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A Post-Modification of Pyrrolopyrrole aza-BODIPY toward High Near Infrared Fluorescence Brightness

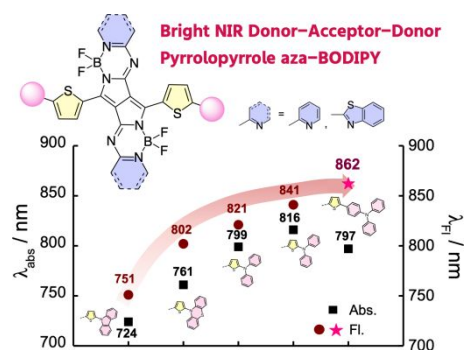
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Supporting Information Placeholder



ABSTRACT: Pyrrolopyrrole aza-BODIPYs (PPABs), dimeric aza-BODIPY analogues, exhibit intense absorption and fluorescence in the visible and near-infrared (NIR) regions. Here, we developed a facile post-modification by palladium-catalyzed coupling reactions to synthesize a series of donor-acceptor-donor (D-A-D) PPABs. Despite the possible fluorescence quenching dictated by the energy-gap low, D-A-D PPABs exhibit high fluorescence brightness in the NIR region, implying their potential use as a bright NIR emitter.

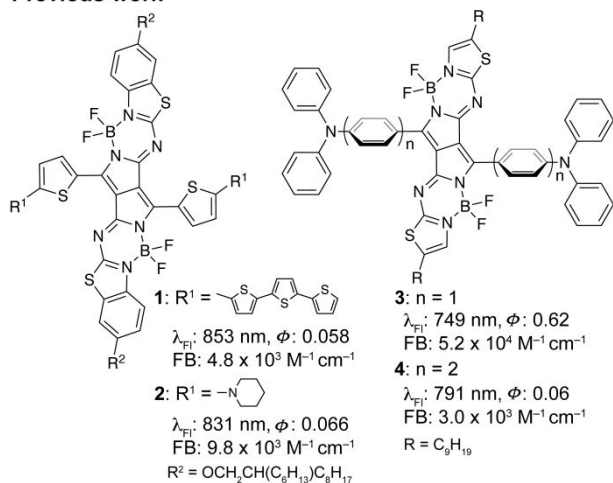
Pyrrolopyrrole aza-BODIPYs (PPABs) are dimeric aza-boron dipyrromethene (BODIPY) analogues, exhibiting intense absorption and fluorescence in the far-red region.¹ Owing to the facile synthesis of PPABs by a Schiff base forming reaction of diketopyrrolopyrrole and azaarylamines² and their high fluorescence brightness, defined by the product of the molar absorption coefficient and the fluorescence quantum yield ($\epsilon_{\text{Abs}} \times \Phi$),³ application studies on PPABs in various fields such as aggregation-induced emission,⁴ two-photon absorption,⁵ photoacoustic imaging,^{6,7} molecular recognition,⁸ and photothermal therapy,⁷ have intensively been investigated. In addition, the high stability of PPABs has also enabled their use in organic photovoltaics,^{9–11} organic light-emitting diodes,¹² and electrogenerated chemiluminescence.¹³

The prominent optical properties of PPABs can be shifted into the near-infrared (NIR) region. In our previous studies, an extension of the π -conjugation through a thienyl linker was examined, and the fluorescence maxima (λ_{Fl}) at 853 nm and quantum yield of 0.058 was achieved for PPAB bearing quaterthienyl substituents (**1**, Figure 1).¹⁰ PPAB with a donor-acceptor-donor (D-A-D) structure (**2**), in which PPAB and 5-piperidinyl-2-thienyl substituents function as acceptor and donor units, respectively, also exhibits the redshift of the fluorescence to the NIR region (λ_{Fl} : 831 nm, Φ_{Fl} : 0.066).¹⁰ Motivated by these results, the influence of the D-A interactions

via a phenylene linker was investigated.¹² D-A-D PPAB with a diphenylamine (DPA) donor (**3**) synthesized in this context exhibits high fluorescence brightness of $5.2 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$ at $\lambda_{\text{Fl}} = 749 \text{ nm}$ in chloroform. The transient absorption spectra and theoretical calculations revealed that the high fluorescence brightness of **3** in the NIR region can be ascribed to the presence of the hybridized local and charge transfer (HLCT) excited state,¹⁴ which is realized by a moderate dihedral angle of 34° between the DPA donor and PPAB acceptor. In contrast, charge transfer becomes dominant in the excited state of D-A-D PPAB with a triphenylamine (TPA) donor (**4**), causing fluorescence quenching in polar solvents. To give a detailed insight into the D-A interactions via a thienyl linker on the redshifts and fluorescence brightness, herein we synthesized a series of D-A-D PPABs (**5–9**) by post-modification means: bromination of PPAB with thienyl substituents followed by Buchwald-Hartwig amination or Suzuki-Miyaura coupling reactions. All the novel D-A-D PPABs exhibit significant redshifts of the fluorescence with minor deterioration of the brightness. Among them, D-A-D PPAB with TPA donors (**9**) shows the longest fluorescence emission at 862 nm with a high fluorescence brightness of $1.8 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$.

According to the procedure reported in our previous work, PPAB with 2-thienyl substituents (**11**) was synthesized by a

Previous work



This work

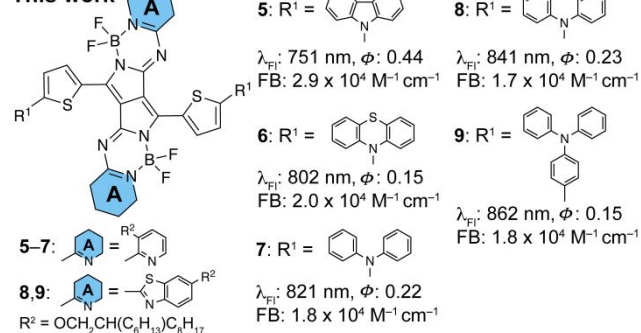
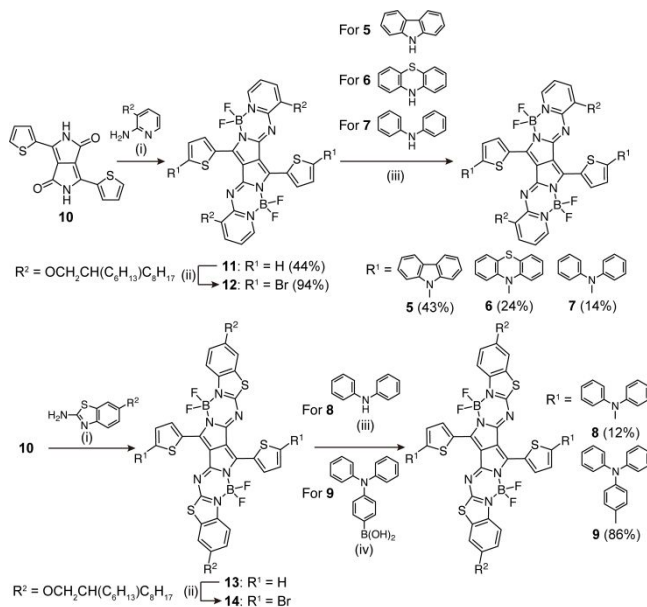


Figure 1. Structures of PPABs and their optical properties; λ_{Fl} : fluorescence peak wavelength, Φ : fluorescence quantum yield, and FB: fluorescence brightness.

Scheme 1. Synthesis of D-A-D PPABs^a

^a(i) TiCl_4 , Et_3N , toluene, reflux, then $\text{BF}_3 \cdot \text{OEt}_2$, toluene, reflux; (ii) NBS , CHCl_3 ; (iii) $\text{Pd}_2(\text{dba})_3$, $[(t\text{-Bu})_3\text{PH}]\text{BF}_4$, $t\text{-BuOK}$, toluene, reflux; (iv) $\text{Pd}(\text{PPh}_3)_4$, Na_2CO_3 aq., toluene, EtOH , 110°C .

Schiff base forming reaction of 2-thienyl-substituted diketopyrrolopyrrole **10** and 2-amino-3-(2-hexyldecyloxy)pyridine, and bromination of **11** provided **12** as a precursor for the D-A-D PPABs in this study (Scheme 1).⁹ From Buchwald-Hartwig amination reactions of **12** with carbazole, phenothiazine, and diphenylamine, D-A-D PPABs (**5–7**) were obtained in 43%, 24%, and 14% yields, respectively. D-A-D PPABs with benzothiazole as a heteroaromatic ring unit (**8** and **9**) were also synthesized from **14** in a similar manner for **8** in 12% yield and by Suzuki-Miyaura coupling reaction for **9** in 86% yield. All the compounds were characterized by high-resolution mass spectrometry and NMR spectroscopy (Figures S1–S21). Suitable crystals of **7** for single crystal X-ray diffraction analysis were obtained, and the structure of **7** was unambiguously elucidated. As a reference compound, D-A-D PPAB with phenylene linkers and DPA donors (**15**) was also synthesized and characterized (Figure 2).

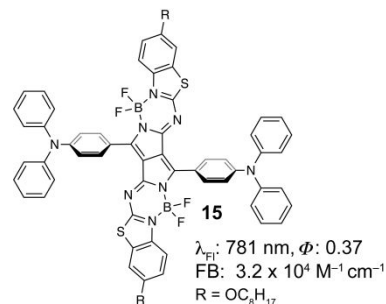


Figure 2. Structures of **15** as a reference compound and its optical properties; λ_{Fl} : fluorescence peak wavelength, Φ : fluorescence quantum yield, and FB: fluorescence brightness.

In the crystal structure of **7** (Figures 3 and S22), the thienyl linkers are almost coplanar to the PPAB core with a small dihedral angle of 14° . This is clearly different from **15**, which exhibits moderate dihedral angles of 35° (Figures S23 and S24). In addition, the C–C bond distance of 1.422(5) Å between the diketopyrrolopyrrole and the α -position of the thienyl substituents is slightly shorter than the regular single C(sp²)–C(aryl) bond distance, and there is almost no bond length alternation in the C–C bonds of the thiophene units. These results indicate the delocalized π -conjugation between the donor and acceptor moieties through the thienyl linkers. The optimized structures of **5–9** based on the DFT method at the $\omega\text{B97XD/6-31G(d,p)}$ level also reveal small dihedral angles between the donor moieties and the PPAB core (Figures S25–S30). In the case of **9**, the phenyl ring of the TPA moieties is moderately twisted from the thienyl linker by the dihedral angle of 29° , resulting in a twisted conformation between the TPA donors and the PPAB core, which correlates with the relatively high fluorescence brightness of **9** (*vide infra*).

Compared with **11** as a reference compound, the absorption and fluorescence spectra of all D-A-D PPABs are significantly redshifted (Figures 4, S31, and S32, and Table 1). The redshifts of a series of compounds (**5–7**) with the same PPAB core follow the order of donor strengths: carbazole (**5**) < phenothiazine (**6**) < DPA (**7**). In the case of **9** with TPA donors, the absorption spectra show blueshifts from those of **8** with DPA donors in all the solvents tested (toluene, chloroform, and benzonitrile), whereas the fluorescence spectra of **9** in chloroform and benzonitrile are redshifted.

Table 1. Photophysical Properties of a Series of D-A-D PPABs in Chloroform.

compd	λ_{max} (nm)	ϵ_{Abs} ($\text{M}^{-1} \text{cm}^{-1}$)	λ_{em} (nm)	Stokes shifts (cm^{-1})	Φ_{Fl}	FB ($\text{M}^{-1} \text{cm}^{-1}$)
5	724	65000	751	497	0.44	29000
6	761	130000	802	672	0.15	20000
7	799	83000	821	335	0.22	18000
8	816	74000	841	364	0.23	17000
9	797	120000	862	946	0.15	18000
11	693	108000	704	165	0.42	45000
15	728	86000	781	932	0.37	32000

λ_{max} : Absorption maximum. λ_{em} : Emission maximum. Φ_{Fl} : Fluorescence quantum yield. FB: Fluorescence brightness ($\epsilon_{\text{Abs}} \times \Phi_{\text{Fl}}$).

Although all the compounds exhibit solvatochromism in the fluorescence spectra due to the more polar nature of the excited state than the ground state, a notable solvatochromic response of **9** along with the large Stokes shifts indicates a significant contribution of the charge transfer nature in the excited state of **9**. Even in the NIR region, D-A-D PPABs (**5–9**) exhibit high fluorescence quantum yields ranging from 0.15 to 0.44. Among them, the fluorescence quantum yield of **9** ($\Phi = 0.15$) at λ_{Fl} of 862 nm is significantly high. Owing to the large molar absorption coefficient ($\epsilon_{\text{Abs}} = 1.2 \times 10^5 \text{ M}^{-1} \text{ cm}^{-1}$), the fluorescence brightness of **9** ($1.8 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$) becomes even higher than that of **8** ($1.7 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$). **8** and **9** are also certainly stable under ambient conditions (Figure S33).

levels can be altered by the dihedral angles between the donor and PPAB moieties (*vide infra*). Therefore, it might be possible that **6** takes different conformations in solvents used for the absorption and electrochemistry measurements. As for **8** and **9**, both the first reduction and oxidation potentials of **9** (−1.03 and 0.21 V) shift to the positive side from those of **8** (−1.16 and −0.05 V) because of the attenuation of the diphenylamine donor effect by the phenylene unit in the case of **9**.

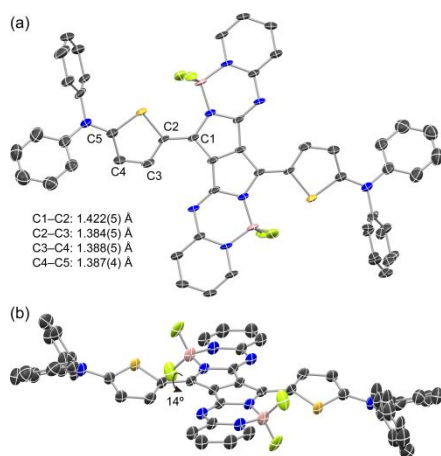


Figure 3. X-ray single crystal structure of **7**, (a) top and (b) side views. Selected bond distances and a twisted angle are shown. Alkoxy substituents and hydrogen atoms are omitted for clarity. The thermal ellipsoids are scaled to the 50% probability level.

The cyclic voltammograms of D-A-D PPABs exhibit two reversible reduction waves and one or two reversible oxidation waves (Figure S34 and Table S3). As the donor strength increases in the order of **5**, **6**, and **7**, the first oxidation potential shift to the negative side compared with **11** (**5**: 0.29 V vs Fc^+/Fc , **6**: 0.01 V, **7**: −0.09 V, and **11**: 0.38 V⁹). **7** also exhibits the negative shift of the reduction potential to −1.37 V. The electrochemical band gaps are 1.41 eV for **5**, 1.14 eV for **6**, 1.28 eV for **7**, and 1.61 eV for **11**.⁹ There is a discrepancy between the optical and electrochemical band gaps of **6**. This can be explained in terms of the rotation of the donor units because the DFT calculations reveal that the HOMO and LUMO energy

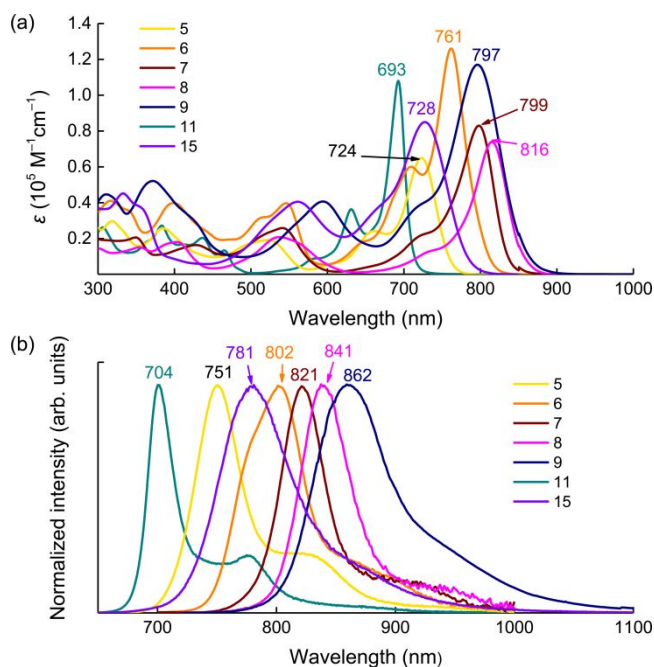


Figure 4. (a) UV/vis/NIR absorption and (b) fluorescence spectra of a series of D-A-D PPABs in chloroform.

To give a detailed insight into the donor-acceptor interactions, time-dependent (TD) DFT calculations at the $\omega\text{B97XD}/6\text{-}31\text{G(d,p)}$ level were performed (Tables S4–S10). Compared with **11**, the HOMO and LUMO of **6** and **7** are destabilized, whereas those of **5** are stabilized. Since the extent of stabilization of the LUMO for **5** and destabilization of the HOMO for **6** and **7** is more significant than that of the HOMO and the LUMO, respectively, the HOMO-LUMO gaps decrease in the order of **11** (5.17 eV), **5** (4.99 eV), **6** (4.79 eV), and **7** (4.75 eV) (Figure S35). Therefore, the longest theoretical absorption band consisting of the HOMO-LUMO transition redshifts in the same order. This agrees well with the observed

redshifts in the absorption and fluorescence spectra. To reveal the discrepancy between the optical and electrochemical band gaps of **6**, the HOMO and LUMO energy levels of **6** were estimated by changing the dihedral angles. When the phenothiazine moieties take a nearly perpendicular orientation, the HOMO and LUMO are stabilized at -6.84 and -1.69 eV, respectively (Figure S36). This result indicates that the observed discrepancy can be ascribed to the rotational isomerism of **6** in different solvents for the absorption and electrochemistry measurements.

The effects of the linkers were also investigated for **8**, **9**, and **15** (Figure S37). Compared with **15**, both the HOMO and LUMO of **8** are destabilized. On the other hand, the stabilization of the LUMO and the slight destabilization of the HOMO are revealed for **9**. Because of a minor effect of the electron-donating TPA moieties on the LUMO energy level due to the moderate twist of the TPA moieties from the thienyl linker (dihedral angles of ca. 30°), the LUMO of **9** is rather stabilized. In both cases, the HOMO-LUMO gaps of **8** and **9** become narrower than **15**. Because the lowest energy band of **8** and **9** also mainly consist of the HOMO-LUMO transition, the TD-DFT calculations reproduce the order of the redshifts in the absorption spectra.

Among the D-A-D PPABs, the high fluorescence brightness and large Stokes shift of **9** are prominent. The natural transition orbital (NTO) calculations on S_1 -to- S_0 detransition (Figures S38–S43) reveal the delocalized hole on the amino nitrogen atoms of the TPA moieties and the localized electron on the PPAB moiety in the case of **9**, implying the HLCT excited state. In contrast, in the cases of other D-A-D PPABs (**5–8**), the delocalized hole and electron all over the molecule indicate a major contribution of the locally excited state to the fluorescence emission. The enhanced ICT nature of **9** also agrees with the large Stokes shift.

In summary, a series of D-A-D PPABs bearing thienyl linkers were synthesized by post-modification means, and the role of the linkers was revealed by the theoretical calculations. Among the D-A-D PPABs, one with TPA donors exhibits the high fluorescence brightness in the NIR region due to the HLCT excited state. Because the HLCT state is realized by the moderate twist of the donor moieties from the PPAB core, the fine-tuning of the dihedral angles is a crucial issue in the molecular design of bright PPABs. Considering the absorption and fluorescence spectra of PPABs can also be controlled by the heteroaromatic ring units in the PPAB core, a combination of these two effects can further create novel bright NIR PPABs. Research in this direction is currently under investigation and will be reported in due course.

ASSOCIATED CONTENT

Data Availability Statement

The data underlying this study are available in the published article and its Supporting Information.

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Experimental procedure, HR-MS spectra, NMR spectra, crystallographic data, cyclic and differential pulse voltammograms, and DFT calculations (PDF)

Accession Codes

CCDC 2245909 and 2245910 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interests.

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