ORGANIC
LETTERS

2013
Vol. 15, No. 18
4674–4677

# Synthesis of a Non-aggregating Bay-Unsubstituted Perylene Bisimide Dye with Latent Bromo Groups for C−C Cross Coupling

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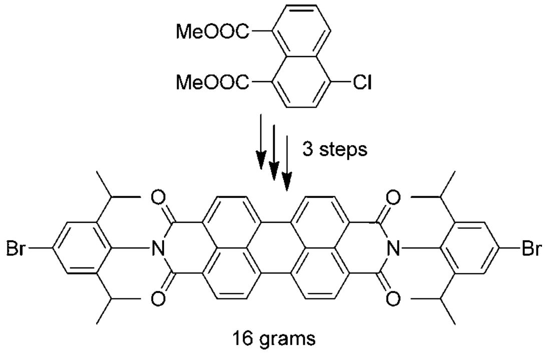
**Received July 10, 2013**

## ABSTRACT



**To address the absence of synthetic routes to access easily functionalizable, non-aggregating, and soluble bay-unsubstituted perylene bisimide dyes, an efficient, three-step, multigram-scale synthesis of the divergent building block *N,N′*-bis(4-bromo-2,6-diisopropylphenyl)perylene-3,4:9,10-tetracarboxylic bisimide is reported. Suzuki coupling yields new dyes that maintain excellent solubility and exhibit unity quantum yields in $CHCl_3$, THF, toluene, and $CH_3CN$. The methodology reported here enables access to dyes with sensitive functional groups such as aldehydes that are not accessible by traditional imidization routes.**

Perylene bisimides (PBIs) constitute a class of multifunctional dyes characterized by their intense visible-light absorption, chemical- and photostability, electron-accepting ability, and unity quantum yields.[1] Because of these desirable properties, PBI dyes have proven useful for a variety of applications ranging from industrial color pigments to active layers in organic field-effect transistors (OFET) and photovoltaic cells (OPV).[2] The large planar $\pi$-conjugated core of PBI that is responsible for many of PBIs advantageous properties also drives self-aggregation of PBI dyes,[3] frequently resulting in luminescence quenching and poor solubility.[1] Although controlled aggregation of dyes is desirable for some light-harvesting applications such as the self-assembly of charge conduits,[4] luminescent J-type aggregates,[5] and for OPV applications due to excitonic coupling that results in broadened absorption bands,[6] dyes that limit or entirely prohibit self-aggregation are valuable for persistent fluorescence at high concentration or in the

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10.1021/ol401946g

solid-state,[7] as probes for single-molecule spectroscopy,[1b,8] for constructing discrete metallosupramolecular light-harvesting antennae and photosensitizers,[9] and for incorporation in polymers with n-type semiconducting or fluorescent properties.[10] In addition, limiting aggregation of PBI acceptors in donor–acceptor films was shown to improve film morphology and promote charge-separation for OPV applications.[11]

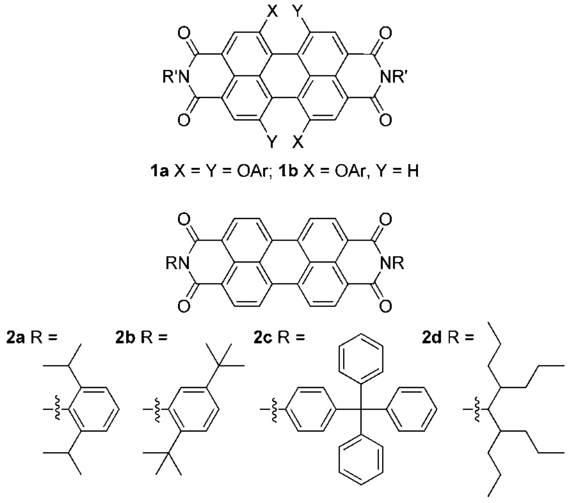

**Figure 1.** Structures of known PBI dyes **1a**, **1b**, and **2a**–**d** that exhibit limited aggregation and near-unity fluorescence quantum yields even at high concentration.

Recent efforts in PBI synthesis have focused on the introduction of bay substituents such as aryloxy groups at the 1,6,7,12-positions to impart solubility and limit aggregation while leaving the imide positions available for further functionalization (Figure 1, **1a** and **1b**).[12] From a synthetic perspective, bay-substituted PBIs are generally favored over bay-unsubstituted PBIs because introducing structural diversity is limited to the imide positions of unsubstituted PBIs, where a compromise must be reached between substituents that impart sufficient solubility and function. Despite the ability of bay substituents to limit dye aggregation, at high concentrations and in certain solvents aggregation is still observed.[12] Additionally, introduction of bay substituents results in a twisting of the PBI core that broadens the otherwise sharp vibronic bands, red-shifts the absorption maximum, alters the redox chemistry, and introduces atropisomerism into the system.[1,12,13] Independently, Langhals and Graser have introduced bulky substituents at the imide position of bay-unsubstituted PBIs to access highly soluble, non-aggregating dyes such as **2a**–**d** depicted in Figure 1.[7] Although these dyes minimize or prevent aggregation-driven fluorescence quenching, they lack sufficient handles for further synthetic modification. Surprisingly, there is a profound absence of synthetic routes to bay-unsubstituted PBI dyes that both persist in a non-aggregated state at high concentration and may be further synthetically manipulated to introduce desirable functional groups. In addition, because of the harsh conditions involved in standard imidization methods (e.g., molten imidazole), it is nearly impossible to install sensitive functional groups on bay-unsubstituted PBI derivatives. To address these shortcomings, we report here the multigram-scale synthesis of a synthetically tractable, bay-unsubstituted PBI scaffold that is both monomeric at high concentration and may be easily manipulated via modern C–C cross coupling chemistry to introduce desirable functional groups.

PBI **3** (Scheme 1), a bromo-functionalized derivative of **2a**, was identified as a suitable bay-unsubstituted target because of its lack of atropisomerism (observed for **2b**)[14] and defined geometry upon substitution. Imidization of perylene-3,4:9,10-tetracarboxylic bisanhydride (PBA) with 2,6-diisopropylaniline yielded **2a** in 66% yield after heating the mixture at 190 °C for 24 h in imidazole.[11] Screening the same imidization conditions with 4-bromo-2,6-diisopropylaniline (**4**) gave virtually no product. A wide breadth of standard PBA imidization conditions were tested such as imidazole/Zn(II) at 140 °C, *m*-cresol/quinoline at 185 °C, quinoline/Zn(II) at 200 °C, refluxing propionic acid, as well as base-promoted direct coupling of *N*-(4-bromo-2,6-diisopropylphenyl)-1,8-naphthalimide.[15] In no instance was the desired PBI **3** obtained in > 5% yield, and often no product was detected even when a large excess of **4** was used (up to 20 equiv). The best caveat for the lack of reactivity is the juxtaposition of low PBA solubility and poor nucleophilicity of **4** due to the combined effects of the bulky 2,6-diisopropyl substituents and the electron-withdrawing nature of the bromo group.

To overcome the lack of reactivity with PBA, a more soluble PBI precursor, tetramethyl 4,4′-binaphthyl-1,1′,-8,8′-tetracarboxylate (**5**), was synthesized to replace PBA (Scheme 1).[16] The improved solubility of **5** compared to PBA in molten imidazole enabled highly efficient imidization with only three equivalents of **4** in the presence of $ZnCl_2$ yielding **6** in excellent yield (99%). Adapting a procedure reported by Müllen and co-workers used to access extended rylene dyes,[17] *N*,*N*′-bis(4-bromo-2,6-diisopropyl)-4,4′-binaphthyl-1,1′,8,8′-teracarboxylic bisimide **6** was oxidatively aromatized in ethanolamine with

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(7) (a) Langhals, H.; Ismael, R.; Yürük, O. *Tetrahedron* **2000**, *56*, 5435. (b) Rademacher, A.; Märkle, S.; Langhals, H. *Chem. Ber.* **1982**, *115*, 2927. (c) Graser, F. Perylenetetracarboxylic acid diimides and their use. US Patent 4446324, May 1, 1984.

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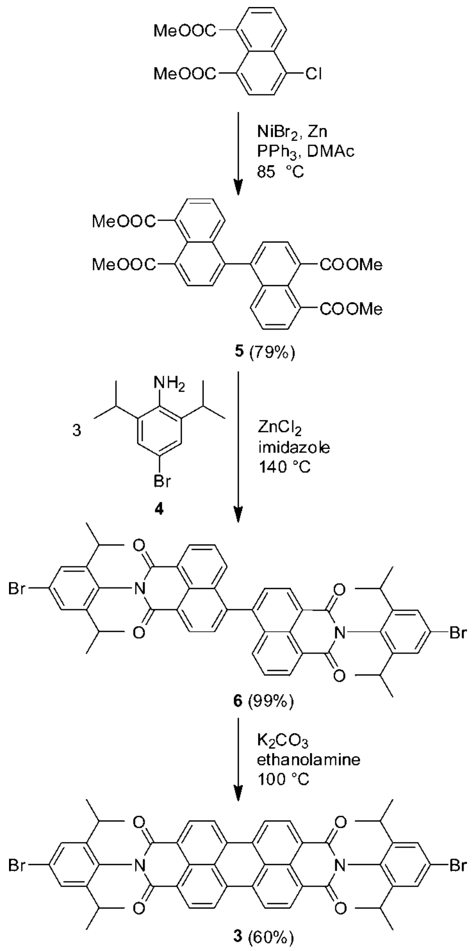
$K_2CO_3$ at 100 °C. Purification by filtration gave target PBI **3** in good yield on a 16-g scale (60%).[18] Remarkably, no column chromatography is required over the three-step synthesis (47% overall).

**Scheme 1.** Synthesis of PBI **3**



The $^1H$ NMR spectrum of **3** in $CDCl_3$ reveals a high-symmetry molecule with two aromatic resonances found at 8.81 and 8.77 ppm corresponding to the PBI core protons, a singlet at 7.48 ppm from the aromatic protons on the imide phenyl ring, a septet at 2.74 ppm from the protons on the tertiary carbon of the *i*-Pr substituents, and a doublet from the methyl groups of the *i*-Pr substituents at 1.19 ppm (Supporting Information, Figure S1). The identity of **3** was further confirmed by standard techniques (Supporting Information). Dye **3** exhibits reasonable to excellent solubility in a range of solvents such as $CHCl_3$, toluene, THF, DMSO, DMF, and MeOH.

The solid-state packing of PBI **3** was elucidated by single-crystal X-ray diffraction (SCXRD), and the results are depicted in Figure 2. Suitable crystals were grown by slow evaporation of a toluene solution of **3** which crystallized in the monoclinic space group $P2_1/c$.[19] The 4-bromo-2,6-diisopropylphenylimide substituents are arranged perpendicular to the planar PBI core, effectively preventing intermolecular $\pi-\pi$ stacking of the PBI dyes. Because the bulky imide substituents prohibit close contacts between the PBI $\pi$-scaffolds, each unit cell contains roughly eight cocrystallized toluene molecules in three unique orientations. One toluene molecule is located directly between two PBI $\pi$-surfaces (PBI−toluene and PBI−PBI $\pi-\pi$ distance ~3.5 and 7.0 Å, respectively). The other two unique cocrystallized toluene molecules are located out of the plane of the toluene−PBI stack (Figure 2b) forming a pseudolamellar organization of the PBI dyes and cocrystallized toluene (Supporting Information, Figure S14). PBI **3** is emissive in the solid state ($\lambda_{abs}$ = 643 nm, $\Phi_F$ = 0.067).

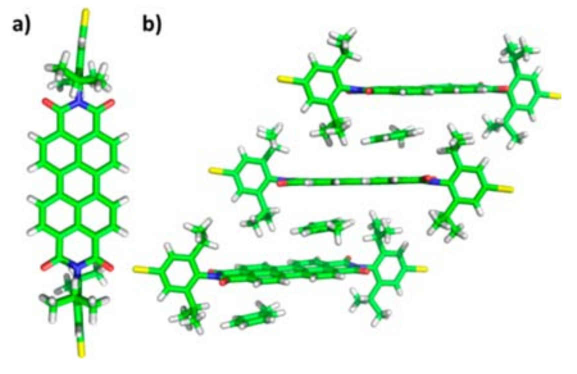


**Figure 2.** Molecular structure of PBI **3** in single crystals grown from toluene. (a) Top-down view of the PBI core highlighting the perpendicular arrangement of the 4-bromo-2,6-diisopropylphenyl imide substituents. (b) View down the *b*-axis showing the cocrystallized toluene molecules located between PBI $\pi$-surfaces. The other two unique toluene environments have been omitted for clarity (C = green, N = blue, O = red, Br = yellow, H = white).

To demonstrate the utility of **3** as a divergent building block for accessing soluble, non-aggregating, bay unsubstituted PBIs, we synthesized dipyridyl- and dialdehyde-substituted derivatives by subsequent Suzuki coupling (Scheme 2). Bay-substituted derivatives of PBI with 4-pyridyl groups at the imide positions have been successfully organized into light-harvesting and photosensitizing macrocycles, cages, and triads by coordination-driven self-assembly.[20] To maximize the performance of photofunctional supramolecules for light-harvesting applications, the

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(18) PBI **3** has been claimed in a patent: Chen, R. Perylene diimide photoelectric functional materials and preparation method thereof. Patent CN 102070771 A, May 25, 2011. However, no synthetic procedures or characterization beyond a $^1H$ NMR spectrum are reported.

(19) X-ray crystal data for **3**: $C_{48}H_{40}Br_2N_2O_4\cdot(C_7H_8)_2$, monoclinic, space group $P2_1/c$, $a$ = 17.341(1) Å, $b$ = 17.764(1) Å, $c$ = 17.827(1) Å, $V$ = 4948.3(5) Å$^3$, Z = 4, R1 = 0.0393, wR2 = 0.0983.

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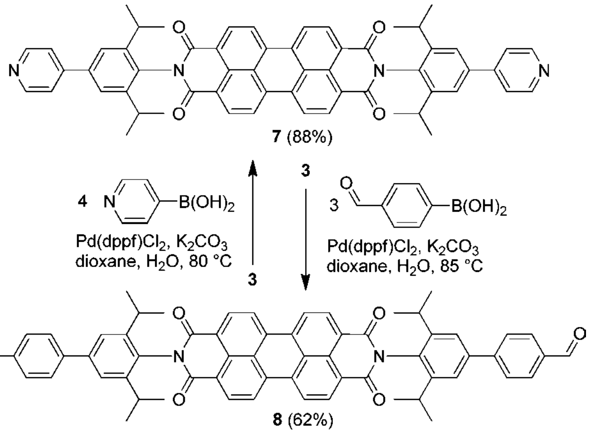
**Scheme 2.** Synthesis of Dipyridyl (**7**) and Dialdehyde (**8**) Substituted PBI Dyes from **3**



ability to tune the absorption maxima and HOMO–LUMO levels of individual components is highly desirable. Therefore, dipyridyl-substituted PBI **7** was first targeted. Heating **3**, pyridine-4-boronic acid, Pd(dppf)$Cl_2$, and aqueous $K_2CO_3$ in 1,4-dioxane for 24 h at 80 °C yielded the desired PBI **7** in 88% after column chromatography. Standard techniques were applied to confirm the identity of **7** (Supporting Information).

The solubility, aggregation strength, and fluorescence quantum yield of dipyridyl PBI **7** were measured in $CHCl_3$, THF, $CH_3CN$, and toluene. These solvents were chosen because they are common media for studying the photophysics of self-assembled systems, in particular, metallosupramolecular complexes. The results are summarized in Table 1. PBI **7** is sufficiently soluble in all four solvents for spectroscopic investigation and highly soluble in $CHCl_3$ and THF. Absorption and emission maxima are nearly independent of solvent polarity. No aggregation was observed by UV–vis spectroscopy in THF, toluene, and $CHCl_3$ (see the Supporting Information for details).[21] A slight degree of aggregation was observed in $CH_3CN$ at the concentration limit; however, the aggregation process was too weak to quantify (Supporting Information Figure S12). Importantly, unity quantum yields are maintained in all four solvents.

Our second target, PBI **8**, has two aldehydes that are excellent starting points for a variety of organic transformations and readily undergo reversible condensation with primary amines and hydrazides, making **8** an interesting fluorescent probe for dynamic combinatorial chemistry.[22] PBI **8** is inaccessible using traditional imidization conditions because the necessary amino-aldehyde building block will self-condense and may deformylate at the elevated temperatures necessary for PBA imidization. However, **8** is easily accessed by heating PBI **3**, 4-formylphenylboronic acid, Pd(dppf)$Cl_2$, and aqueous $K_2CO_3$ in 1,4-dioxane for 24 h at 85 °C (Scheme 2). Chromatography yielded **8** in 62%, and the identity was confirmed by standard techniques (Supporting Information).

**Table 1.** Solubility and Photophysical Properties of **7** in Selected Solvents

| solvent | solubility (g $L^{-1}$) | $\lambda_{abs}$ (nm) | $\lambda_F$ (nm) | $\Phi_F$ |
|---|---|---|---|---|
| $CHCl_3$ | >59[a] | 529 | 537 | 1.00 |
| THF | 8.5 | 525 | 535 | 1.00 |
| $CH_3CN$ | 0.6 | 525 | 535 | 1.00 |
| toluene | 0.3 | 529 | 539 | 1.00 |

[a] Rough estimate due to high solubility.

In summary, we have developed an efficient, multigram-scale synthetic route to dibromo-substituted PBI **3**. Two new functional PBI dyes, **7** and **8**, have been isolated by Suzuki coupling, establishing PBI **3** as an excellent building block to access soluble, non-aggregating, and highly luminescent bay-unsubstituted PBI derivatives. Functional groups that are incompatible with modern imidization procedures, such as aldehydes, may be accessed using this route. We anticipate dye **3** will be a valuable divergent building block for constructing functional PBI dyes using other C–C bond forming protocols such as Stille, Heck, and Sonogashira coupling. A broad range of polymers bearing PBI functional units will become accessible as well.

**Acknowledgment.** P.D.F. thanks the Alexander von Humboldt Foundation for a postdoctoral fellowship. We thank A.-M. Krause and C. Burschka (Universität Würzburg) for the SCXRD analysis. Generous financial support by the Bavarian State Ministry of Science, Research, and the Arts for the Collaborative Research Network "Solar Technologies go Hybrid" is gratefully acknowledged.

**Supporting Information Available.** Experimental procedures, characterization, and crystallographic details. This material is available free of charge via the Internet at http://pubs.acs.org.

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(21) In $CHCl_3$, the high solubility and large extinction coefficient of **7** prevented aggregation studies at concentrations above 3.2 mmol $L^{-1}$.

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The authors declare no competing financial interest.