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Facile synthesis of 1-bromo-7-alkoxyl perylene diimide dyes: toward unsymmetrical functionalizations at the 1,7-positions

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ABSTRACT

In this Letter, we report a facile approach to synthesize unsymmetrical 1-bromo-7-alkoxyl perylene diimides by the nucleophilic substitution of one of the two 1,7-dibromo units with an alkyl alcohol using K_2CO_3 as the base. A further replacement of another bromo, for example, by using 4-hydroxylpyridine resulted in unsymmetrical functionalizations at the 1,7-positions. The optical properties of the unsymmetrical PDI derivative were reported and compared with those of the symmetrical derivative.

Perylene diimide (PDI) dyes are remarkably photostable and airstable and the monomeric PDI dyes are highly fluorescent. Notably, they are so far typical n-type organic semiconductors[1] and show potential applications in bioimaging,[2] single-molecular spectroscopy (SMS),[3] electron-accepting materials for organic photovoltaics (OPVs),[4] and n-channel materials for organic field-effect transistors (OFETs).[5] PDI dyes can be functionalized by utilizing a wide range of groups at either the bay-positions or imide-positions, acting as versatile building blocks for self-assembly, or as molecular codes to template some organic reactions,[6,7] or as an electron-accepting unit in optically and electronically functional polymers.[8]

Some applications of PDI dyes, for examples, for liquid crystalline applications, may require unsymmetrical modifications on either the imide or bay positions.[9,10] Unsymmetrical substitutions of PDI chromophore at the imide-positions were generally carried out by using monoimide as the key intermediate, which was obtained from the partial saponification of the symmetrical diimide under catalysis of either concentrated sulfuric acid at high temperature[10] or using a strong base such as KOH and DMSO or *t*-BuOH as the reaction medium.[11] Alternatively, utilization of a mixture of primary amines yielded a mixture of two symmetrical PDIs and one unsymmetrical PDI, but the products were difficult to be purified.[12] Recently, Zang et al. reported an approach toward unsymmetrical N-substitutions directly by using alcohol and water as the reaction medium.[13] Differently, unsymmetrical substitutions at the 1,7-positions were carried out by the stoichiometric control of base and alcohol.[9d,e,14] Such a stoichiometric control led to a mixture of partially and fully substituted products and unreacted 1,7-dibrominated PDI, the reactants, which need to be purified carefully.

After the facile preparation of 1,7-dibrominated PDI **3** by following the procedure shown in Scheme 1 (**1**–**3**),[15] we occasionally utilized 5 molar equivalence of K_2CO_3 as the base and 5 molar equivalence of N-Boc-aminoethanol as the nucleophile to substitute the bromine atoms at the 1,7-positions of PDI **3**, and surprisingly, an unsymmetrical product (**4a**) was isolated in a yield of 85% (entry 1, Table 1). Meanwhile, about 10% of PDI **3** was recovered and only a trace of 1,7-bis(N-Boc-aminoethoxyl) PDI, the symmetrical product, was isolated. As controls, utilization of one molar equivalence of NaH (entry 2, Table 1) or *n*-BuLi (entry 3, Table 1) as the base yielded 50% or 23% of the unsymmetrical product (**4a**), respectively.

Using 2-methoxyethanol as the nucleophile yielded 92% of the unsymmetrical product (**4b**) (entry 4, Table 1). Various reaction temperatures and reaction times were checked out to optimize the reaction conditions. 80 °C and 1–2 h were better for this

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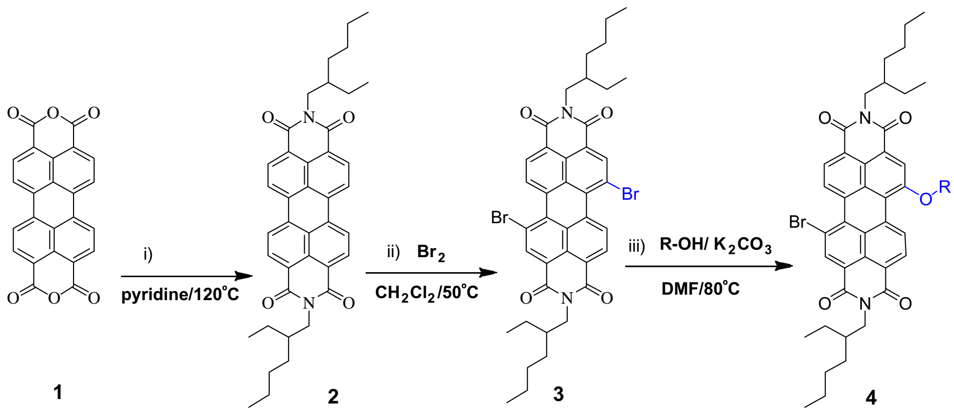


Scheme 1. A typical synthetic procedure to unsymmetrical 1-bromo-7-alkoxyl perylene diimide (**4**).

Table 1
Partial etherization of the 1,7-dibromo groups of PDI **3** with alkyl alcohols and aromatic alcohols[a]

Entry	R–OH	Time (h)	Yield[b] (%)	Product
1	Boc-$NHCH_2CH_2OH$	1	85 (10)	**4a**
2	Boc-$NHCH_2CH_2OH$	1	50 (15)[c]	**4a**
3	Boc-$NHCH_2CH_2OH$	1	23 (5)[d]	**4a**
4	$CH_3OCH_2CH_2OH$	1	92 (3)	**4b**
5	CH_3OH	2	80 (20)	**4c**
6	$CH_3(CH_2)_3OH$	4	60 (30)	**4d**
7	$CH_3(CH_2)_4OH$	4	52 (35)	**4e**
8	$CH_3(CH_2)_9OH$	4	39 (50)	**4f**
9	$CH_3(CH_2)_{17}OH$	12	–(95)[e]	**4g**
10	$(CH_3)_3COH$	12	–(95)[e]	**4h**
11	4-Br-Ph-CH_2OH	2	77 (20)	**4i**
12	Ph-CH_2OH	2	74 (22)	**4j**
13	4-CH_3-Ph-CH_2OH	2	61 (35)	**4k**
14	4-*Tert*-butylphenol	0.5	>90 (–)	**5**[f]
15	4-Hydroxylpyridine	0.5	>93 (–)	**6**[f]

[a] Note: Reactants and conditions for the step of (iii) in Scheme 1: 0.1 mmol PDI **3**, 0.5 mmol ROH, 0.5 mmol K_2CO_3, 5 mL DMF, 80 °C.

[b] Isolated yields for the unsymmetrical product and recovered PDI **3** in parentheses (%).

[c] The reaction was carried out under RT using one molar equivalence of NaH as the base and THF as the reaction medium.

[d] The reaction was carried out under −76 °C using one molar equivalence of *n*-BuLi as the base and THF as the reaction medium.

[e] The reaction was monitored by TLC.

[f] This reaction only yielded symmetrical products, 1,7-di(4-*tert*-butylphenoxyl) PDI (**5**) and 1,7-bispyridyloxyl PDI (**6**), while no unsymmetrical products were detected.

reaction. Low reaction temperature, for example, 30–60 °C, yielded only a trace of the desired product (**4b**). High reaction temperature (>100 °C) and a long reaction time (>4 h) produced several by-side products with R_f values all lower than the expected product.

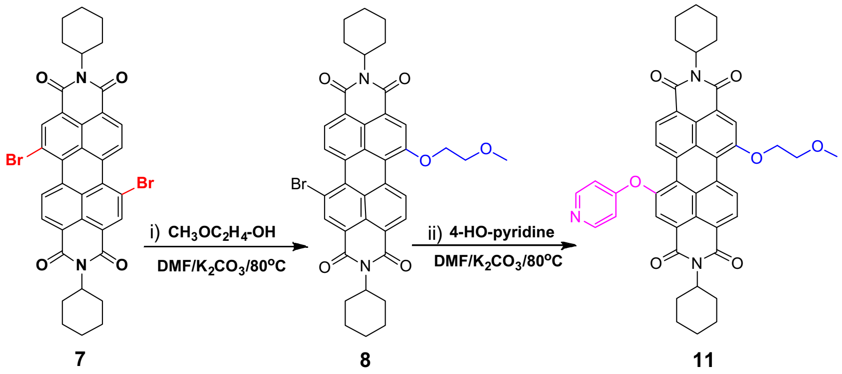
Entries 5–9 in Table 1 illustrate the unsymmetrical substitutions using various alkyl alcohols as nucleophiles, typically, ranging from methanol to 1-octadecanol. The yield of the unsymmetrical product is likely controlled by alkyl length of the alcohol because the alkyl length affects the negative charge and thus nucleophilicity of the neutral oxygen atom of alcohol. Methanol gave out a yield of 80% and *n*-butanol, *n*-pentanol, and *n*-decanol yielded the unsymmetrical product in a yield of 60%, 52%, and 39%, respectively, whereas 1-octadecanol produced only a trace of unsymmetrical product of **4g** and up to 95% of PDI **3** was recovered even after the reaction had been held at 80 °C for 12 h. *Tert*-butanol is a weaker nucleophile than *n*-butanol because of the steric hindrance from the three methyl groups and the experiment revealed that it produced only a trace of unsymmetrical product **4h** (entry 10, Table 1). Both electron-rich (4-methyl) and electron-deficient (4-bromo) groups slightly affect the nucleophilicity of benzyl alcohols and utilizations of 4-methylbenzyl alcohol, benzyl alcohol, and 4-bromobenzyl alcohol as the nucleophiles all gave out a yield of >60% (entries 11–13, Table 1). These experimental data suggest that a S_N2-type reaction may account for the unsymmetrical substitution of the 1,7-dibromo groups.

Oppositely, 4-*tert*-butylphenol can be easily and straightforwardly converted into 4-*tert*-butylphenolate ion when it is treated with K_2CO_3 as the base in DMF. The oxide anion ($-O^-$) is a much better nucleophile than the neutral oxygen atom in the alkyl alcohol. As a result, reaction of 5 mmol of 4-*tert*-butyl-phenol, 5 mmol of K_2CO_3, and 1 mmol of PDI **3** at 80 °C always produced symmetrical product **5** (entry 14, Table 1) in a yield of about 90–95%. TLC indicated that the symmetrical product appeared even after 10 min, while no unsymmetrical products were detected. Similarly, 4-hydroxylpyridine also yielded the symmetrical product only and no unsymmetrical products were detected by TLC (entry 15, Table 1) because the reaction of 4-hydroxylpyridine and K_2CO_3 also produced a strongly nucleophilic oxide anion ($-O^-$). The symmetrical substitutions from the strong nucleophiles of $-O^-$ further support that the S_N2-type reaction may account for the unsymmetrical substitution of the 1,7-dibromo groups.

When 2-ethylhexyl groups on the imide positions of PDI **3** are replaced with cyclohexyl units, the reaction of PDI **7** with 2-methoxyethonal under similar reaction conditions (Scheme 2) also yielded the unsymmetrical product **8** in a high yield of 85%. From this reaction, about 10% of starting materials was recovered (entry 1, Table 2). As a comparison, reaction of **7** with either 4-hydroxylpyridine or 4-*tert*-butylphenol only yielded symmetrical products of **9** or **10** and no unsymmetrical products were detected by TLC (entries 2 and 3, Table 2).

Accordingly, we proposed that the unsymmetrical substitutions of the 1,7-dibromo groups is likely related with the weak nucleophilicity of the neutral oxygen atom of alkyl alcohols (–OH). Upon etherization at the 1-position, the electron delocalization between the electron-rich alkoxyl group and the strong electron-deficient core perylene[16] will weaken the electrophilicity of the carbon atom (C–Br bond) at the 7-position, and thus, the nucleophilic substitution at the 7-bromo was then deactivated for the weakly nucleophilic alkyl alcohol (–OH), but not for the 4-*tert*-butyl phenol and 4-hydroxylpyridine, both of which yielded much stronger nucleophiles, the oxide anion ($-O^-$), when treated with K_2CO_3.

To investigate further functionalizations mediated by 1-bromo-7-alkoxyl PDI, we selected PDI **8** as an example. Reaction of PDI **8** with 4-hydroxylpyridine yielded an unsymmetrical product of **11** in a high yield of 96% (Scheme 2).



Scheme 2. Synthetic procedure toward unsymmetrical 1-bromo-7-(2-methoxyethoxyl) PDI (**8**) with a yield of 85% and 1-(4-pyridyloxyl)-7-(2-methoxyethoxyl) PDI (**11**) with a yield of 96%.

Table 2
Partial etherization of the 1,7-dibromo groups of PDI (**7**) with alkyl alcohols and aromatic alcohols[a]

Entry	R–OH	Time (h)	Yield[b] (%)	Product
1	$CH_3OCH_2CH_2OH$	1	85 (10)	**8**
2	4-Hydroxylpyridine	0.5	93 (–)	**9**[b]
3	4-*Tert*-butylphenol	0.5	95 (–)	**10**[b]
4	4-Hydroxylpyridine	1	96	**11**

[a] Note: Reactants and conditions for the step of (i) in Scheme 2 are similar to those described in the note (a) of Table 1.

[b] This reaction only yielded symmetrical products, 1,7-bispyridyloxyl PDI (**9**) and 1,7-di(4-*tert*-butylphenoxy) PDI (**10**), while no unsymmetrical products were detected.

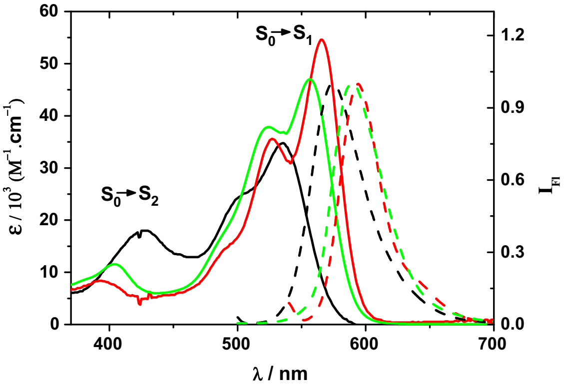


Figure 1. Absorption spectra (solid lines) and fluorescence spectra (dashed lines) of PDI **9** (black lines) and **11** (green lines), and 1,7-di(2-methoxyethoxyl) PDI (**12**, red lines). All have [dye] = 1 × 10^6 M in dichloromethane (DCM).

Table 3
Optical properties of the unsymmetrical PDI **11** in DCM

PDI	λ_{max}^{a} (nm) (0→0, 0→1)	ε/10^3 (M^{-1} cm^{-1}) (0→0, 0→1)	λ^a (nm) $S_0 \rightarrow S_2$	λ_{max}^{f} (nm)
9	535, –504	34.7, 25.0	428	575
11	556, 524	47.0, 37.9	404	590
12	566, 527	54.6, 35.6	393	594

Figure 1 collects the absorption and fluorescence spectra of the unsymmetrical PDI **11** (the green lines) and the symmetrical PDI **9** (the black lines) and 1,7-bis(2-methoxyethoxyl) perylene diimide (**12**, the red lines),[16] as comparisons. PDI **9** contains two pyridyloxyl groups and PDI **12** has two 2-methoxyethoxyl groups at the 1,7-positions, whereas the 1,7-positions in PDI **11** are, respectively, occupied by one pyridyloxyl group and one 2-methoxyethoxyl group. Such a structural difference results in quite different optical properties, as reflected from the $S_0 \rightarrow S_1$ and $S_0 \rightarrow S_2$ absorption bands.

For example, the $S_0 \rightarrow S_1$ absorption band is increased from PDIs **9**–**11** and then **12** with $\varepsilon_{max}^{0\rightarrow 0}$ increasing from 34.7 × 10^3 to 47.0 × 10^3 M^{-1} cm^{-1} and then 54.6 × 10^3 M^{-1} cm^{-1} (Table 3), indicating that substitution with 2-methoxyethoxyl group strengthens the oscillator strength for the electronic $S_0 \rightarrow S_1$ transition. Additionally, the $S_0 \rightarrow S_1$ absorption band is red shifted from PDIs **9**–**11** and then **12** with $\lambda_{max}^{a,0\rightarrow 0}$ moving from 535 nm to 556 and then to 566 nm. All these spectral changes are consistent with the stronger electronic interactions between the electron-rich alkoxyl groups and electron-deficient core perylene.[17]

Quantum chemical calculations were applied to these three molecules to get an insight into this. Replacement of the pyridyloxyl groups by one and then two 2-methoxyethoxyl groups significantly changes the charge distributions: The total Mulliken charge-density on the core perylene varies from −0.104 (PDI **9**) to −0.156 (PDI **11**) and then to −0.208 (PDI **12**), whereas that on the bay groups changes from 0.392 (PDI **9**) to 0.454 (PDI **11**) and then to 0.519 (PDI **12**) (Table S1). These data confirm the stronger electronic interactions between the core perylene and alkoxyl groups.

Differently to those observed from the $S_0 \rightarrow S_1$ absorption band, the $S_0 \rightarrow S_2$ absorption band is decreased and blue shifted as the two 1,7-bispyridyloxyl groups (PDI **9**) are replaced by one 2-methoxyethoxyl group (PDI **11**) and further by two 2-methoxyethoxyl groups (PDI **12**).

PDIs **9**, **11**, and **12** all fluoresce strongly and show an unstructured fluorescent band. The fluorescent peak is red shifted from 575 nm for DPI **9** to 590 nm for PDI **11** and then to 594 nm for PDI **12**, also consistent with the stronger electronic interactions between the electron-deficient core perylene and electron-rich alkoxyl groups.

In summary, we have developed a straightforward approach to synthesize 1-bromo-7-alkoxyl PDIs, in which the remained 1-bromo can be further functionalized, for example, by using 4-hydroxylpyridine, producing asymmetrically functionalized PDIs. To our interest, such unsymmetrical functionalizations on the 1,7-positions result in different optical properties, as compared with the symmetrical functionalizations. Accordingly, our results not only provide a facile route to asymmetrically function the 1,7-positions but also provide new models to understand the relationship between the optical property of PDIs and the molecular structure, especially from the unsymmetrical functionalizations on the bay positions.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2011.12.080.

References and notes

1. (a) Zhan, C. L.; Li, A. D. Q. *Curr. Org. Chem.* **2011**, *15*, 1314–1339; (b) Zang, L.; Che, Y. K.; Moore, J. S. *Acc. Chem. Res.* **2008**, *41*, 1596–1608; (c) Wasielewski, M. R. *J. Org. Chem.* **2006**, *71*, 5051–5066; (d) Würthner, F. *Chem. Commun.* **2004**, 1564–1579.
2. (a) Zhu, L.; Wu, W.; Zhu, M.-Q.; Han, J. J.; Hurst, J. K.; Li, A. D. Q. *J. Am. Chem. Soc.* **2007**, *129*, 3524–3526; (b) Peneva, K.; Mihov, G.; Nolde, F.; Rocha, S.; Hotta, J.-I.; Braeckmans, K.; Hofkens, J.; Uji-i, H.; Herrmann, A.; Müllen, K. *Angew. Chem., Int. Ed.* **2008**, *47*, 3372–3375.
3. (a) Han, J. J.; Wang, W.; Li, A. D. Q. *J. Am. Chem. Soc.* **2006**, *128*, 672–673; (b) Melnikov, S. M.; Yeow, E. K. L.; Uji-i, H.; Cotlet, M.; Müllen, K.; De Schryver, F. C.; Enderlein, J.; Hofkens, J. *J. Phys. Chem. B* **2007**, *111*, 708–719.
4. (a) Tang, C. W. *Appl. Phys. Lett.* **1986**, *48*, 183–185; (b) Schmidt-Mende, L.; Fechtenkötter, A.; Müllen, K.; Moons, E.; Friend, R. H.; MacKenzie, J. D. *Science* **2001**, *293*, 1119–1122; (c) Peumans, P.; Uchida, S.; Forrest, S. R. *Nature* **2003**, *425*, 158–162.
5. (a) Jones, B. A.; Ahrens, M. J.; Yoon, M.-H.; Facchetti, A.; Marks, T. J.; Wasielewski, M. R. *Angew. Chem., Int. Ed.* **2004**, *43*, 6363–6366; (b) Schmidt, R.; Oh, J. H.; Sun, Y.-S.; Deppisch, M.; Krause, A.-M.; Radacki, K.; Braunschweig, H.; Könemann, M.; Erk, P.; Bao, Z.; Würthner, F. *J. Am. Chem. Soc.* **2009**, *131*, 6215–6228; (c) Weitz, R. T.; Amsharov, K.; Zschieschang, U.; Villas, E. B.; Goswami, D. K.; Burghard, M.; Dosch, H.; Jansen, M.; Kern, K.; Klauk, H. *J. Am. Chem. Soc.* **2008**, *130*, 4637–4645.
6. (a) Balakrishnan, K.; Datar, A.; Naddo, T.; Huang, J.; Oitker; Yen, R. M.; Zhao, J.; Zang, L. *J. Am. Chem. Soc.* **2006**, *128*, 7390–7398; (b) Wang, W.; Li, L.-S.; Helms, G.; Zhou, H.-H.; Li, A. D. Q. *J. Am. Chem. Soc.* **2003**, *125*, 1120–1121; (c) Zhang, R.; Wang, Z.; Wu, Y.; Fu, H.; Yao, J. *Org. Lett.* **2008**, *10*, 3065–3068; (d) Rodríguez-Morgade, M.; Torres, T.; Atienza-Castellanos, C.; Guldi, D. M. *J. Am. Chem. Soc.* **2006**, *128*, 15145–15154; (e) You, C.-C.; Würthner, F. *J. Am. Chem. Soc.* **2003**, *125*, 9716–9725; (f) Fan, L.; Xu, Y.; Tian, H. *Tetrahedron Lett.* **2005**, *46*, 4443–4447; (g) He, X.; Liu, H.; Li, Y.; Wang, S.; Li, Y.; Wang, N.; Xiao, J.; Xu, X.; Zhu, D. *Adv. Mater.* **2005**, *17*, 2811–2815; (h) Xu, S.; Sun, J.; Ke, D.; Song, G.; Zhang, W.; Zhan, C. *J. Colloid Interface Sci.* **2010**, *349*, 142–147.
7. (a) Wang, W.; Shaller, A. D.; Li, A. D. Q. *J. Am. Chem. Soc.* **2008**, *130*, 8271–8279; (b) Shaller, A. D.; Wang, W.; Gan, H.; Li, A. D. Q. *Angew. Chem., Int. Ed.* **2008**, *47*, 7705–7709.
8. (a) Zhan, X.; Tan, Z.; Domercq, B.; An, Z.; Zhang, X.; Barlow, S.; Li, Y.; Zhu, D.; Kippelen, B.; Marder, S. R. *J. Am. Chem. Soc.* **2007**, *129*, 7246–7247; (b) Sommer, M.; Lang, A. S.; Thelakkat, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 7901–7904.
9. (a) Yang, X.; Xu, X.; Ji, H.-F. *J. Phys. Chem. B* **2008**, *112*, 7196–7202; (b) Zhang, X.; Chen, Z.; Würthner, F. *J. Am. Chem. Soc.* **2007**, *129*, 4886–4887; (c) Sun, R.; Xue, C.; Owak, M.; Peetz, R. M.; Jin, S. *Tetrahedron Lett.* **2007**, *48*, 6696–6699; (d) Golubkov, G.; Weissman, H.; Shirman, E.; Wolf I. Pinkas, S. G.; Rybtchinski, B. *Angew. Chem., Int. Ed.* **2009**, *48*, 926–930; (e) Baram, J.; Shirman, E.; Ben-Shitrit, N.; Ustinov, A.; Weissman, H.; Pinkas, I.; Wolf, S. G.; Rybtchinski, B. *J. Am. Chem. Soc.* **2008**, *130*, 14966–14967.
10. Wicklein, A.; Lang, A.; Muth, M.; Thelakkat, M. *J. Am. Chem. Soc.* **2009**, *131*, 14442–14453.
11. (a) Nagao, Y.; Misono, T. *Dyes Pigments* **1984**, *5*, 171–188; (b) Nagao, Y.; Misono, T. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 1191–1194.
12. Kaiser, H.; Lindner, J.; Langhals, H. *Chem. Ber.* **1991**, *124*, 529–535.
13. Huang, H.; Che, Y.; Zang, L. *Tetrahedron Lett.* **2010**, *51*, 6651–6653.
14. Li, Y.; Zheng, H.; Li, Y.; Wang, S.; Wu, Z.; Liu, P.; Gao, Z.; Liu, H.; Zhu, D. *J. Org. Chem.* **2007**, *72*, 2878–2885.
15. Rajasingh, P.; Cohen, R.; Shirman, E.; Shimon, L. J. W.; Rybtchinski, B. *J. Org. Chem.* **2007**, *72*, 5973–5979.
16. PDI **12** was previously synthesized in our lab, please see: Ke, D.; Zhan, C.; Xu, S.; Ding, X.; Peng, A.; Sun, J.; He, S.; Li, A. D. Q.; Yao, J. *J. Am. Chem. Soc.* **2011**, *133*, 11022–11025.
17. Chen, Z.; Baumeister, U.; Tschierske, C.; Würthner, F. *Chem. Eur. J.* **2007**, *13*, 450–465.