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m-Phenylene-Linked Dipyrrins and Their Boron−Difluoride Complexes as Variously Shaped Macrocyclic Oligomers

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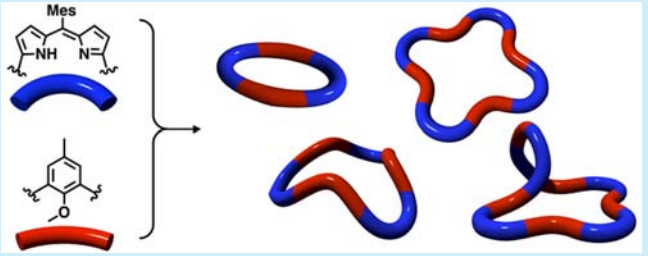
Supporting Information

ABSTRACT: The effectiveness of a *m*-phenylene linker, which has rigidity as well as rotational flexibility, is presented to produce a series of variously shaped macrocyclic oligomers of dipyrrins and BODIPYs, whose structures were revealed by X-ray crystallography and ^{1}H NMR analysis. Although the chemical structures of the repeating units are the same for dipyrrin/BODIPY oligomers, their absorbance and emission properties changed significantly depending on the size and shape of the macrocycles.



Macrocyclic dipyrrin oligomers have attracted a great deal of interest because they provide binding sites to metal ions and organic molecules.[1,2a,b,e] The complexation with metal ions affords multimetal complexes in which the metal ions are arranged in well-defined positions that result in characteristic properties and functions.[3−5] One of the most investigated dipyrrin complexes is the boron complex, BODIPY (4,4-difluoro-4-bora-3a,4a-diaza-*s*-indacene).[6] The BODIPYs have often been utilized in fluorescent sensors,[7] photovoltaic devices,[8] and components of macrocyclic compounds.[9] In addition, we have reported molecular recognition by linear and macrocyclic BODIPY oligomers through nonclassical hydrogen bonding between the fluorine atoms of the BF_2 units and a cationic guest.[2c−e] Noteworthy is that a macrocyclic BODIPY trimer bearing *m*-phenylene spacers has a nonplanar C_{3v} structure that gives rise to unidirectional threading upon the rotaxane formation with an unsymmetrical secondary ammonium guest.[2e] Consequently, the characteristic properties and functions dependent on the unique structures of the macrocyclic BODIPY oligomers would be modulated by introducing different linkers and substituents into the macrocyclic skeletons.

In this paper, the effectiveness of the *m*-phenylene linker, which has a rigidity as well as rotational flexibility, is presented to produce a series of variously shaped macrocyclic oligomers of dipyrrins and BODIPYs (Figure 1a). We designed and synthesized the dimers to pentamers of the macrocyclic 5-mesityldipyrrin linked at the 1,9 positions by 1-methoxy-4-methyl-2,6-phenylenes (Figure 1b). X-ray crystallography revealed that their structures substantially differ depending on the number of repeating units; the shape of the trimer was a nonplanar bowl, that of the tetramer was a four-pointed star, and the pentamer had a vertical loop moiety (Figure 2). Furthermore, the trimeric and tetrameric BODIPYs were synthesized by reaction of their corresponding dipyrrins with $BF_3{\cdot}Et_2O$ (see Figure 4). Although the chemical structures of the repeating units are the same for a series of dipyrrin/BODIPY oligomers, their absorbance and emission properties changed significantly depending on the size and shape of the macrocycles.

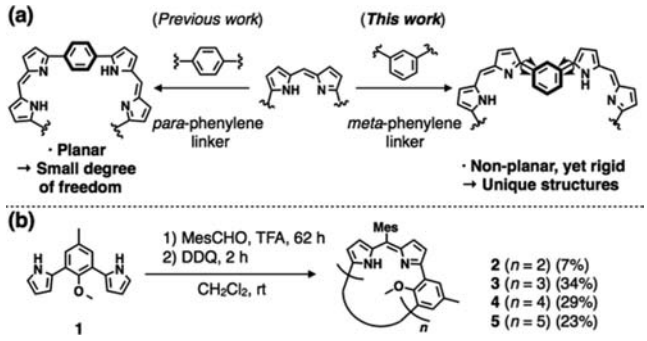


Figure 1. (a) *m*-Phenylene linking of dipyrrin units to produce rigid, nonplanar macrocycles with unique shapes. (b) Synthesis of macrocyclic dipyrrin oligomers **2**−**5** (Mes: 2,4,6-trimethylphenyl).

We have previously studied the linear and macrocyclic oligomers of dipyrrins and their boron complexes (BODIPYs) synthesized from bis-pyrrole precursors and mesitaldehydes. *p*-Phenylene linking of the α positions of the dipyrrin/BODIPYs effectively connects the π-system of each unit (Figure 1a).[2b−d] *p*-Phenylene linkers tend to result in overall planar structures due to their shape characteristics. For example, the macrocyclic trimers of the dipyrrins/BODIPYs with *p*-phenylene linkers have triangular planar structures.[2b,c,3] In contrast, *m*-phenylene linking[2e,4] instead of *p*-phenylene linking produces a larger degree of freedom in conformation, which leads to the creation of various shapes of the macrocycles.

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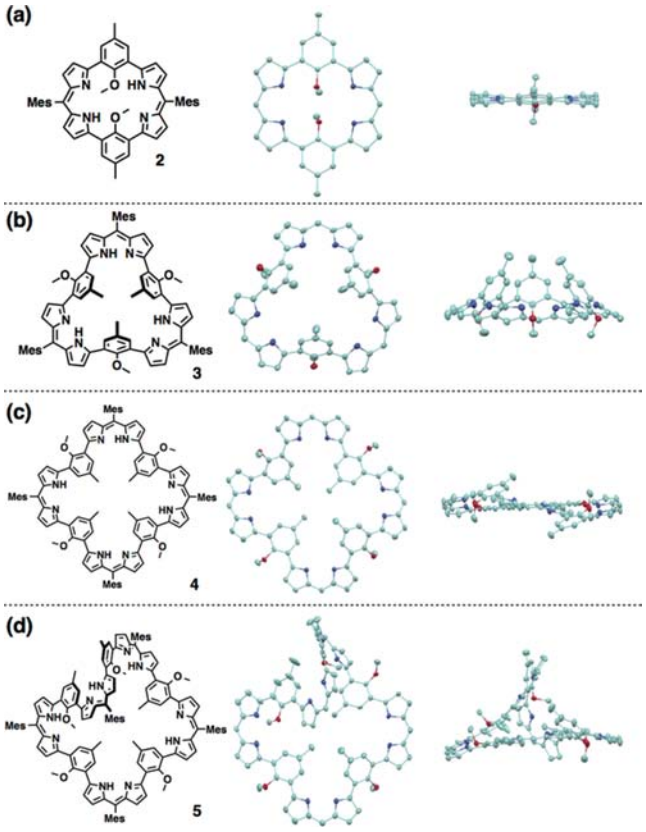

Figure 2. Chemical structures and X-ray crystal structures of cyclic dipyrrin oligomers with *m*-phenylene linkers. An ellipsoidal model (50% probability). Hydrogen atoms, solvents, and Mes groups were omitted for clarity. Key: C, light green; N, blue; O, red. (a) Dipyrrin dimer **2**. (b) Dipyrrin trimer **3**. (c) Dipyrrin tetramer **4**. (d) Dipyrrin pentamer **5**.

The macrocyclic oligomeric dipyrrins **2**–**5** were synthesized by the acid-catalyzed condensation reaction of 2,6-bis(2-pyrrolyl)-4-methylanisol (**1**) (7 mM in dichloromethane) and mesitaldehyde, followed by oxidation with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) (Figure 1b). Separation was performed by gel permeation chromatography, and each oligomer was isolated in moderate yields (dimer **2** (7%), trimer **3** (34%), tetramer **4** (29%), and pentamer **5** (23%)).

The unique structures of the macrocycles **2**–**5** were revealed by X-ray diffraction analysis of the single crystals (Figure 2). If there were no geometrical restraints, the most stable conformation between the dipyrrin units and phenylene groups is a relatively flat, coplanar conformation for the sake of π-conjugation between each component (Figure S27). Interestingly, however, the planarity of the macrocyclic framework was clearly different depending on the number of repeating dipyrrin–*m*-phenylene units. Dimer **2** and tetramer **4** had relatively coplanar frameworks, but the structures of trimer **3** and pentamer **5** largely deviated from a plane. The shape of the dimer **2** is roughly regarded as a planar rhombus where the *m*-phenylene linkers (~130°) constitute the obtuse angle vertices and the 3,5-dipyrrin units (~50°) are the acute angle ones (Figure 2a). Meanwhile, the trimer **3** did not take a conformation in which the sum of the interior angles equal $180 \cdot n°$ (n = 1,2,3, ...) and thus deviated from a planar shape and took a bowl-shaped structure (Figure 2b). The structure of **3** was different from a previously reported dipyrrin trimer with 2,6-anisole linkers (a derivative of **3** without methyl groups in the linkers), which took a distorted L-shape.[2e] The steric hindrance of the methyl groups is considered to destabilize the L-shape conformer of **3**, which leads to its bowl shape. The tetramer **4** took the shape of a planar four-pointed star. The 3,5-dipyrrin moieties were positioned at the pointed vertices, and the *m*-phenylene linkers were at the inner reflex angle vertices (Figure 2c). Here, one repeating unit of dipyrrin–*m*-phenylene made a roughly 90° angle, thus resulting in the shape of a four-pointed star. The pentamer **5** again took a nonplanar shape, but the three repeating units of the dipyrrin–*m*-phenylene (the bottom half the top view of **5** in Figure 2d) resembled those of tetramer **4**. This part of a four-pointed star shape is considered to be a stable conformation that the dipyrrin–*m*-phenylene oligomers took. The other two repeating units made an interesting vertical loop structure so as to connect the short distance of both ends of the "bottom" three dipyrrin-*m*-phenylene units.

It is worth noting that a series of these macrocycles were obtained in one reaction, which suggests that the energy difference between each oligomer was small. In the cyclization reaction of utilizing reversible bonds, smaller products made from fewer components were usually favorable in terms of entropy. However, the cyclization reaction presented here produced the [4 + 4] dipyrrin tetramer **4** in 29% yield and [5 + 5] dipyrrin pentamer **5** in 23% yield. One of the reasons is the relative destabilization of the smaller cyclic oligomers. Based on the DFT calculations of the model compound, it is suggested that the conformer in which the methoxy group of the *m*-phenylene linker directed toward the β-carbon of the dipyrrin ("out" conformation) was more stable by ~10 kJ/mol than the one in which the methoxy group is directed toward the nitrogen atom ("in" conformation) (Figure S27). Thus, the *m*-phenylene linker in the dimer **2** took an energetically unfavorable conformation. This preference for the "out" conformation of the 2-methoxy-5-methylphenylene linker also explains the four-pointed star shape seen in the tetramer **4** and pentamer **5**. To summarize, the effectiveness of this *m*-phenylene linker in making larger, various uniquely shaped macrocycles was demonstrated.

The spectroscopic data of the dipyrrin oligomers **2**–**5** are shown in Figure 3 and Table 1. The absorption maxima of **2** and **3** were found to be at 475 and 474 nm, and those of **4** and **5** were at 513 nm, respectively. Considering that the monomeric 3,5-bis(2-methoxyphenyl)dipyrrin derivative **9**[2e] exhibited its absorption at 520 nm, the *m*-phenylene linking of the oligomers **2**–**5** did not significantly connect the π-conjugation between the dipyrrin units. The small contribution of the π conjugation would be one of the major factors to realize the various shapes of the macrocycles as already

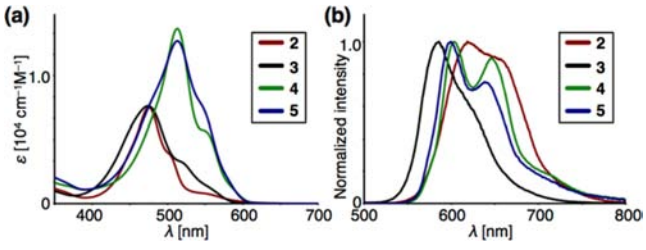

Figure 3. (a) Absorbance and (b) fluorescence spectra of dipyrrin dimer **2**, trimer **3**, tetramer **4**, and pentamer **5** ($CHCl_3$, 10 μM, 298 K).

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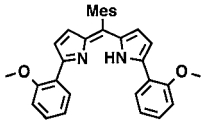
Table 1. Spectroscopic Data of Dipyrrins and BODIPYs Investigated in This Study ($CHCl_3$, 298 K)

compd	λ_{abs} (nm)	ε (M^{-1} cm^{-1})	λ_{em} (nm)	Φ_F	Stokes shift (cm^{-1})
2	475	90200	618	0.033	4900
3	474	91400	586	0.009	4000
4	513	164000	603	0.037	2900
5	513	153000	599	0.014	2800
9[2e]	520	33000	590	0.004	2300
6	512	249000	620	0.59	3500
8	542	249000	618	0.60	2300
10[2d]	551	48000	600	0.88	1500



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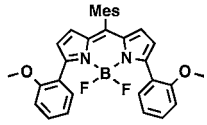

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discussed. The emission properties of the dipyrrin macrocycles showed an interesting dependence on the number of repeating units. Among **2**–**5**, the dimer **2** had the most red-shifted emission (618 nm) and the largest Stokes shift (4900 cm^{-1}), while the trimer **3** showed its emission maximum at the shortest wavelength (586 nm).

The complexation of the dipyrrin trimer **3** and the tetramer **4** with $BF_3{\cdot}Et_2O$ resulted in the BODIPY trimer **6** and tetramer **8**, respectively. For the reaction of the tetramer, the mixed dipyrrin-BODIPY tetramer **7**, in which only the two diagonal dipyrrin moieties were converted to boron complexes, was also obtained. Figure 4 shows the molecular structures of **6**–**8** determined by X-ray crystallography. It was revealed that the

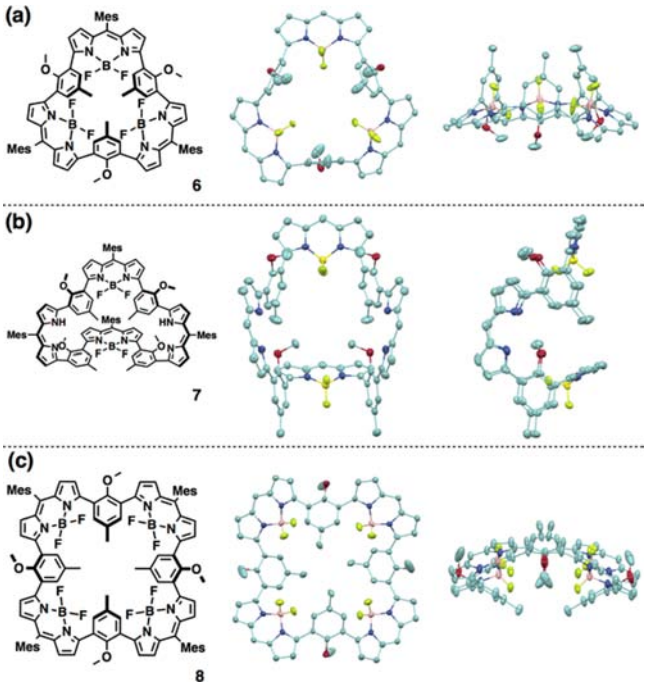

Figure 4. Chemical structures and X-ray crystal structures of cyclic BODIPY oligomers with *m*-phenylene linkers. An ellipsoidal model (50% probability). Hydrogen atoms, solvents, and Mes groups were omitted for clarity. Key: C, light green; N, blue; O, red; B, pink; F, yellow green. (a) BODIPY trimer **6**. (b) Dipyrrin-BODIPY tetramer **7**. (c) BODIPY tetramer **8**.

complexation with $BF_3{\cdot}Et_2O$ fixed the geometries of the dipyrrin units and resulted in the shape change of the BODIPY macrocycles compared to the free dipyrrin counterparts. The BODIPY trimer **6** took a pseudo-C_3-symmetric bowl-shaped structure. The three methyl groups of the *m*-phenylene linkers pointed toward the convex face of the macrocycle, while the methoxy groups pointed toward the concave one. The *m*-phenylene linkers of BODIPY **6** made greater angles against the dipyrrin units (average dihedral angles: 66°) than those of the corresponding dipyrrin **3** (average dihedral angles: 48°), which made a macrocyclic cavity larger and well-defined. The dipyrrin-BODIPY tetramer **7** had an interesting pseudo-C_s-symmetric shape resembling an armchair, where one BODIPY constitutes a back, two dipyrrin units make up the armrests, and the other BODIPY corresponds to a seat. The BODIPY tetramer **8** had a four-pointed star shape similar to the dipyrrin tetramer **4**, but the *m*-phenylene linkers were pushed alternatively up and down. The average dihedral angles of the macrocyclic tetramer between the *m*-phenylene linkers and dipyrrin units became larger after the boron complexation, as in the case of the trimer (BODIPY **8**, 52°; dipyrrin **4**, 23°).

The molecular structures of the BODIPY macrocycles **6** and **8** were investigated by ^1H and ^{19}F NMR at various temperatures. The ^1H NMR spectrum of the BODIPY trimer **6** at 298 K gave two signals for the aryl protons of the mesityl groups (δ = 6.97, 6.44 ppm), which indicated that the two sides of the macrocycle **6** were differentiated, and **6** possessed a time-averaged C_{3v} symmetry (Figure S10). The ^{19}F NMR spectrum of **6** gave two separated signals (δ = −123.6, −148.3 ppm), which also confirmed that **6** took a bowl-shaped conformation as observed in the crystal structure, and its bowl-inversion was suppressed on the NMR time scale (Figure S13). For the BODIPY tetramer **8**, the ^1H NMR spectra were measured at 240–320 K (Figure S18). At 240 K, the ^1H NMR measurement gave sharp signals for all of the protons. The number of observed signals was consistent with the time-averaged D_{2d} symmetry with alternative up–down–up–down conformations for the four *m*-phenylene linkers, which was observed in the X-ray crystallographic analysis (Figure 4c). Upon increasing the temperature to 280 K, the signals of the aryl protons of the *m*-phenylene linkers became broadened. Further heating of the solution to 320 K again resulted in a sharper spectrum while keeping its symmetry. One plausible explanation for this result is that the most stable conformation in solution was the D_{2d} symmetric one as observed in the crystal structure, which was the dominant species at 240 K. Upon increasing the temperature, the other conformers with higher energy than the D_{2d} conformer also became accessible, and the exchange rate between the conformers was comparable to the NMR time scale at 280 K and faster at 320 K. This explanation coincides with the ^{19}F NMR spectra in the temperature range of 240–320 K, in which one sharp quartet signal was observed at 240 K (δ = −131.5, $J_{19F-11B}$ = 32 Hz) but the signal became broad as the temperature increased (Figure S19).

The absorbance and emission data of the BODIPY macrocycles **6** and **8** are shown in Figure 5 and Table 1. Both compounds exhibited strong emissions in the red region (**6**: λ_{em} = 620 nm (Φ_F = 0.59); **8**: λ_{em} = 618 nm (Φ_F = 0.60). Compared to the monomeric BODIPY **10**,[2d] the fluorescent properties of the BODIPY units were not impaired by the oligomerization, and the effectiveness of the *m*-phenylene linking to maintain the good properties of the chromophores was demonstrated as in the case of the dipyrrin macrocycles.

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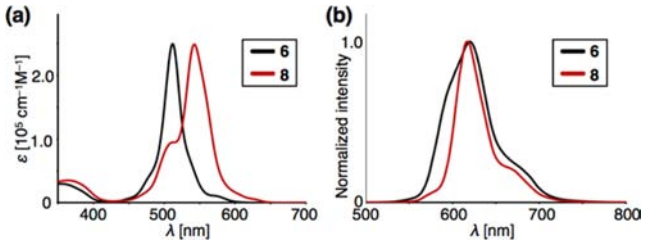

Figure 5. (a) Absorbance and (b) fluorescence spectra of BODIPY trimer **6** and tetramer **8** ($CHCl_3$, 4.0 μM, 298 K).

In conclusion, the *m*-phenylene linking of the dipyrrin units produced a series of macrocyclic oligomers, from dimer **2** to pentamer **5**, whose unique molecular structures were unambiguously determined by X-ray crystallography. The dipyrrin macrocycles can be converted to their BODIPY counterparts by a complexation reaction with $BF_3{\cdot}Et_2O$, upon which the shapes of the macrocyclic scaffolds were drastically changed. It is notable that the dipyrrin tetramer **4** and pentamer **5** were obtained in relatively good yields (29% and 23%, respectively), considering that the [4 + 4] or [5 + 5] condensation reaction between a bis-pyrrole derivative **1** and mesitaldehyde was needed to make their large macrocyclic frameworks. The metal or main group element complexes of these dipyrrins are expected to show interesting properties as photo/redox-active molecules that utilize cooperative interactions between multiple functional units,[2a] and investigations in such directions are now in progress.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.6b02761.

Experimental details, spectral data, and crystallographic information (PDF)
Crystallographic data for **2** (CIF)
Crystallographic data for **3** (CIF)
Crystallographic data for **4** (CIF)
Crystallographic data for **5** (CIF)
Crystallographic data for **6** (CIF)
Crystallographic data for **7** (CIF)
Crystallographic data for **8** (CIF)

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Notes

The authors declare no competing financial interest.

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■ NOTE ADDED AFTER ASAP PUBLICATION

The structures of compounds **9** and **10** were missing in Table 1. The correct version reposted on October 12, 2016.

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