjected to oxidation by treating with MnO_2 in CH_2Cl_2 at reflux temperature and the progress of the reaction was followed by TLC analysis. The reaction was slow and took ∼30 h for the formation of monoformyl azaBODIPY **1a**/**1b** and diformyl azaBODIPY **2a**/**2b** as judged by TLC analysis. The reaction mixture containing mixture of **1a**/**1b** and **2a**/**2b** was subjected to silica gel column chromatography and collected the fast moving diformyl azaBODIPY **2a**/**2b** followed by monoformyl azaBODIPY **1a**/**1b** using petroleum ether/ethyl acetate and afforded compound **2a**/**2b** in 40−43% yield and compound **1a**/**1b** in 32−35% yield as golden solids (Scheme 1a/1b).

The compounds **1a**/**1b** and **2a**/**2b** were confirmed by corresponding molecular ion peak in HRMS spectra and deduced the molecular structures by detailed 1D/2D NMR spectroscopy. In ^{1}H NMR, compound **2a** showed less number of resonances compared to compound **1a** because of its symmetric nature. The compound **1a** showed two singlets at 7.08 and 7.09 ppm for 2 and 6-pyrrole protons respectively; a singlet at 4.80 ppm for $-CH_2$ protons of $-CH_2OH$; a singlet at 10.07 ppm for −CHO; and six sets of resonances in the region 7.29−8.22 ppm for protons of aryl groups. The compound **2a** showed a singlet at 7.15 ppm for 2,6-pyrrole protons; a singlet at 10.10 ppm for two −CHO protons; and three sets of resonances at 7.31, 7.97, and 8.18 ppm for protons of aryl groups. Both compounds **1a** and **2a** showed typical triplet at ∼1.20 ppm in ^{11}B NMR and a typical quartet at ∼ −131 ppm in ^{19}F NMR. Similar NMR features were observed for formylated compounds **1b**/**2b**.

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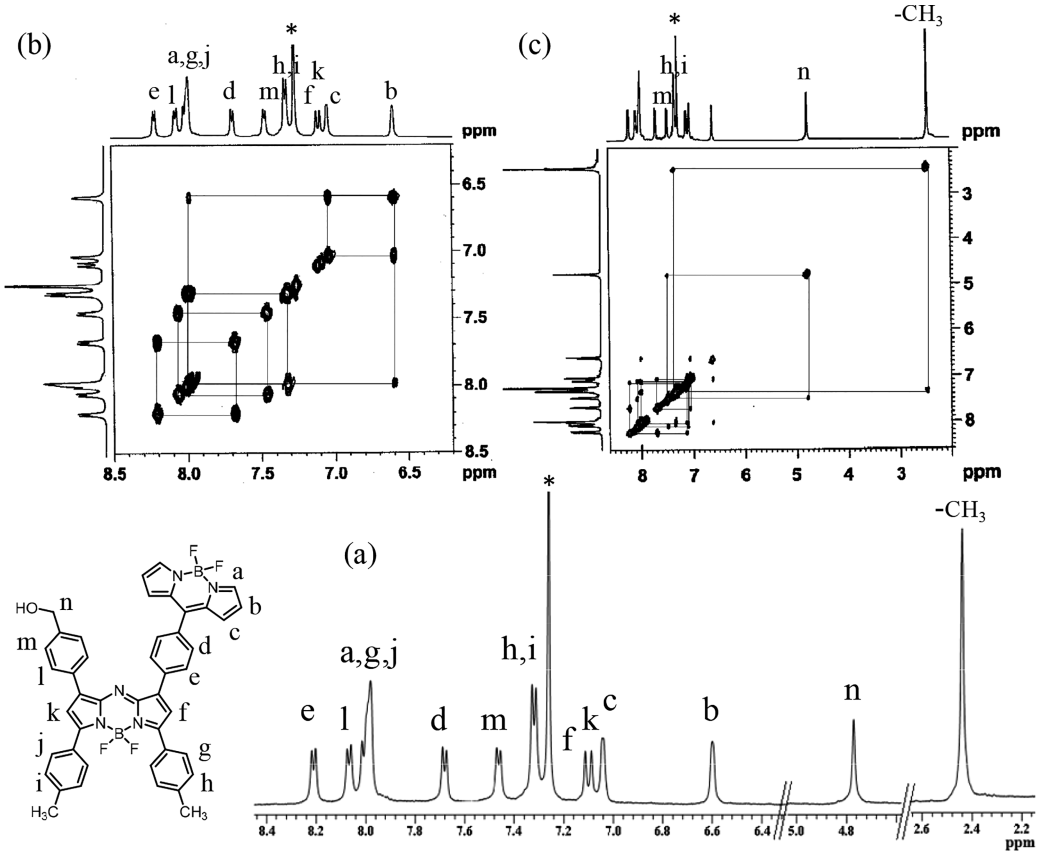

Figure 2. (a) ^{1}H NMR, (b) ^{1}H−^{1}H COSY, and (c) NOESY spectra of azaBODIPY−BODIPY dyad **3a** recorded in $CDCl_3$.

The formylated compounds **1a**/**1b** and **2a**/**2b** were used as building blocks to prepare azaBODIPY−BODIPY dyads **3a**/**3b** and azaBODIPY-$(BODIPY)_2$ triads **4a**/**4b** over sequence of steps as shown in Scheme 2. The compounds **1a**/**1b** and **2a**/**1b** were reacted with excess pyrrole in CH_2Cl_2 at room temperature in the presence of catalytic amount of $BF_3{\cdot}Et_2O$ under inert atmosphere for 15 min. A clear color change of the reaction mixture from green to blue was observed as the reaction progressed.

TLC analysis showed a new single polar spot corresponding to the desired product and disappearance of spot corresponding to the starting precursor. The crude compounds were subjected to silica gel column chromatography and afforded the dipyrromethanyl appended azaBODIPYs **8a**/**8b** and **9a**/**9b** in ∼70% yield. The formation of compounds **8a**/**8b** and **9a**/**9b** were confirmed by HR-MS, ^{1}H, ^{19}F, and ^{11}B NMR spectroscopic techniques (Supporting Information). The compounds **8a**/**8b** and **9a**/**9b** were subjected to oxidation by treating them with DDQ in CH_2Cl_2 at room temperature in open air for 30 min to generate the corresponding dipyrrin appended azaBODIPYs, which were without isolation, reacted further with $BF_3{\cdot}OEt_2$ in the presence of triethylamine for additional 30 min. The crude compounds were subjected to silica gel column chromatography and afforded pure azaBODIPY−BODIPY dyad **3a**/**3b** in ∼30% and azaBODIPY-$(BODIPY)_2$ triad **4a**/**4b** in ∼25% yields. The formation of compounds **3a**/**3b** and **4a**/**4b** were confirmed by HR-MS analysis. The dyads **3a**/**3b** and triads **4a**/**4b** were freely soluble in all common organic solvents and characterized in detail by 1D and 2D NMR spectroscopy.

NMR Studies. The ^{1}H, ^{1}H−^{1}H COSY, and NOESY NMR spectra of azaBODIPY−BODIPY dyad **3a** is presented in Figure 2 and azaBODIPY-$(BODIPY)_2$ triad **4a** is presented in Supporting Information (Figure S73). All protons in azaBODIPY−BODIPY dyad **3a** and azaBODIPY-$(BODIPY)_2$ triad **4a** were identified based on their location, integration, coupling constant, and cross-peak correlations in 2D NMR spectra. The azaBODIPY−BODIPY dyad **3a** showed more number of resonances in ^{1}H NMR spectrum because of its asymmetry. In azaBODIPY−BODIPY dyad **3a**, the six tolyl-CH_3 protons observed at 2.43 ppm showed NOE correlation with a resonance at 7.31 ppm which we identified as *h*- and *i*-types of protons of aryl groups present at the 3,5-positions. The *h*- and *i*-types of protons resonance at 7.31 ppm showed cross-peak correlation with a resonance at 8.00 ppm which we assigned as g- and *j*-types aryl protons. The two singlets at 7.08 and 7.11 ppm were assigned as *f*- and *k*-types of pyrrole protons based on their NOE correlations with *g*- and *j*-types protons. The *k-type* resonance at 7.08 ppm showed NOE correlation with *l*-type proton resonance at 8.06 ppm which in turn showed cross-peak correlation with *m*-type proton resonance at 7.46 ppm The singlet observed at 4.76 ppm was assigned to $-CH_2$ protons (*n*-type). The *f*-type resonance at 7.11 ppm showed NOE correlation with *e*-type proton at 8.21 ppm which in turn showed cross peak correlation with *d*-type of proton at 7.68 ppm.

The *d*-type resonance at 7.68 ppm showed NOE correlation with *c*-type pyrrole proton at 7.03 ppm which in turn showed cross-peak correlation with *b*-type resonance at 6.59 ppm and the *b*-type proton showed cross-peak correlation with a-type of proton at 8.00 ppm. Thus, all resonances were identified and

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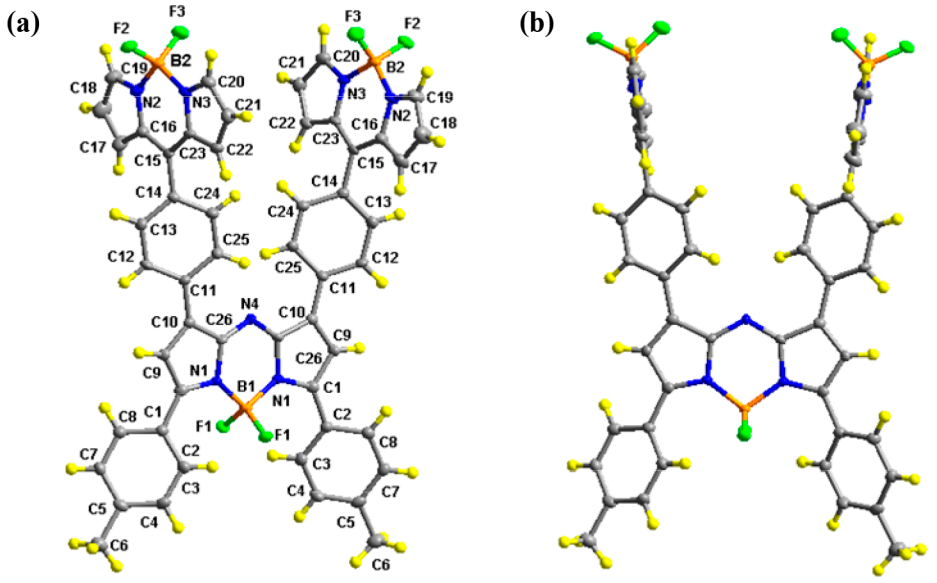

Figure 3. Single crystal X-ray structure of azaBODIPY-$(BODIPY)_2$ **4a**: (a) perspective view (b) side view (toward azaBODIPY plane). The thermal ellipsoids represent 50% probability.

Table 1. Photophysical and Electronic Properties of the Compounds[a]

				Φ			electrochemical data		
comp.	λ_{abs} (nm)	λ_{em} (nm)	log ε	BODIPY[b]	Aza-BODIPY[d]	τ (ns)	$E_{1/2red}$ [V]		
BODIPY	476, 501	518	4.33, 4.75	0.05			−0.81		
7a	665	696	4.66		0.26	2.08	−0.20		−0.93
7b	664	692	4.59		0.21	2.12	−0.24		−0.99
1a	676	707	4.57		0.28	2.58	−0.14		−0.80
1b	667	694	4.52		0.29	2.64	−0.19		−0.94
2a	684	718	4.81		0.28	2.80	−0.06		−0.65
2b	670	698	4.79		0.32	2.88	−0.15		−0.88
8a	668	699	4.82		0.29	1.79	−0.23		−0.98
8b	667	694	4.81		0.19	1.81	−0.23		−0.97
9a	669	699	4.84		0.27	1.47	−0.23		−0.92
9b	662	691	4.78		0.15	1.90	−0.25		−1.07
3a	484, 506, 680	710	4.25, 4.35, 4.40	≤0.001	0.30	2.87	−0.14	−0.62	−1.11
3b	479, 504, 669	698	4.29, 4.37, 4.81	≤0.001	0.21	2.55	−0.19	−0.64	−1.04
4a	483, 506, 675	716	4.40, 4.53, 4.75	≤0.001	0.34	3.08	−0.08	−0.60	−1.16
4b	480, 502, 673	700	4.38, 4.63, 4.50	≤0.001	0.39	n. d.	−0.15	−0.63	−1.16

[a] $\log(\varepsilon/mol^{-1}dm^3\ cm^{-1})$-molar extinction coefficient, λ_{abs} (absorption maxima), λ_{em} (emission maxima), Φ (quantum yield), τ (lifetime). [b] Emission observed at 518 nm; [c] λ_{ex} = 488 nm; [d] λ_{ex} = 630 nm, and λ_{em} is the emission peak maxima of the azaBODIPY moiety. n. d. (not determined).

assigned to deduce the molecular structure of azaBODIPY−BODIPY dyad **3a**. Similar approach was adopted in identifying and assigning all resonances of triad **4a**. Furthermore, azaBODIPY−BODIPY dyad **3a** and triad **4a** showed two typical quartets at ∼ −131 ppm and ∼ −144 ppm in ^{19}F NMR corresponding to azaBODIPY and BODIPY moieties and two typical triplets at ∼1.30 ppm and ∼0.50 ppm in ^{11}B NMR corresponding to azaBODIPY and BODIPY units, respectively. Similarly, the molecular structures of the compounds **3b**/**4b** were characterized by detailed NMR studies (Supporting Information).

X-ray Crystallography of AzaBODIPY−BODIPY Triad 4a. Suitable crystals for X-ray diffraction were obtained via slow diffusion of the pet ether solution of the compound **4a** into dichloromethane solution. The molecule **4a** crystallizes in monoclinic system with space group *C*2/*c*, containing four molecules in a unit cell. Crystallographic parameters are enlisted in table (see Supporting Information). The structural investigation reveals that the compound **4a** mainly comprises of three units; one central azaBODIPY unit, and two parallel BODIPY units which were covalently linked to the central azaBODIPY unit (Figure 3). The asymmetric unit of the molecule indicates the presence of overall half symmetry due to a 2-fold rotational axis as well as a mirror plane passing through a B1−N4 of the central azaBODIPY unit. This observation was indeed confirmed from exactly similar bond parameters between one-half of the molecule with the other half of the azaBODIPY unit. The *meso* carbons of the BODIPY unit are covalently linked to the *β* and *β*′′ positions of azaBODIPY via a benzene spacer group. Further, it is observed that the spacer group exhibits moderate degree of twisting from the mean plane of the azaBODIPY unit, making a dihedral angle of 24°. On the other hand, the terminal BODIPY units are appreciably distorted from the mean plane of azaBODIPY, making a dihedral angle of 83° between two distinct planes of each other. Similarly, the tolyl group attached to the C1 carbon of the

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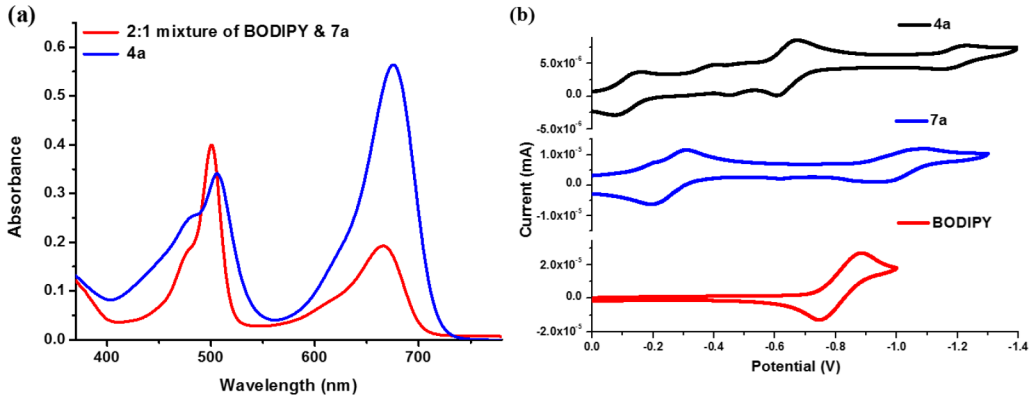

Figure 4. (a) Comparison of absorption spectra of azaBODIPY-$(BODIPY)_2$ triad **4a** (blue line) and a 2:1 mixture of BODIPY and azaBODIPY **7a** (red line) recorded in a chloroform and (b) Comparison of cyclic voltammogram of **BODIPY** (red line), compound **7a** (blue line), and **4a** (black line) recorded in CH_2Cl_2 with saturated calomel electrodes as reference electrode and 0.1 M TBAP as the supporting electrolyte recorded at a scan rate of 50 mVs^{-1}.

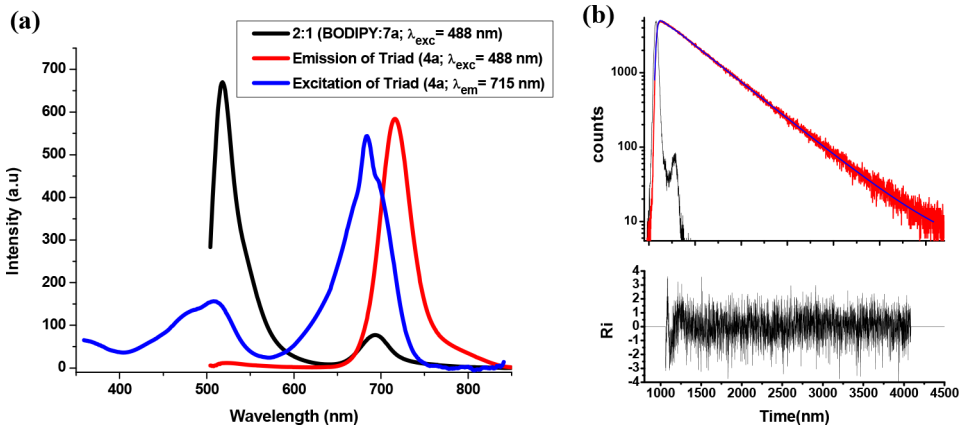

Figure 5. (a) Comparison of emission and excitation spectra of azaBODIPY-$(BODIPY)_2$ triad **4a** (red and blue lines, respectively) and a 2:1 mixture of BODIPY and azaBODIPY **7a** (black line) recorded in chloroform. (b) Fluorescence-decay profile and the corresponding weighted residual-distribution fit of the fluorescence decay of triad **4a** in chloroform. The excitation wavelength used was 630 nm and emission was detected at the emission-peak maxima (716 nm) of triad **4a** in chloroform.

azaBODIPY unit is slightly tilted by an angle of 32.88° from the central core of azaBODIPY plane.

The analysis of C−N bond distances (C26−N4 1.322(2) Å) in the bridging nitrogen and the respective carbons of pyrrole adjacent to it indicate appreciable extensive delocalization of π-electrons in the azaBODIPY unit. The six B−N bond lengths lie in the range of 1.541(3)−1.575(3) Å, which corroborates well with the reported B−N bond lengths bearing a testimony to usual delocalization between electron deficient boron and electron rich nitrogen center.[9] Thus, the crystal structural identity ascertains that the azaBODIPY unit and terminal BODIPY units in compound **4a** exists in perpendicular orientation with each other.

Spectral and Electrochemical Properties. The absorption, electrochemical and fluorescence properties of dyads **3a**/**3b** and triads **4a**/**4b** along with reference compounds were studied in $CHCl_3$ and the relevant data of all compounds are tabulated in Table 1. The comparison of absorption spectra of azaBODIPY-$(BODIPY)_2$ triad **4a** with its constituted monomers BODIPY and **7a** in 2:1 ratio is shown in Figure 4a. The triad **4a** showed same absorption features like its 2:1 ratio of constituted monomers but extinction coefficients of absorption bands were significantly enhanced. Thus, triad **4a** showed absorption bands at 675, 506, and a shoulder band at 480 nm. In this, the band at 675 nm is mainly due to azaBODIPY moiety whereas the band at 506 nm was due to BODIPY moiety. These observations indicate that the BODIPY and azaBODIPY moieties may interact but the interaction is not strong enough to alter the electronic properties of independent moieties significantly. Hence, BODIPY and azaBODIPY units in triad **4a** retain their individual identities. Similar observations were made with the dyads **3a**/**3b** and the triad **4b** compared to their constituted 1:1/2:1 monomers, BODIPY and azaBODIPY **7a**/**7b**.

The redox properties of dyads **3a**/**3b**, triads **4a**/**4b**, and their reference monomers were studied by cyclic voltammetry and differential pulse voltammetry at a scan rate of 50 mV/s using tetrabutylammonium perchlorate as the supporting electrolyte and the relevant redox data of all compounds is included in Table 1. The comparison of reduction waves of triad **4a** along with BODIPY and azaBODIPY **7a** is shown in Figure 4b. The triad **4a** showed three reversible reduction waves at −0.08, −0.60, and −1.16 V. In this, the reductions at −0.08 and −1.16 V were due to azaBODIPY moiety and the reduction at −0.60 V was due to BODIPY moiety. These assignments were based on the potentials observed for the constituted monomers (Figure 4b). The dyads **3a**/**3b** and triad **4b** also showed similar redox features (Figures S88 and S89). The inspection of data

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presented in Table 1 indicate that the first reduction potentials of both BODIPY and azaBODIPY moieties in dyads **3a**/**3b** and triads **4a**/**4b** were shifted toward less negative indicating that both the moieties became electron deficient and can be reduced easily compared to their corresponding monomers.

The steady state and time-resolved fluorescence studies were carried out on dyads **3a**/**3b** and triads **4a**/**4b** along with their associated reference compounds and the relevant data is included in Table 1. All azaBODIPY reference compounds were excited at 630 nm and emissions were noted at ∼680 nm and the quantum yields were in the range of 0.26−0.29. The dyads **3a**/**3b** and triads **4a**/**4b** were excited at 488 and 630 nm where BODIPY and azaBODIPY, respectively, absorbs strongly. In dyads **3a**/**3b** and triads **4a**/**4b**, the BODIPY moiety absorbs at higher energy and acts as energy donor whereas the azaBODIPY moiety absorbs at lower energy and acts as energy acceptor. The dyads **3a**/**3b** and triads **4a**/**3b**, upon excitation at 630 nm showed emission from azaBODIPY unit at ∼700 nm with quantum yield is in close match with the azaBODIPY monomers. The comparison of steady state fluorescence spectra of triad **4a** along with its constituted monomers BODIPY and azaBODIPY **7a** in 2:1 ratio recorded using wavelength of 488 nm is shown in Figure 5a. Upon excitation of triads **4a**/**4b** at 488 nm where BODIPY unit absorbs strongly, the emission of BODIPY unit at 520 nm was significantly quenched and a strong emission was observed at ∼700 nm corresponding to azaBODIPY moiety. On the other hand, the excitation of 2:1 mixture of BODIPY and azaBODIPY **7a**/**7b** at 488 nm, the emission was mainly noted from the BODIPY unit.

These observations support efficient energy transfer from donor BODIPY moieties to acceptor azaBODIPY moiety in triads **4a**/**4b**. Similar observations were made in dyads **3a**/**3b** where the emission from donor BODIPY moiety was quenched significantly because of transfer of energy to acceptor azaBODIPY moiety. We also recorded the excitation spectra of dyads **3a**/**3b** and triads **4a**/**4b** which matched closely with their corresponding absorption spectra supporting the energy transfer from donor BODIPY units to the acceptor azaBODIPY moiety (Figure S87) . Similar observations were reported earlier on related light harvesting BODIPY systems.[5d,10]

The singlet state lifetimes were measured using time-resolved single photon counting technique. The azaBODIPY monomers were excited at 630 nm and emissions were collected at their corresponding emission peak maxima. All fluorescence decays of azaBODIPY monomers were fitted to single exponential decay with lifetimes were in the range of 1.47 to 2.88 ns. The dyads **3a**/**3b** and triads **4a**/**4b** were excited at 440 nm and monitored at emission peak maxima of donor BODIPY moiety (520 nm) as well as excited at 630 nm and monitored at emission peak maxima of acceptor azaBODIPY moiety (716 nm). The representative fluorescence decay profile of triad **4a** obtained at 716 nm using the excitation wavelength of 630 nm is shown in Figure 5b. The decays of dyads **3a**/**3b** and triads **4a**/**4b** recorded at emission peak maxima of azaBODIPY moiety using excitation wavelength of either 440 or 630 nm were fitted to single exponential and the lifetimes were in the range of 2.8 to 3.1 ns. The singlet state lifetimes of azaBODIPY moieties of dyads **3a**/**3b** and triads **4a**/**4b** are higher than their corresponding dipyrromethanyl substituted azaBODIPYs **8a**/**8b** and **9a**/**9b**, respectively. This is attributed to restriction of nonradiative decay paths in dyads **3a**/**3b** and triads **4a**/**4b** due to BF_2 complexation of dipyrrin moiety unlike in **8a**/**8b** and **9a**/**9b** in which the dipyrramethanyl unit enhances the nonradiative decay channels. However, when fluorescence decays were monitored at donor BODIPY moiety at 520 nm using an excitation wavelength of 440 nm, the decays were very fast and not within our instrument limit (IRF limit at 440 nm is 290 ps). The detailed ultrafast photophysical studies are required to understand the excited state dynamics of dyads **3a**/**3b** and triads **4a**/**4b**.

CONCLUSIONS

In conclusion, we synthesized the first examples of formylated azaBODIPYs over sequence of steps. The formyl groups were introduced at the aryl groups present at the 1,7-positions of azaBODIPY core. The formylated azaBODIPYs are very useful synthons to prepare wide variety of azaBODIPY-based fluorescent systems. To demonstrate the further use of formylated azaBODIPYs, we prepared covalently linked azaBODIPY−BODIPY dyads and azaBODIPY-$(BODIPY)_2$ triads in decent yields. The crystal structure obtained for one of the azaBODIPY-$(BODIPY)_2$ triad showed that azaBODIPY and BODIPY moieties were in perpendicular orientation with each other. The absorption and electrochemical studies showed the features of both the constituted monomers with negligible changes indicating a weak interaction among the moieties and the BODIPY and azaBODIPY units retain their individual identities in dyads and triads. The preliminary fluorescent studies indicated an efficient energy transfer from donor BODIPY moiety to acceptor azaBODIPY moiety in dyads and triads. Detailed photophysical studies are underway to understand the excited state dynamics of dyads **3a**/**3b** and triads **4a**/**4b**.

MATERIALS AND METHODS

General Experimental. The chemicals, such as $BF_3{\cdot}Et_2O$ and 2, 3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ), were used as obtained from Aldrich. All other chemicals used for the synthesis were reagent grade unless otherwise specified. Column chromatography was performed on silica gel. The ^1H, ^{11}B, and ^{19}F NMR spectra were recorded in $CDCl_3$ on Bruker 400 and 500 MHz instruments. The frequencies for ^{13}C nucleus are 100.06 and 125.77 MHz, for ^{19}F nucleus are 376.49 and 470.56 MHz, and for ^{11}B nucleus are 128.37 and 160.46 MHz for 400 and 500 MHz instruments, respectively. Tetramethylsilane $[Si(CH_3)_4]$ was used as an internal standard for ^1H and ^{13}C NMR, tetrafluorotoluene as an external standard for ^{19}F NMR and boric acid as an external standard for ^{11}B NMR. Absorption and steady state fluorescence spectra were obtained with PerkinElmer Lambda-35 and PC1 photon counting spectrofluorometer manufactured by ISS, USA instruments, respectively. The elemental analyses were performed on a Thermo Quest microanalysis instrument. The fluorescence quantum yields (Φ) were calculated from the emission and absorption spectra by comparative method at the excitation wavelength of 488 nm using Rhodamine 6G (Φ = 0.88 in ethanol)[11] and at the excitation wavelength of 630 nm using 3,5-dianisyl−1,7-di(p-phenyl) azaBODIPY (Φ = 0.36 in chloroform)[12] as standard. The time-resolved fluorescence decay measurements were carried out at magic angle using a picosecond diode laser based time correlated single photon counting (TCSPC) fluorescence spectrometer from IBH, UK. All the decays were fitted to single exponential. The good fit criteria were low chi-square (1.0) and random distributions of residuals. Cyclic voltammetric (CV) studies were carried out with BAS electrochemical system utilizing the three electrode configuration consisting of a glassy carbon (working electrode), platinum wire (auxiliary electrode) and saturated calomel (reference electrode) electrodes. The experiments were done in dry dichloromethane using 0.1 M tetrabutylammonium perchlorate as supporting electrolyte. The HR mass spectra were recorded with a Q-TOF micro mass

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spectrometer. For UV−vis and fluorescence titrations, the solution for all compounds (1×10^{-5} M) was prepared by using spectroscopic grade $CHCl_3$ solvent.

X-ray Crystal Structure Analysis. Single-crystal X-ray structure analysis was performed on a Rigaku Saturn724 diffractometer that was equipped with a low-temperature attachment. Data were collected at 100 K using graphite-monochromated Mo−K_α radiation (λ_α= 0.71073 Å) by ω-scan technique. The data were reduced by using CrystalClear-SM Ex-pert 2.1 b24 software. The structures were solved by direct methods and refined by least-squares against F^2 utilizing the software pack-ages SHELXL-97,[13a,b] SIR-92,[13c] and WINGX.[13d] All non-hydrogen atoms were refined anisotropically. CCDC No. 1445133 (for **4a**) contains the supplementary 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.

*3-(4-(Hydroxymethyl)phenyl)-1-(p-tolyl)prop-2-en-1-one (**5a**).* Samples of 4-(hydroxymethyl)benzaldehyde (1 g, 8.20 mmol), 4-methylbenzaldehyde (1 g, 8.3 mmol) were dissolved in absolute ethanol (40 mL). An aqueous solution of potassium hydroxide (40 mL, 2.5 M) was added dropwise at 0 °C and the solution was stirred at room temperature for a period of 24 h. The reaction mixture was allowed to cool in ice bath, during which the product precipitated. Filtration of the reaction mixture gave a pale white solid product **5a**. Yield: 1.85 g (90%); mp: 114−116 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm2.44 (s, 3H), 4.75 (s, 2H), 7.30 (d, ^3J (H, H) = 7.9 Hz, 2H), 7.42 (d, ^3J (H, H) = 8.1 Hz, 2H), 7.53 (d, ^3J (H, H) = 15.6 Hz, 1H), 7.64 (d, ^3J (H, H) = 8.1 Hz, 2H), 7.80 (d, ^3J (H, H) = 15.6 Hz, 1H), 7.93 (d, ^3J (H, H) = 8.2 Hz, 2H; Ar). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.8, 64.9, 122.1, 127.5, 128.7, 128.8, 129.4, 134.4, 135.7, 143.5, 143.8, 144.1, 190.1. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{17}H_{16}O_2Na$ 275.1043; Found 275.1042.

*3-(3-(Hydroxymethyl)phenyl)-1-(p-tolyl)prop-2-en-1-one (**5b**).* Compound **5b** (off white solid) was prepared from 3-(hydroxymethyl)benzaldehyde and 4-methylbenzaldehyde in ethanol by following same procedure reported for compound **5a**. Yield: 1.85 g (86%); mp: 86−88 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm):): 2.46 (s, 3H), 4.78 (s, 2H), 7.33 (d, ^3J (H, H) = 8.0, 2H), 7.43 (d, ^3J (H, H) = 4.9, 2H), 7.60−7.55 (m, 2H), 7.69 (s, 1H), 7.81 (d, ^3J (H, H) = 15.7, 1H), 7.96 (d, ^3J (H, H) = 8.1, 2H). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.71, 64.91, 122.3, 126.6, 127.9, 128.7, 129.0, 129.2, 129.4, 135.38, 135.6, 141.7, 143.8, 144.2, 190.1. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{17}H_{16}O_2Na$ 275.1043; Found 275.1048.

*3-(4-(Hydroxymethyl)phenyl)-4-nitro-1-(p-tolyl)butan-1-one (**6a**).* Samples of 3-(4-(hydroxymethyl)phenyl)-1-(p-tolyl)prop-2-en-1-one **5a** (1 g, 3.96 mmol), nitromethane (1 mL, 19 mmol), and diethylamine (2 mL, 19 mmol) were dissolved in ethanol (50 mL) and refluxed for 24 h. The solution was cooled, acidified with hydrochloric acid (20 mL, 2.5 M) and extracted using DCM (50 mL × 3). The separated organic layers were combined, dried over sodium sulfate and evaporated under vacuum yielded **6a** as a viscous pale yellow liquid. Yield: 1 g (80%).^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.39 (s, 3H), 3.39 (m, 2H), 4.18 (p, 1H), 4.58 (s, 2H), 4.60−4.65 (dd, 1H), 4.76−4.79 (dd, 1H), 7.22−7.28 (m, 6H), 7.79 (d, ^3J (H, H) = 8.2 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.7, 39.1, 41.3, 64.6, 79.6, 127.6, 127.7, 128.2, 129.4, 133.8, 138.4, 140.6, 144.6, 196.7. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{18}H_{19}NO_4Na$ 336.1206; Found 336.1204.

*3-(3-(Hydroxymethyl)phenyl)-4-nitro-1-(p-tolyl)butan-1-one (**6b**).* Compound **6b** (viscous pale yellow liquid) was prepared from compound **5b**, nitromethane, and diethylamine in methanol by following same procedure reported for compound **6a**. Yield: 85%. ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm): 2.41 (s, 3H), 3.54−3.32 (m, 2H), 4.24 (m, 1H), 4.90−4.60 (m, 4H), 7.41−7.17 (m, 6H), 7.82 (d, ^3J (H, H) = 8.2 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.7, 39.3, 41.4, 65.0, 79.6, 125.9, 126.4, 128.2, 129.3, 129.4, 133.8, 139.6, 141.7, 196.1. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{18}H_{19}NO_4Na$ 336.1206; Found 336.1214.

*AzaBODIPY **7a**.* A solution of 3-(4-(hydroxymethyl)phenyl)-4-nitro-1-(p-tolyl)butan-1-one **6a** (1 g, 3.2 mmol) and ammonium acetate (6.20 g, 80 mmol) in *n*-butanol (30 mL) was heated under reflux for 24 h. During the course of the reaction, the product precipitated as blue-black solid. The reaction was allowed to cool to room temperature and solid was filtered and washed with ethanol to afford the intermediate product. To a solution of the intermediate product in dichloromethane, triethylamine (100 equiv), was added followed by the successive addition of $BF_3{\cdot}Et_2O$ (110 equiv) without delay, and stirring was continued for an additional 30 min. The mixture was washed with water and the organic layer was separated, dried over Na_2SO_4 and evaporated to dryness. The solvent was evaporated under reduced pressure and the crude product was purified using silica gel column chromatography with petroleum ether/ethyl acetate (30:70), to afford pure azaBODIPY **7a** as brown solid. Yield (0.94 g, 50%); mp: 195−197 °C ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.42 (s, 6H), 4.72 (s, 2H), 7.03 (s, 2H), 7.29 (d, ^3J (H, H) = 8.0 Hz, 4H), 7.46 (d, ^3J (H, H) = 8.1 Hz, 4H), 7.96 (d, ^3J (H, H) = 8.1 Hz, 4H), 8.06 (d, ^3J (H, H) = 8.1 Hz, 4H).^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.21 (t, ^1J (B−F) = 31 Hz, 1B). ^{19}F NMR (470 MHz, $CDCl_3$, δ in ppm): −131.58 (q, ^1J (F−B) = 28 Hz, 2F). ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm): 21.7, 29.8, 65.1, 118.9, 127.21, 128.3, 128.9, 129.5, 128.7, 131.0, 131.8, 141.7, 142.3, 143.4, 145.6, 159.4. HRMS (ESI-TOF) m/z: $[M+H]^+$ Calcd for $C_{36}H_{31}BF_2N_3O_2$ 586.2478; Found 586.2479.

*AzaBODIPY **7b**.* Compound **7b** (dark brown solid) was prepared from **6b** and ammonium acetate by following the procedure reported for compound **7a**. Yield = 39%. mp: 178−180 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.43 (s, 6H), 4.71 (s, 4H), 7.04 (s, 2H), 7.30 (d, 3*J* (H H) 8.3 Hz, 4H), 7.50−7.40 (m, 4H), 7.88 (d, 3*J* (H H) 7.5 Hz, 2H), 7.97 (d, 3*J* (H H) 8.1 Hz, 4H), 8.07 (s, 2H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.22 (t, ^1J (B−F) = 23.3 Hz, 1B). ^{19}F NMR (470 MHz, $CDCl_3$, δ in ppm): −131.70 (q, ^1J (F−B) = 28 Hz, 2F). ^{13}C NMR (125 MHz, CDCl3, δ in ppm): 21.7, 64.6, 119.3, 127.9, 128.1, 128.1, 128.7, 129.5, 129.7, 132.7, 141.5, 141.6, 143.8, 145.3, 159.1. HRMS (ESI-TOF) m/z: $[M+H]^+$ Calcd for $C_{36}H_{31}BF_2N_3O_2$ 586.2478; Found 586.2507.

*Mono/Diformyl azaBODIPYs (**1a/2a**).* To a solution of azaBODIPY **7a** (0.3 g, 0.51 mmol) in dichloromethane (100 mL), activated MnO_2 (5.10 mmol) was added and the mixture was stirred at room temperature until the consumption of alcohol **7a** was completed (30 h, as monitored by TLC). The reaction mixture was filtered through Celite, the filtrate was evaporated, and then the solid residue was purified using silica gel column chromatography with petroleum ether-ethyl acetate. The fast moving band corresponding to diformyl azaBODIPY **2a** were collected with 6:4 mixture of petroleum ether/ethyl acetate and the second band corresponding to monoformyl azaBODIPY **1a** was collected with 5:5 mixture of petroleum ether/ethyl acetate. The solvent was removed on rotary evaporator under vacuo and afforded pure mono- and diformyl azaBODIPYs (**1a**/**2a**) as a brown solids.

(**1a**): Yield (0.100 g, 32%); mp: 228−231 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.42 (s, 6H), 4.80 (s, 2H), 7.08 (s, 1H), 7.09 (s, 1H), 7.29−7.31 (m, 4H), 7.48 (d, ^3J (H, H) = 8.1 Hz, 2H), 7.95 (q, ^3J (H, H) = 8.3 Hz, 4H), 7.99 (d, ^3J (H, H) = 8.2 Hz, 2H), 8.04 (d, ^3J (H, H) = 8.2 Hz, 2H), 8.21 (d, ^3J (H, H) = 8.2 Hz, 2H), 10.07 (s, 1H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.20 (t, ^1J (B−F) = 31.0 Hz, 1B). ^{19}F NMR (470 MHz, $CDCl_3$, δ in ppm): −131.75 (q, ^1J (F−B) = 32.9 Hz, 2F). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 14.2, 21.7, 21.8, 22.8, 29.8, 32.0, 65.0, 119.6, 119.7, 127.2, 128.5, 128.8, 129.5, 129.6, 129.7, 129.7, 129.9, 130.0, 131.4, 136.0, 138.4, 141.6, 142.5, 142.9, 144.5, 158.0, 161.2, 192.0. HRMS (ESI-TOF) m/z: $[M+H]^+$ Calcd for $C_{36}H_{29}BF_2N_3O_2$ 584.2323; Found 584.2316.

(**2a**): Yield (0.125 g, 40%); mp: 283−285 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.43 (s, 6H), 7.15 (s, 2H), 7.31 (d, ^3J (H, H) = 8.4 Hz, 4H), 7.96−7.99 (m, 8H), 8.18 (d, ^3J (H, H) = 8.3 Hz, 4H), 10.10 (s, 2H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.20 (t, ^1J (B−F) = 30.7 Hz, 1B). ^{19}F NMR (470 MHz, $CDCl_3$, δ in ppm): −131.89 (q, ^1J (F−B) = 30.5 Hz, 2F). ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm): 21.8, 29.8, 120.5, 124.6, 127.3, 127.7, 128.4, 128.7, 129.1, 129.7, 129.9,

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130.0, 136.4, 138.0, 142.1, 142.4, 145.8, 160.0, 191.9. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{36}H_{26}BF_2N_3O_2Na$ 604.1985; Found 604.1988.

*Mono/Diformyl azaBODIPY (**1b/2b**).* Synthesis of mono- and diformyl azaBODIPYs (**1b**/**2b**) was carried out similarly from compound **7b** by following the procedure reported for compounds **1a** and **2a**.

(**1b**, dark brown solid): Yield (35%); mp: 219−221 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.43 (s, 6H), 4.73 (s, 2H), 7.08 (s, 1H), 7.10 (s, 1H), 7.30 (m, 4H), 7.46 (d, ^3J (H, H) 6.1 Hz, 2H), 7.64 (t, ^3J (H, H) 7.7 Hz, 1H), 8.03−7.89 (m, 7H), 8.29 (d, ^3J (H, H) = 7.8 Hz, 1H), 8.57 (s, 1H), 10.04 (s, 1H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.21 (t, ^1J (B−F) = 30.1 Hz, 1B). ^{19}F NMR (470 MHz, $CDCl_3$, δ in ppm): −131.8 (q, ^1J (F−B) = 31.2 Hz, 2F). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.7, 65.2, 127.7, 128.8, 129.0, 129.3, 129.5, 129.6, 129.7, 129.8, 130.0, 130.5, 132.5, 133.5.134.8, 136.8, 141.6, 142.1, 142.4 192.4. HRMS (ESI-TOF) m/z: $[M+H]^+$ Calcd for $C_{36}H_{29}BF_2N_3O_2$ 584.2322; Found 584.2323.

(**2b**, dark brown solid): Yield (43%); mp: 259−261 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.44 (s, 6H), 7.15 (s, 2H), 7.32 (d, ^3J (H, H)= 8.1 Hz, 4H), 7.66 (t, ^3J = (H, H) 7.7 Hz, 2H), 7.94 (d, ^3J = (H, H) 7.5 Hz, 2H), 8.00 (d, ^3J = (H, H) 8.1 Hz, 4H), 8.32 (d, ^3J (H, H) = 7.8 Hz, 2H), 8.53 (s, 2H), 10.05 (s, 2H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.21 (t, ^1J (B−F) = 31.1 Hz, 1B). ^{19}F NMR (470 MHz, $CDCl_3$, δ in ppm): −131.68 (q, ^1J (F−B) = 31.3 Hz, 2F). ^{13}C NMR (101 MHz, $CDCl_3$) δ 21.6, 29.6, 119.8, 128.4, 129.6, 129.7, 129.7, 129.9, 130.51, 133.2, 134.8, 136.8, 142.1, 159.7, 191.9. HRMS (ESI-TOF) m/z: $[M+H]^+$ Calcd for $C_{36}H_{27}BF_2N_3O_2$ 582.2165; Found 582.2165.

*Monodipyrromethanyl azaBODIPY **8a**.* To a solution of monoformyl azaBODIPY **1a** (100 mg, 0.17 mmol) and pyrrole (1.7 mmol) in dichloromethane (100 mL), catalytic amount of $BF_3.Et_2O$ (0.017 mmol) was added under N_2 atmosphere. The reaction mixture was stirred at room temperature for 15 min. The reaction was quenched with 0.1 M NaOH solution and the combined organic layers were extracted with CH_2Cl_2 and dried over Na_2SO_4. The solution was concentrated under vacuum to afford crude paste which was purified by silica gel column chromatography using petroleum ether/ethyl acetate (40:60) and afforded monodipyrromethanyl azaBODIPY **8a** as a blue solid. Yield (84 mg, 70%). mp: decomposes at ∼250 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.42 (s, 6H), 4.76 (s, 2H), 5.56 (s, 1H), 5.99 (s, 2H), 6.19−6.21 (m, 2H), 6.74−6.76 (m, 2H), 7.00 (s, 1H), 7.02 (s, 1H), 7.28−7.32 (m, 6H), 7.41 (d, ^3J (H, H) = 8.3 Hz, 2H), 7.96 (q, ^3J (H, H) = 8.1 Hz, 4H), 8.00 (d, ^3J (H, H) = 8.3 Hz, 2H), 8.02 (d, ^3J (H, H) = 8.3 Hz, 2H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.23 (t, ^1J (B−F) = 31.0 Hz, 1B). ^{19}F NMR (470.54 MHz, $CDCl_3$, δ in ppm): −131.62 (q, ^1J (F−B) = 32.0 Hz, 2F). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.7, 21.8, 29.5, 29.8, 44.0, 65.1,107.6, 108.7, 117.5, 118.8, 124.6, 127.1, 127.7, 128.4, 128.7, 128.8, 128.9, 129.1, 129.6, 129.6, 129.7, 130.0, 131.3, 131.8, 132.2, 141.7, 142.3, 143.4, 143.6, 145.7, 159.4. HRMS (ESI-TOF) m/z: $[M+K]^+$ Calcd for $C_{44}H_{36}BF_2N_5OK$ 738.2620; Found 738.2642.

*Monodipyrromethanyl azaBODIPY **8b**.* Synthesis of monodipyrromethanyl azaBODIPY **8b** was carried out at 0 °C by following the same procedure reported for the compound **8a** by using **1b** and excess pyrrole. Yield (73%). mp: decomposes at ∼272 °C; ^{1}H NMR (400 MHz, $CDCl_3$) 2.42 (s, 6H), 4.71 (s, 2H), 5.51 (s, 1H), 5.94 (s, 2H), 6.15 (s, 2H), 6.65 (s, 1H), 6.96 (s, 1H) 7.03 (s, 3H), 7.30 (m, 6H), 7.42 (s, 2H), 7.79 (s, 1H), 8.03−7.86 (m, 7H), 8.11 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$, δ in ppm): 20.79, 21.60, 65.05, 119.31, 124.48, 126.49, 127.93, 128.01, 128.20, 128.53, 128.76, 128.97, 129.42, 129.65, 132.75, 141.48, 143.76, 158.74. ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.22 (t, ^1J (B−F) = 24.1 Hz, 1B). ^{19}F NMR (470.54 MHz, $CDCl_3$, δ in ppm): −131.61 (q, ^1J (F−B) = 18.6 Hz, 2F). HRMS (ESI-TOF) m/z: $[M+H]^+$ Calcd for $C_{44}H_{37}BF_2N_5O$ 700.3061; Found 700.3049.

*Didipyrromethanyl azaBODIPY **9a**.* This compound was prepared by following the same procedure reported for monodipyrromethanyl azaBODIPY **8a**. The crude compound was purified by silica gel column chromatography using petroleum ether/ethyl acetate (60:40) and afforded didipyrromethanyl azaBODIPY **9a** as a blue solid. Yield (98 mg, 70%). mp: decomposes at ∼243 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.42 (s, 6H), 5.52 (s, 2H), 5.97 (s, 4H), 6.15−6.17 (m, 4H), 6.69−6.70 (m, 4H), 6.99 (s, 2H), 7.27−7.30 (m, 8H), 7.95−8.00 (m, 8H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.25 (t, ^1J (B−F) = 30.3 Hz, 1B). ^{19}F NMR (470.54 MHz, $CDCl_3$, δ in ppm): −131.60 (q, ^1J (F−B) = 28.2 Hz, 2F). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.7, 29.8, 44.1, 107.5, 108.6, 116.6, 116.7, 117.6, 118.4, 118.7, 128.7, 128.9, 129.5, 129.7, 131.2, 132.2, 141.7, 143.4, 143.6, 154.7, 145.7, 159.4. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{52}H_{42}BF_2N_7Na$ 836.3464; Found 836.3466.

*Didipyrromethanyl azaBODIPY **9b**.* The compound **9b** was prepared from compound **2b** and pyrrole by following the procedure reported for monodipyrromethanyl azaBODIPY **9a** at 0 °C. The crude compound was purified by silica gel column chromatography using petroleum ether/ethyl acetate (30:70) and afforded didipyrromethanyl azaBODIPY **9b** as a blue solid. Yield (19%); mp: decomposes at ∼265 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.41 (s, 6H), 5.47 (s, 2H), 5.84 (d, ^3J (H, H) = 2.1 Hz, 4H), 6.10 (d, ^3J (H, H) = 2.6 Hz, 4H), 6.67 (s, 4H), 6.81 (s, 2H), 7.42−7.27 (m, 6H), 7.47 (m, 3H), 7.56 (s, 2H), 7.91 (m, 5H), 7.95 (s, 2H). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 1.04 (t, ^1J (B−F) = 23.5 Hz, 1B). ^{19}F NMR (370.54 MHz, $CDCl_3$, δ in ppm): 131.74 (q, ^1J (F−B) = 32.8 Hz, 2F). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.7, 44.2, 107.2, 108.2, 117.2, 127.5, 128.7, 129.3, 129.4, 129.6, 130.0, 131.9, 133.7, 141.7, 142.3, 158.8. HRMS (ESI-TOF) m/z: $[M+H]^+$ Calcd for $C_{52}H_{43}BF_2N_7$ 814.3644; Found 814.3643.

*AzaBODIPY−BODIPY Dyad **3a**.* To a solution of dipyrromethanyl azaBODIPY **8a** (50 mg, 0.07 mmol) in dichloromethane (50 mL), DDQ (0.084 mmol) was added with continuous stirring at room temperature. To the resulting reaction mixture, triethylamine (2.8 mmol, 0.4 mL) was added followed by the successive addition of $BF_3.Et_2O$ (2.8 mmol, 0.4 mL) without delay, and stirring was continued for an additional 30 min. The solvent was evaporated under reduced pressure and the crude product was purified using silica gel column chromatography with petroleum ether/ethyl acetate (50:50), to afford pure azaBODIPY−BODIPY dyad **3a** as brown solid. Yield (16 mg, 30%). mp: > 300 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.42 (s, 6H; CH_3), 4.76 (s, 2H; CH_2), 6.59 (s, 2H; py), 7.03 (s, 2H; py), 7.08 (s, 1H; py), 7.11 (s, 1H; py), 7.31 (d, ^3J (H, H) = 7.7 Hz, 4H; Ar), 7.46 (d, ^3J (H, H) = 7.6 Hz, 2H; Ar), 7.68 (d, ^3J (H, H) = 7.7 Hz, 2H; Ar), 7.97−8.01 (m, 6H; Ar, py), 8.06 (d, ^3J (H, H) = 7.7 Hz, 2H; Ar), 8.21 (d, ^3J (H, H) = 7.5 Hz, 2H; Ar). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 0.58 (t, ^1J (B−F) = 30.8 Hz, 1B), 1.26 (t, ^1J (B−F) = 28.8 Hz, 1B). ^{19}F NMR (376 MHz, $CDCl_3$, δ in ppm): −131.69 (q, ^1J (F−B) = 31.2 Hz, 2F), −144.98 (q, ^1J (F−B) = 28.5 Hz, 2F). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.8, 21.8, 29.8, 65.0, 108.3, 117.8, 118.8, 119.1, 119.6, 127.2, 128.3, 128.6, 128.9, 129.1, 129.2, 129.6, 129.7, 129.9, 130.9, 131.0, 131.6, 131.7, 134.4, 135.0, 135.3, 141.4, 141.7, 142.3, 142.8, 144.4, 145.2, 146.3, 146.9, 158.5, 161.0. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{44}H_{33}B_2F_4N_5ONa$ 768.2714; Found 768.2715.

*AzaBODIPY−BODIPY Dyad **3b**.* The dyad **3b** (dark brown solid) was prepared from the compound **8b** by following the similar procedure reported for the dyad **3a**. Yield (45%). mp: > 300 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.43 (s, 6H; CH_3), 4.61 (s, 2H; CH_2), 6.50 (dd, ^3J (H, H) = 4.2, ^5J (H, H) = 1.7 Hz, 2H; Py), 6.98 (d, ^3J (H, H) = 4.2 Hz, 2H; Py), 7.04 (s, 1H; Py), 7.10 (s, 1H; Py), 7.12 (s, 1H; Py), 7.32 (m, 6H; Ar), 7.61 (m, 2H; Ar), 7.77 (d, ^3J (H, H) = 7.8 Hz, 1H; Ar), 7.83 (s, 1H; py), 8.00−7.94 (m, 6H; Ar), 8.25 (dt, ^3J (H, H) = 7.6, ^5J (H, H) = 1.5 Hz, 1H; Ar), 8.41 (s, 1H; Ar). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 0.58 (t, ^1J (B−F) = 22.4 Hz, 1B), 1.22 (t, ^1J (B−F) = 24.1 Hz, 1B). ^{19}F NMR (376 MHz, $CDCl_3$, δ in ppm): −131.81 (q, ^1J (F−B) = 31.2 Hz, 2F), −144.98 (q, ^1J (F−B) = 28.5 Hz, 2F). ^{13}C NMR (125 MHz, $CDCl_3$, δ in ppm): 21.8, 21.8, 29.8, 65.0, 108.3, 117.8, 118.8, 119.1, 119.6, 127.2, 128.3, 128.6, 128.9, 129.1, 129.2, 129.6, 129.7, 129.9, 130.9, 131.0, 131.6, 131.7, 134.4, 135.0, 135.3, 141.4, 141.7, 142.3, 142.8, 144.4, 145.2, 146.3, 146.9, 158.5, 161.0. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{44}H_{33}B_2F_4N_5ONa$ 768.2714; Found 768.2723.

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AzaBODIPY-(BODIPY)$_2$ Triad ***4a***. This compound was prepared by following the same procedure used for the synthesis of azaBODIPY−BODIPY dyad **3a**. The crude triad was purified by silica gel column chromatography using petroleum ether/ethyl acetate (70:30) and afforded azaBODIPY-(BODIPY)$_2$ triad **4a** as a brown solid. Yield (14 mg, 25%). mp: > 300 °C; ^{1}H NMR (500 MHz, $CDCl_3$, δ in ppm): 2.45 (s, 6H; CH_3), 6.48−6.49 (m, 4H; py), 6.98 (d, ^3J (H, H) = 4.1 Hz, 4H; py), 7.17 (s, 2H; py), 7.34 (d, ^3J (H, H) = 8.0 Hz, 4H; Ar), 7.68 (d, ^3J (H, H) = 8.3 Hz, 4H; Ar), 7.94 (s, 4H; py),8.02 (d, ^3J (H, H) = 8.2 Hz, 4H; Ar), 8.21 (d, ^3J (H, H) = 8.3 Hz, 4H; Ar. ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 0.52 (t, ^1J (B−F) = 27.2 Hz, 1B), 1.29 (t, ^1J (B−F) = 30.7 Hz, 1B). ^{19}F NMR (376 MHz, $CDCl_3$, δ in ppm): −131.80 (q, ^1J (F−B) = 30.8 Hz, 2F), −144.98 (q, ^1J (F−B) = 28.5 Hz, 2F). ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm): 21.8, 47.1, 118.8, 119.9, 128.5, 129.2, 129.7, 129.9, 131.0, 131.4, 134.8, 134.9, 142.4, 144.5, 145.8, 146.5, 160.0. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{52}H_{36}B_3F_6N_7Na$ 928.3131; Found 928.3142.

AzaBODIPY-(BODIPY)$_2$ Triad ***4b***. The triad **4b** (brown solid) was prepared from compound **9b** by following the similar procedure reported for the dyad **4a** Yield (15 mg, 26%). mp: > 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm): 2.43 (s, 6H; CH_3), 6.51−6.51 (m, 4H; py), 6.91 (d, ^3J (H, H) = 4.0 Hz, 4H; py), 7.09 (s, 2H; py), 7.26 (m, 2H; Ar), 7.30 (d, ^3J (H, H) = 8.2 Hz, 4H; Ar), 7.51 (d, ^3J (H, H) = 7.8 Hz, 2H; Ar), 7.98−7.95 (m, 8H; py, Ar),8.07(d, ^3J (H, H) = 7.6 Hz, 2H; Ar), 8.21 (s, 2H; Ar). ^{11}B NMR (160 MHz, $CDCl_3$, δ in ppm): 0.55 (t, ^1J (B−F) = 28.3 Hz, 1B), 1.23 (t, ^1J (B−F) = 30.5 Hz, 1B). ^{19}F NMR (376 MHz, $CDCl_3$, δ in ppm): −131.80 (q, ^1J (F−B) = 30.8 Hz, 2F), −144.81 (m, 2F). ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm): 29.8, 114.2, 118.8, 119.7, 128.6, 128.8, 129.8, 129.9, 130.7, 131.2, 131.5, 131.8, 132.6, 134.3, 135.0, 142.4, 144.5, 146.8, 159.4. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd for $C_{52}H_{36}B_3F_6N_7Na$ 928.3131; Found 928.3130.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.7b00542.

Characterization data of all new compounds (PDF)
X-ray crystallographic data for compound **4a** (CIF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Loudet, A.; Burgess, K. *Chem. Rev.* **2007**, *107*, 4891. (b) Batat, P.; Cantuel, M.; Jonusauskas, G.; Scarpantonio, L.; Palma, A.; O'Shea, D. F.; McClenaghan, N. D. *J. Phys. Chem. A* **2011**, *115*, 14034−14039. (c) Bessette, A.; Hanan, G. S. *Chem. Soc. Rev.* **2014**, *43*, 3342. (d) Parisotto, S.; Lace, B.; Artuso, E.; Lombardi, C.; Deagostino, A.; Scudu, R.; Garino, C.; Medana, C.; Prandi, C. *Org. Biomol. Chem.* **2017**, *15*, 884−893. (e) Wang, J.; Li, J.; Chen, N.; Wu, Y.; Hao, E.; Wei, Y.; Mu, X.; Jiao, L. *New J. Chem.* **2016**, *40*, 5966−5975. (f) Jiang, X.; Li, S.; Le Guennic, B.; Jacquemin, D.; Escudero, D.; Xiao, L. *Phys. Chem. Chem. Phys.* **2016**, *18*, 32686−32690. (g) Zatsikha, Y. V.; Holstrom, C. D.; Chanawanno, K.; Osinski, A. J.; Ziegler, C. J.; Nemykin, V. N. *Inorg. Chem.* **2017**, *56*, 991−1000. (h) Ge, Y.; O'Shea, D. F. *Chem. Soc. Rev.* **2016**, *45*, 3846−3864.

(2) (a) Lakshmi, V.; Rao, M. R.; Ravikanth, M. *Org. Biomol. Chem.* **2015**, *13*, 2501. (b) Tasior, M.; O'Shea, D. F. *Bioconjugate Chem.* **2010**, *21*, 1130. (c) Grossi, M.; Palma, A.; McDonnell, S. O.; Hall, M. J.; Rai, D. K.; Muldoon, J.; O'Shea, D. F. *J. Org. Chem.* **2012**, *77*, 9304. (d) Lu, H.; Shimizu, S.; Mack, J.; Shen, Z.; Kobayashi, N. *Chem. - Asian J.* **2011**, *6*, 1026.

(3) (a) Lakshmi, V.; Ravikanth, M. *J. Org. Chem.* **2011**, *76*, 8466. (b) Awuah, S. G.; Polreis, J.; Biradar, V.; You, Y. *Org. Lett.* **2011**, *13*, 3884. (c) Madhu, S.; Gonnade, R.; Ravikanth, M. *J. Org. Chem.* **2013**, *78*, 5056.

(4) (a) Farber, S. A.; Pack, M.; Ho, S.-Y.; Johnson, I. D.; Wagner, D. S.; Dosch, R.; Mullins, M. C.; Hendrickson, H. S.; Hendrickson, E. K.; Halpern, M. E. *Science* **2001**, *292*, 1385. (b) Reents, R.; Wagner, M.; Kuhlmann, J.; Waldmann, H. *Angew. Chem., Int. Ed.* **2004**, *43*, 2711. (c) Kamkaew, A.; Lim, S. H.; Lee, H. B.; Kiew, L. V.; Chung, L. Y.; Burgess, K. *Chem. Soc. Rev.* **2013**, *42*, 77. (d) Lu, H.; Mack, J.; Yang, Y.; Shen, Z. *Chem. Soc. Rev.* **2014**, *43*, 4778.

(5) (a) El-Khouly, M. E.; Fukuzumi, S.; D'Souza, F. *ChemPhysChem* **2014**, *15*, 30. (b) Bandi, V.; D'Souza, F. P.; Gobeze, H. B.; D'Souza, F. *Chem. - Eur. J.* **2015**, *21*, 2669. (c) Grossi, M.; Morgunova, M.; Cheung, S.; Scholz, D.; Conroy, E.; Terrile, M.; Panarella, A.; Simpson, J. C.; Gallagher, W. M.; O'Shea, D. F. *Nat. Commun.* **2016**, *7*, 10855. (d) Guo, S.; Ma, L.; Zhao, J.; Küçüköz, B.; Karatay, A.; Hayvali, M.; Yaglioglu, H. G.; Elmali, A. *Chem. Sci.* **2014**, *5*, 489.

(6) (a) Killoran, J.; O'Shea, D. F. *Chem. Commun.* **2006**, 1503. (b) Liu, H.; Mack, J.; Guo, Q.; Lu, H.; Kobayashi, N.; Shen, Z. *Chem. Commun.* **2011**, *47*, 12092. (c) Díaz-Moscoso, A.; Emond, E.; Hughes, D. L.; Tizzard, G. J.; Coles, S. J.; Cammidge, A. N. *J. Org. Chem.* **2014**, *79*, 8932. (d) Zhang, X.; Yu, H.; Xiao, Yi. *J. Org. Chem.* **2012**, *77*, 669. (e) Wu, D.; O'shea, D. F. *Org. Lett.* **2013**, *15*, 3392.

(7) (a) Bandi, V.; Ohkubo, K.; Fukuzumi, S.; D'Souza, F. *Chem. Commun.* **2013**, *49*, 2867. (b) El-Khouly, M. E.; Amin, A. N.; Zandler, M. E.; Fukuzumi, S.; D'Souza, F. *Chem. - Eur. J.* **2012**, *18*, 5239. (c) Shi, W.-J.; El-Khouly, M. E.; Ohkubo, K.; Fukuzumi, S.; Ng, D. K. P. *Chem. - Eur. J.* **2013**, *19*, 11332. (d) Liu, Y.; Zhu, J.; Xu, Y.; Qin, Y.; Jiang, D. *ACS Appl. Mater. Interfaces* **2015**, *7*, 11141. (e) Khan, T. K.; Sheokand, P.; Agarwal, N. *Eur. J. Org. Chem.* **2014**, *2014*, 1416. (f) Kumar, S.; Khan, T. K.; Ravikanth, M. *Tetrahedron* **2015**, *71*, 7608. (g) Kumar, S.; Gobeze, H. B.; Chatterjee, T.; D'Souza, F.; Ravikanth, M. *J. Phys. Chem. A* **2015**, *119*, 8338.

(8) (a) Bandi, V.; Gobeze, H. B.; Nesterov, V. N.; Karr, P. A.; D'Souza, F. *Phys. Chem. Chem. Phys.* **2014**, *16*, 25537. (b) Bandi, V.; El-Khouly, M. E.; Ohkubo, K.; Nesterov, V. N.; Zandler, M. E.; Fukuzumi, S.; D'Souza, F. *Chem. - Eur. J.* **2013**, *19*, 7221. (c) Hall, M. J.; Allen, L. T.; O'Shea, D. F. *Org. Biomol. Chem.* **2006**, *4*, 776. (d) Jiao, L.; Wu, Y.; Wang, S.; Hu, X.; Zhang, P.; Yu, C.; Cong, K.; Meng, Q.; Hao, E.; Vicente, M. G. H. *J. Org. Chem.* **2014**, *79*, 1830. (e) Yuan, M.; Yin, X.; Zheng, H.; Ouyang, C.; Zuo, Z.; Liu, H.; Li, Y. *Chem. - Asian J.* **2009**, *4*, 707.

(9) (a) Gorman, A.; Killoran, J.; O'Shea, C.; Kenna, T.; Gallagher, W. M.; O'Shea, D. F. *J. Am. Chem. Soc.* **2004**, *126*, 10619. (b) Loudet, A.; Bandichhor, R.; Burgess, K.; Palma, A.; McDonnell, S. O.; Hall, D. F.; O'Shea, D. F. *Org. Lett.* **2008**, *10*, 4771. (c) Wang, Y.; Chen, L.; El-Shishtawy, R. M.; Aziz, S. G.; Mullen, K. *Chem. Commun.* **2014**, *50*, 11540.

(10) Kostereli, Z.; Ozdemir, T.; Buyukcakir, O.; Akkaya, E. U. *Org. Lett.* **2012**, *14*, 3636.

(11) Olmsted, J. *J. Phys. Chem.* **1979**, *83*, 2581.

(12) Killoran, J.; Allen, L.; Gallagher, J. F.; Gallagher, W. M.; O'Shea, D. F. *Chem. Commun.* **2002**, *17*, 1862.

(13) (a) Sheldrick, G. M. *Acta Crystallogr., Sect. A: Found. Crystallogr.* **2008**, *64*, 112. (b) *Program for Crystal Structure Solution and Refinement*; University of Göttingen: Göttingen, Germany, 1997. (c) Altomare, A.; Cascarano, G.; Giacovazzo, C.; Guagliardi, A. *J. Appl. Crystallogr.* **1993**, *26*, 343. (d) Farrugia, L. *J. Appl. Crystallogr.* **1999**, *32*, 837.

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