JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

Synthesis and Functionalization of BF_2-Complexes of *meso*-Free 25-Oxasmaragdyrin

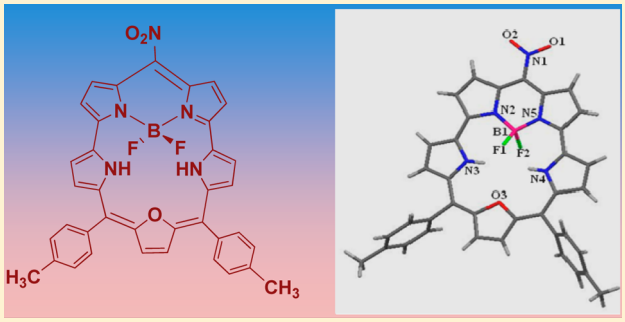
Hemanta Kalita,[†] Way-Zen Lee,[‡] and Mangalampalli Ravikanth*[,†]

[†]Department of Chemistry, Indian Institute of Technology, Powai, Mumbai 400076, India

[‡]Instrumentation Center, Department of Chemistry, National Taiwan Normal University, 88 Sec. 4 Ting-Chow Road, Taipei, 11677, Taiwan

Supporting Information

ABSTRACT: BF_2-complex of *meso*-free 25-oxasmaragdyrin is synthesized under simple reaction conditions in high yield, and the reactivity of *meso*-free carbon atom was demonstrated by carrying out functionalization followed by coupling reactions.



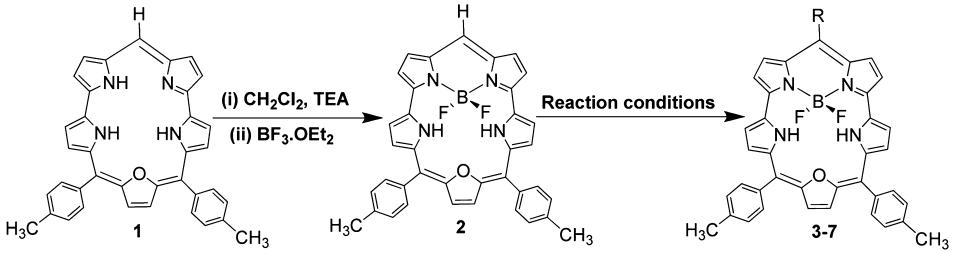
Smaragdyrins, the pentapyrrolic 22-π electron expanded porphyrin macrocycles[1] containing two direct pyrrole−pyrrole bonds, have not been explored like the other pentapyrrolic macrocycles such as sapphyrin,[2,3] which contains one direct pyrrole−pyrrole bond. This is because of lack of proper synthetic protocols, difficulties in accessing the desired stable precursors, and their own unstable nature. In 1999, Chandrashekar and co-workers[4,5] reported the first stable *meso*-triaryl-25-oxasmaragdyrin by TFA-catalyzed oxidative coupling of *meso*-aryl dipyrromethane with 16-oxatripyrrane and studied their anion and metal binding properties. Oxasmaragdyrins absorb and emit in red region with decent extinction coefficients and quantum yields and are stable under redox conditions. Because of the novel properties of smaragdyrins, recently several oxasmaragdyrin-based conjugates have been synthesized.[6−9] We recently found that BF_2-complexation of oxasmaragdyrin[10] resulted in significant alteration in its properties such as three times enhancement in the intensity of the absorption band at ∼700 nm, higher quantum yields and low reduction potentials compared to free base smaragdyrins. Recently, Chandrashekar and co-workers[11] reported the *meso*−*meso*-linked oxasmaragdyrin dyad by Ag(I)-promoted oxidative coupling of mono-*meso*-free 25-oxasmaragdyrin **1**, which showed unusual absorption properties. We thought that the *meso*-free position of mono-*meso*-free 25-oxasmaragdyrin can be activated by introducing suitable functional groups, which can be further derivatized to tune the electronic properties of 25-oxasmaragdyrin macrocycle. However, we realized that the mono-*meso*-free 25-oxasmaragdyrin **1** is not very stable to carry out any reactions. All our efforts to introduce functional group at *meso*-free position of oxasmaragdyrin **1** resulted in decomposition of the macrocycle. Since our earlier studies[10] clearly showed that BF_2-oxasmaragdyrin is more stable and robust compared to free base oxasmaragdyrin, we anticipated that BF_2-complexation of **1** would stabilize the macrocycle, and thus the *meso*-free position can be activated by introducing suitable functional groups. In this paper, we report our successful synthesis of BF_2-complex of *meso*-free 25-oxasmaragdyrin **2** and functionalization at *meso*-position with functional groups such as -Br, -CHO, -NO_2, -CCH. We also showed that the functionalized BF_2-oxasmaragdyrins are very useful precursors to synthesize novel substituted BF_2-oxasmaragdyrins with interesting photophysical properties.

The desired *meso*-free oxasmaragdyrin **1** was prepared by following the literature procedure.[11] In ^{1}H NMR spectrum, the compound **1** showed four sets of doublets at 8.53, 9.26, 9.44, and 9.53 ppm corresponding to eight pyrrole protons, one sharp singlet at 8.87 ppm corresponding to two furan protons, and one singlet at 10.09 ppm corresponding to *meso*-CH proton. The three inner -NH protons were not observed because of rapid tautomerism. The BF_2-complexation was carried out by treating compound **1** (Scheme 1) in CH_2Cl_2/triethylamine with 50 equiv of $BF_3{\cdot}OEt_2$ at room temperature for 45 min. The crude compound was subjected to basic alumina column chromatography using CH_2Cl_2/petroleum ether (30/70) and afforded **2** as green fluorescent compound in 74% yield. The peak at 615.2145 in HR-MS (Figure S2, Supporting Information) confirmed the identity of the compound **2**. The compound **2** was further characterized by ^{1}H, ^{13}C, ^{19}F, ^{11}B NMR, and the proton assignments of various protons of compound **2** were made on the basis of the ^{1}H−^{1}H

Received: March 16, 2013
Published: May 20, 2013

   dx.doi.org/10.1021/jo400540u | *J. Org. Chem.* 2013, 78, 6285−6290

Scheme 1. Synthesis of *meso*-Free BF_2-Oxasmaragdyrin 2 and Functionalization of 2 with -Br (3), -CHO (4), -NO_2 (5), and -CCH (7) Groups



Compound No.	R	Reaction Conditions	Yield (%)
3	Br	THF, N_2, -78 °C 1 eq. NBS	78
4	CHO	(i) $POCl_3$, DMF, DCE, N_2 (ii) $NaHCO_3$, H_2O	75
5	NO_2	$CHCl_3$, N_2, CH_3CN, $AgNO_2$	74
6	CCTMS	Toluene, TEA, N_2, 60 °C, CuI, $Pd_2(PPh_3)_2Cl_2$, $HCCSi(CH_3)_3$	58
7	CCH	(i) Toluene, TEA, N_2, 60 °C, CuI, $Pd_2(PPh_3)_2Cl_2$, $HCCSi(CH_3)_3$ (ii) THF, CH_3OH, N_2, K_2CO_3	69

COSY NMR spectrum (Figure S5, Supporting Information). In ^{1}H NMR spectrum, the eight pyrrole protons appeared as four sets of doublets at 9.05, 9.77, 10.28, 10.36 ppm, a sharp singlet for two furan protons at 9.53 ppm, and a singlet at 10.65 ppm for *meso*-methine proton. The *β*-pyrrole and *β*-furan protons in compound **2** were slightly downfield shifted compared to free base oxasmaragdyrin **1** (Figure S5, Supporting Information), since BF_2-complexation alters the *π*-electronic delocalization of the oxasmaragdyrin ring. Furthermore, the inner -NH protons, which are involved in rapid tautomerism in free base oxasmaragdyrin **1**, were localized in BF_2-oxasmaragdyrin **2** and appeared as an unresolved triplet in very upfield region at −4.22 ppm because of strong hydrogen bonding with the two fluoride ions of the BF_2- unit, which exposes the inner -NH protons to experience the strong ring current effect of the macrocycle. The absorption spectrum of compound **2** showed two Soret type bands at 439 and 467 nm and six well-defined Q-bands in 540−695 nm region (Figure S29, Supporting Information). Compared to free base oxasmaragdyrin **1**, the absorption bands in compound **2** are slightly red-shifted with increase in their extinction coefficients. The most interesting feature of compound **2** is the strong absorption band at 691 nm, which is seven times more intense than the absorption band of compound **1** present in the same region (Table S1, Supporting Information). The compound **2** showed one strong fluorescence band at 694 nm with a quantum yield of 0.011. The cyclic voltammogram studies of compound **2** (Table S2, Supporting Information) showed one reversible oxidation at 0.63 V and one reversible reduction at −1.05 V indicating that compound **2** is stable under redox conditions. Thus, BF_2-complexation of *meso*-free oxasmaragdyrin **2** altered the electronic properties of the macrocycle, which reflected in the bathochromic shifts in absorption and emission maxima significant enhancement in the extinction coefficients and quantum yield compared to free base oxasmaragdyrin **1** (Table S1, Supporting Information) . Similar observations were made earlier with BF_2-complex of *meso*-triaryl-25-oxasmaragdyrin compared to its free base *meso*-triaryl-25-oxasmaragdyrin.[10] Furthermore, the ground and excited state properties of compound **2** are also significantly different from BF_2-complex of *meso*-triaryl-25-oxasmaragdyrin because of the absence of one *meso*-aryl group.

The reactivity of *meso*-free position of compound **2** was tested by carrying out various functionalization reactions (Scheme 1). First we carried out bromination reaction since *meso*-brominated BF_2-oxasmaragdyrin can be used in various Pd-catalyzed cross-coupling reactions. The *meso*-brominated BF_2-oxasmaragdyrin **3** was synthesized by treating compound **2** with 1 equiv of *N*-bromosuccinimide in dry THF at −78 °C under inert atmosphere for 30 min and at room temperature for additional 1 h. The *meso*-formylated BF_2-oxasmaragdyrin **4** was prepared by treating compound **2** with Vilsmeier reagent in 1,2-dichloroethane at room temperature for 2 h followed by 15 min reflux. The nitration of compound **2** was carried out by treating compound **2** with commonly used nitrating agents such as diluted $HNO_3/(CH_3CO)_2O$ and HNO_3/H_2SO_4 but resulted in the formation of mixture of polynitro compounds. Osuka and co-workers[12] reported regiospecific nitration on porphyrins using $AgNO_2$. Thus, the *meso*-nitrated BF_2-oxasmaragdyrin **5** was prepared by treating compound **2** with $AgNO_2$ in $CHCl_3/CH_3CN$ at 0 °C for 8 h. The BF_2-oxasmaragdyrin bearing trimethylsilylethynyl functional group **6** was prepared by reacting *meso*-bromo BF_2-oxasmsragdyrin **3** with trimethylsilylacetylene at 80 °C in the presence of catalytic amount of $Pd(PPh_3)_2Cl_2$/CuI for 3 h. The compound **7** was prepared by deprotecting trimethylsilyl group of compound **6** with K_2CO_3 in dry THF/CH_3OH at 60 °C for 4 h. The compounds **3**−**7** were purified by basic alumina column chromatography and characterized by the observation of molecular ion peak in mass spectra and by NMR. The absorption, fluorescence (Table S1, Supporting Information), and electrochemical properties (Table S2, Supporting Information) of compounds **3**−**7** were

dx.doi.org/10.1021/jo400540u | J. Org. Chem. 2013, 78, 6285−6290

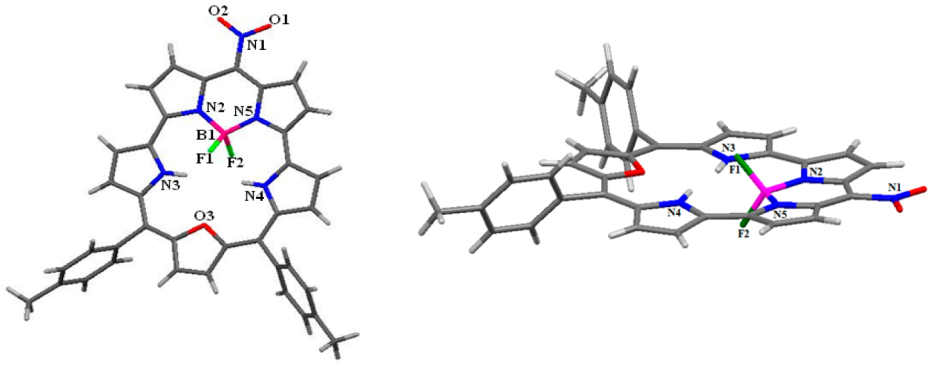


Figure 1. Crystal structure of compound **5**, (a) perspective view and (b) side view.

investigated, and the properties were dependent on the kind of substituent present at the *meso*-position.

We attempted to grow single crystals for functionalized BF_2-oxasmaragdyrins since the crystal structure of any BF_2-oxasmaragdyrin is not reported to date. Fortunately, we obtained single crystals for compound **5** (CCDC 929083) by the slow evaporation of *n*-hexane/$CHCl_3$ (1:1) solution at room temperature over a period of seven days, and the compound was crystallized in an orthorhombic space group *Pbcn*. Thus, the first single crystal X-ray structure of BF_2-complex of oxasmargdyrin **5** bearing -NO_2 functional group on the free *meso*-position is shown in Figure 1.

The X-ray structure showed that the macrocyclic ring is almost planar and the BF_2- unit is approximately tetrahedral with F1−B1−F2, N5−B1−N2, N5−B1−F1 and N2−B1−F2 angles are in the range of 106°−110° (Table 1). The boron atom of the BF_2- unit is in the same plane defined by the four pyrrole nitrogen atoms. Furthermore, among the two fluorine atoms of BF_2- unit, one fluorine atom is above the plane of the macrocycle and the other fluorine atom is below the plane of the macrocycle. The two B−F distances are equal (Table 1). The nitro group at *meso*-position is trigonal planar (Table 1). The -NO_2 group is almost in the same plane of the macrocycle defined by three *meso*-carbon atoms. The *meso*-tolyl rings were observed to have the dihedral angles of 63.2° and 89.4° relative to the macrocycle. The two N−O bonds were equivalent (Table 1), which is in accordance with the literature for N−O bond length in NO_2^- ion.[13] Furthermore, the fluorine atoms of the BF_2- unit are involved in intramolecular H-bonding with the inner hydrogen atoms (N4−H···F1 distance 1.93 Å and N3−H···F2 distance 2.20 Å) of the macrocycle. Also, the crystal packing diagram shows that the fluorine atoms of one BF_2-oxasmaragdyrin unit are involved in the intermolecular H-bonding with *β*-pyrrole protons of neighboring BF_2-oxasmaragdyrin unit (Figure S35, Supporting Information). Similarly, the oxygen atom of the *meso*-nitro group of one BF_2-oxasmaragdyrin unit is involved in weak intermolecular H-bonding with *meso*-aryl proton of another macrocycle (O2···H distance 2.55 Å) leading to supramolecular architectures.

Table 1. Selected Bond Lengths [Å] and Angles [°] for 5

F1−B1	1.41(4)
F2−B1	1.41(4)
N1−O1	1.24(4)
N1−O2	1.23(4)
N4−H···F1	1.93
N3−H···F2	2.20
F1−B1−F2	106.1(3)
N5−B1−N2	110.4(3)
N5−B1−F1	109.9(3)
N2−B1−F2	110.3(3)
O1−N1−O2	120.5(3)
O1−N1−C1	118.9(4)
O2−N1−C1	120.6(4)

To demonstrate the use of *meso*-free BF_2-oxasmaragdyrin **2** and *meso*-functionalized BF_2-oxasmsragdyrins **3**−**7**, we subjected the macrocycles for various reactions (Scheme 2). The *meso*-bromo BF_2-oxasmaragdyrin **3** was reacted with phenyl acetylene under Sonogashira coupling conditions[14] and afforded *meso*-phenyl acetylene substituted BF_2-oxasmaragdyrin **8** in 80% yield. The *meso*-formyl BF_2-oxasmsragdyrin **4** is subjected to Wittig reaction by treating it with phosphorus ylide and afforded compound **9** in 90% yield. We also subjected the *meso*-free BF_2-oxasmaragdyrin **2** under Ag(I) coupling conditions[11] followed by chromatographic purification to yield *meso*−*meso*-linked BF_2-oxasmaragdyrin−BF_2-oxasmsragdyrin dyad **10** in 33% yield. All compounds were characterized by various spectroscopic techniques, and preliminary spectral studies are quite promising.

■ CONCLUSION

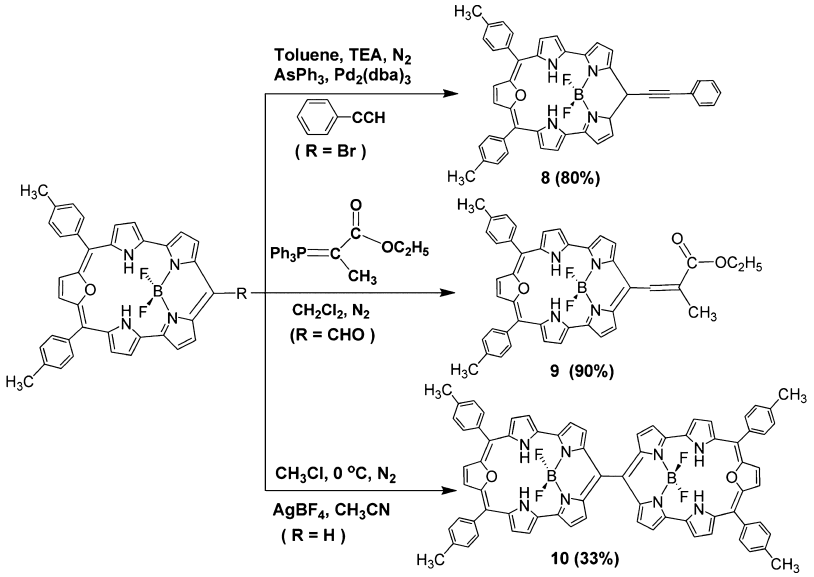
In conclusion, we have prepared stable BF_2-complex of *meso*-free oxasmaragdyrin **2** in high yield under simple reaction conditions, which showed interesting optical, electrochemical and photophysical properties. The *meso*-free position is activated by introducing functional groups such as -Br, -CHO, -NO_2, -CCH. The first crystal structure solved for *meso*-nitro BF_2-25-oxasmaragdyrin **5** indicated that boron atom is in the plane of macrocycle with one fluoride above and the other fluoride is below the plane of the macrocycle. The *meso*-functionalized BF_2-oxasmaragdyrins are very useful synthons to prepare several novel *meso*-substituted BF_2-oxasmaragdyrins as demonstrated in this paper.

■ EXPERIMENTAL SECTION

General Methods. The ^1H, ^{13}C, ^{11}B and ^{19}F NMR spectra were recorded in $CDCl_3$ using tetramethylsilane ($Si(CH_3)_4$) as internal standard. The fluorescence quantum yields (Φ_f) were estimated from the emission and absorption spectra by comparative method at the excitation wavelength of 420 nm using H_2TTP (Φ_f = 0.11) as standard. Cyclic voltammetric (CV) studies were carried out utilizing the three electrode configuration consisting of a glassy carbon

dx.doi.org/10.1021/jo400540u | J. Org. Chem. 2013, 78, 6285−6290

Scheme 2. Synthesis of Compounds 8−10



(working electrode), platinum wire (auxiliary electrode), and saturated calomel (reference electrode) electrodes. The experiments were done in dry CH_2Cl_2 using 0.1 M tetrabutylammonium perchlorate as supporting electrolyte. Half wave potentials were measured using DPV (differential pulse voltammetry) and also calculated manually by taking the average of the cathodic and anodic peak potentials. The HR-MS and LR-MS mass spectra were recorded by using ESI method and quadrupole analyzer.

Compound 2. A sample of mono-*meso*-free oxasmaragdyrin **1** (100 mg, 0.184 mmol) was dissolved in CH_2Cl_2 (30 mL), and triethylamine (1.02 mL, 6.28 mmol) was added to it. The mixture was stirred at room temperature. After 5 min, $BF_3{\cdot}Et_2O$ (1.16 mL, 7.85 mmol) was added, and the stirring was continued at room temperature for additional 30 min. The reaction mixture was diluted with CH_2Cl_2 and washed thoroughly twice with 0.1 M NaOH solution and water. The organic layers were combined, dried over Na_2SO_4, and filtered. The solvent was removed on a rotary evaporator under a vacuum, and the resulting crude compound was purified by basic alumina column chromatography. The desired compound **2** was collected as green band using petroleum ether/dichloromethane (65:35) and afforded pure compound **2** as a green powder in 74% (80 mg) yield: mp > 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −4.22 (m, 2H), 2.80 (s, 6H), 7.69 (d, 4H, ^3J(H,H) = 7.56 Hz), 8.29 (d, 4H, ^3J(H,H) = 7.77 Hz), 9.05 (d, 2H, ^3J(H,H) = 2.64 Hz), 9.53 (s, 2H), 9.77 (d, 2H, ^3J(H,H) = 4.32 Hz), 10.28 (d, 2H, ^3J(H,H) = 2.44 Hz), 10.36 (d, 2H, ^3J(H,H) = 4.32 Hz), 10.65 (s, 1H); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −149.39 (bs); ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −12.84 (bs); ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm) 21.87, 106.93, 120.51, 121.00, 123.62, 124.34, 125.03, 129.38, 130.06, 130.47, 130.59, 132.40, 134.50, 135.27, 138.08, 139.87, 149.84; UV−vis (in $CHCl_3$, λ_{max}/nm (logε)) 439 (5.5), 467 (5.3), 545 (3.8), 572 (3.8), 586 (4.1), 621 (4.2), 681 (4.3), 691 (4.4); HR-MS calcd for $C_{37}H_{27}BF_2N_4ONa$ $(M + Na)^+$ m/z 615.2144, observed 615.2145. Anal. Calcd for $C_{37}H_{27}BF_2N_4O$: C, 75.01; H, 4.59; N, 9.46. Found: C, 75.14; H, 4.64; N, 9.53.

Compound 3. A solution of BF_2-oxasmaragdyrin **2** (38 mg, 0.064 mmol) in dry THF was treated with *N*-bromosuccinimide (12 mg, 0.064 mmol), and the reaction mixture was allowed to stir at −78 °C for 30 min initially and continued stirring for additional 1 h at room temperature. The solvent was removed on a rotary evaporator under a vacuum. The crude compound was purified by basic alumina column chromatography using petroleum ether/dichloromethane (75/25) and afforded pure compound **3** in 78% (32 mg) yield as green solid: mp > 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −4.09 (m, 2H), 2.79 (s, 6H), 7.68 (d, 4H, ^3J(H,H) = 7.38 Hz), 8.27 (d, 4H, ^3J(H,H) = 7.39 Hz), 9.03 (d, 2H, ^3J(H,H) = 3.22 Hz), 9.51 (s, 2H), 9.88 (d, 2H, ^3J(H,H) = 4.22 Hz), 10.24 (d, 2H, ^3J(H,H) = 3.21 Hz), 10.34 (d, 2H, ^3J(H,H) = 4.12 Hz); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −149.33 (bs); ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −13.49 (bs); ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm) 21.85, 107.53, 120.95, 121.46, 122.51, 123.86, 124.34, 125.45, 128.50, 130.73, 131.03, 131.89, 134.45, 135.27, 138.21, 139.56, 150.22; UV−vis (in $CHCl_3$, λ_{max}/nm (logε)) 442 (5.4), 476 (5.1), 552 (3.5), 578 (3.6), 596 (3.8), 629 (4.0), 652 (4.2), 703 (4.5); HR-MS calcd for $C_{37}H_{27}BBrF_2N_4O$ $(M + H)^+$ m/z 671.1429, observed 671.1430. Anal. Calcd for $C_{37}H_{26}BBrF_2N_4O$: C, 66.20; H, 3.90; N, 8.35. Found: C, 66.40; H, 3.81; N, 8.43.

Compound 4. In a 100 mL 3-neck round-bottom flask, DMF (100 μL, 12.85 mmol) was taken and cooled to 5−10 °C and flushed with nitrogen for 5 min. $POCl_3$ (100 μL, 1.07 mmol) was added as dropwise, and after 5 min stirring, 8 mL of dichloroethane was added to the reaction mixture and continued stirring for 15 min at room temperature. The reaction mixture was cooled to 0 °C, and the sample of BF_2-oxasmaragdyrin **2** (100 mg, 0.170 mmol) in dichloroethane was added dropwise using dropping funnel for a period of 30 min. The reaction mixture was warmed to 50 °C and stirred for 15 min. A saturated $NaHCO_3$ solution (20 mL) was added to the reaction mixture and stirred vigorously at room temperature for 2 h. The reaction mixture was extracted with dichloromethane, the solvent was evaporated on rotary evaporator under a vacuum, and the resulted crude compound was purified by basic alumina column chromatography. The desired green band was collected with petroleum ether/dichloromethane (60:40) and afforded the pure compound **4** in 75% (79 mg) yield as a green solid: mp > 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −5.08 (m, 2H), 2.83 (s, 6H), 7.73 (d, 4H, ^3J(H,H) = 7.68 Hz), 8.33 (d, 4H, ^3J(H,H) = 7.76 Hz), 9.36 (d, 2H, ^3J(H,H) = 3.74 Hz), 9.78 (s, 2H), 10.52 (m, 2H), 10.60 (d, 2H, ^3J(H,H) = 4.49 Hz), 10.74 (d, 2H, ^3J(H,H) = 4.52 Hz), 12.73 (s, 1H); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −147.03 (bs); ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −13.84 (bs); ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm) 21.88, 104.25, 109.34, 121.41, 123.09, 125.11, 125.39, 125.45, 126.21, 127.32, 128.54, 131.58, 134.66, 134.21, 138.62, 139.25, 150.68, 191.30; UV−vis (in $CHCl_3$, λ_{max}/nm (logε)) 457 (5.7), 492 (5.4), 582 (3.9), 628 (4.8), 662 (4.2), 695 (4.6), 735 (4.9); HR-MS calcd for $C_{38}H_{27}BF_2N_4O_2Na$ $(M + Na)^+$ m/z 643.2093, observed 643.2094. Anal. Calcd for $C_{38}H_{27}BF_2N_4O_2$: C, 73.56; H, 4.39; N, 9.03. Found: C, 73.65; H, 4.47; N, 9.21.

Compound 5. A solution of BF_2-oxasmaragdyrin **2** (40 mg, 0.068 mmol) in $CHCl_3$ was shielded from light and cooled to 0 °C under inert atmosphere. A solution of $AgNO_2$ (11 mg, 0.071 mmol) in acetonitrile was added, and the mixture was stirred for 2 h initially at 0

dx.doi.org/10.1021/jo400540u | J. Org. Chem. 2013, 78, 6285−6290

°C, brought to room temperature, and continued stirring for additional 6 h. The solvent was removed on rotary evaporator under a vacuum, and the resulted crude residue was subjected to basic alumina column chromatographic purification. The desired brown-green band eluted with petroleum ether/dichloromethane (50:50) was collected and afforded the pure compound **5** as a brownish green solid in 74% (32 mg) yield: mp > 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −4.61 (m, 2H), 2.82 (s, 6H), 7.73 (d, 4H, ^3J(H,H) = 7.72 Hz), 8.29 (d, 4H, ^3J(H,H) = 7.85 Hz), 9.31 (dd, 2H, ^3J(H,H) = 3.89 Hz, ^4J(H,H) = 1.92 Hz), 9.70 (s, 2H), 10.41 (dd, 2H, ^3J(H,H) = 4.23 Hz, ^4J(H,H) = 1.98 Hz), 10.59 (d, 2H, ^3J(H,H) = 4.60 Hz), 10.62 (d, 2H, ^3J(H,H) = 4.64 Hz); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −145.51 (bs); ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −14.51 (bs); ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm) 21.88, 104.36, 106.34, 121.41, 123.87, 125.85, 126.30, 126.38, 126.51, 128.65, 129.02, 134.56, 136.17, 138.73, 138.89, 139.54, 151.34; UV−vis (in $CHCl_3$, λ_{max}/nm (logε)) 472 (5.5), 503 (4.1), 561 (3.6), 603 (3.8), 678 (sh), 756 (4.8); HR-MS calcd for $C_{37}H_{26}BF_2N_5O_3Na$ $(M + Na)^+$ m/z 660.1994, observed 660.1995. Anal. Calcd for $C_{37}H_{26}BF_2N_5O_3$: C, 69.72; H, 4.11; N, 10.99. Found: C, 69.80; H, 4.07; N, 11.06.

Compound 6. To a solution of *meso*-bromo-BF_2-oxasmaragdyrin **3** (40 mg 0.068 mmol) in toluene/triethylamine (1:1), trimethylsilylacetylene (12 μL, 0.086 mmol) was added, and the mixture was stirred for 15 min under N_2 atmosphere. The coupling was initiated by addition of catalytic amounts of CuI (0.005 equiv) and $Pd(PPh_3)_2Cl_2$ (0.005 equiv), and the reaction mixture was stirred at 80 °C for 3 h. The solvent was removed on rotary evaporator under a vacuum. The crude product was subjected to basic alumina column chromatographic purification using petroleum ether/dichloromethane (75:25) and afforded pure compound **6** as green solid in 58% (23 mg) yield: mp > 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −4.32 (m, 2H), 0.72 (s, 9H), 2.79 (s, 6H), 7.69 (d, 4H, ^3J(H,H) = 7.76 Hz), 8.28 (d, 4H, ^3J(H,H) = 7.84 Hz), 9.09 (dd, 2H, ^3J(H,H) = 4.44 Hz, ^4J(H,H) =1.76 Hz), 9.56 (s, 2H), 9.99 (d, 2H, ^3J(H,H) = 4.37 Hz), 10.29 (dd, 2H, ^3J(H,H) = 3.49 Hz, ^4J(H,H) = 1.92 Hz), 10.40 (d, 2H, ^3J(H,H) = 4.40 Hz); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −149.06 (bs); ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −13.08 (bs); UV−vis (in $CHCl_3$, λ_{max}/nm (logε)) 450 (5.4), 491 (5.0), 573 (3.7), 615 (3.8), 650 (4.0), 673 (4.1), 724 (4.5); ES-MS calcd for $C_{42}H_{35}BF_2N_4OSi$ (M^+) m/z 688.2641, observed 688.3322. Anal. Calcd for $C_{42}H_{35}BF_2N_4OSi$: C, 73.25; H, 5.12; N, 8.14. Found: C, 73.32; H, 5.19; N, 8.19.

Compound 7. The sample of compound **6** (60 mg, 0.089 mmol) was dissolved in dry and distilled THF/CH_3OH (3:1) in a 100 mL round-bottom flask fitted with a reflux condenser. An excess of K_2CO_3 (123 mg, 0.891 mmol) was added, and the reaction mixture was allowed to stir for 4 h at 60 °C. The crude compound was subjected to basic alumina column chromatography using petroleum ether/dichloromethane (70:30) and afforded pure compound **7** in 69% (37 mg) yield: mp > 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −4.48 (m, 2H), 2.79 (s, 6H), 4.44 (s, 1H), 7.69 (d, 4H, ^3J(H,H) = 7.91 Hz), 8.28 (d, 4H, ^3J(H,H) = 7.42 Hz), 9.12 (dd, 2H, ^3J(H,H) = 4.23 Hz, ^4J(H,H) =1.91 Hz), 9.59 (s, 2H), 10.02 (d, 2H, ^3J(H,H) = 4.23 Hz), 10.32 (dd, 2H, ^3J(H,H) = 4.61 Hz, ^4J(H,H) = 1.81 Hz), 10.44 (d, 2H, ^3J(H,H) = 4.60 Hz); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −148.99 (bs); ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −13.12 (bs); ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm) 22.89, 85.91, 107.78, 121.33, 122.32, 122.64, 122.72, 124.17, 124.65, 124.75, 125.29, 128.49, 129.17, 130.96, 134.56, 134.70, 138.26, 139.65, 150.20; UV−vis ($CHCl_3$, λ_{max}/nm (logε)) 449 (5.3), 489 (4.9), 571 (3.6), 593 (3.7), 611 (3.8), 648 (4.0), 671 (4.1), 719 (4.4); HR-MS calcd for $C_{39}H_{28}BF_2N_4O$ $(M + H)^+$ m/z 617.2324, observed 617.2325. Anal. Calcd for $C_{39}H_{27}BF_2N_4O$: C, 75.98; H, 4.41; N, 9.09. Found: C, 75.94; H, 4.37; N, 9.13.

Compound 8. Samples of *meso*-bromo-BF_2-oxasmaragdyrin **3** (40 mg, 0.068 mmol) and phenylacetylene (8.2 μL, 0.074 mmol) were dissolved in dry toluene/triethylamine (3:1) in a 25 mL round-bottomed flask fitted with a reflux condenser, gas inlet and gas outlet tubes for nitrogen purging. The reaction vessel was placed in an oil bath preheated to 45 °C. After purging with nitrogen for 15 min, $AsPh_3$ (3.5 equiv) and $Pd_2(dba)_3$ (0.44 equiv) were added, and the reaction was stirred at 50 °C for 2 h. TLC analysis of the reaction mixture indicated the appearance of a major green new spot apart from the faded starting materials. The crude compound was subjected to basic alumina column chromatography and collected the desired compound using petroleum ether/dichloromethane (75:25). The solvent was removed on rotary evaporator under a vacuum and afforded pure compound **8** in 80% (33 mg) yield: mp > 300 °C, ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −4.14 (m, 2H), 2.80 (s, 6H), 7.68 (m, 6H, Ar), 8.17 (m, 3H), 8.29 (d, 4H, ^3J(H,H) = 7.48 Hz), 9.09 (d, 2H, ^3J(H,H) = 4.32 Hz), 9.55 (s, 2H), 10.05 (d, 2H, ^3J(H,H) = 4.31 Hz), 10.28 (m, 2H), 10.40 (d, 2H, ^3J(H,H) = 4.31 Hz) ; ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −149.01 (bs); ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm) 21.86, 89.17, 97.42, 99.00, 107.71, 121.05, 122.03, 122.30, 122.65, 122.75, 124.15, 124.75, 125.28, 128.49, 128.99, 129.31, 130.89, 132.232, 134.14, 134.51, 138.21, 139.63, 150.21. UV−vis (in $CHCl_3$, λ_{max}/nm) 459, 497, 574, 599, 616, 657, 678, 734. HR-MS calcd for $C_{45}H_{32}BF_2N_4O$ $(M + H)^+$ m/z 693.2637, observed 693.2639.

Compound 9. The compound **4** (10 mg, 0.016 mmol) was added to the solution of phosphorus ylide (15 mg, 0.040 mmol) in dichloromethane maintaining the temperature at 0 °C. The reaction mixture was allowed to stir at room temperature for ∼16 h after the addition of the compound to the ylide solution. The disappearance of starting material in the reaction mixture was monitored by TLC, and a new major less polar spot corresponding to the desired compound was observed. The solvent was evaporated under reduced pressure, and the residue purified by column chromatography on basic alumina with petroleum ether/dichloromethane (70:30, v/v), giving the desired compound **9** as green solid in 90% (10 mg) yield: mp > 300 °C, ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −4.07 (m, 2H), 1.63 (t, 3H, ^3J(H,H) = 7.16 Hz), 2.42 (s, 3H), 2.79 (s, 6H), 4.65 (q, 2H, ^3J(H,H) = 7.08 Hz), 7.68 (d, 4H, ^3J(H,H) =7.61 Hz), 8.28 (d, 4H, ^3J(H,H) = 7.72 Hz), 9.04 (d, 2H, ^3J(H,H) = 3.04 Hz), 9.52 (s, 2H), 9.69 (d, 2H, ^3J(H,H) = 4.36 Hz), 10.09 (s, 1H), 10.24 (d, 2H, ^3J(H,H) = 2.64 Hz), 10.34 (d, 2H, ^3J(H,H) = 4.36 Hz); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −149.25; ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −12.88 (bs); UV−vis (in $CHCl_3$, λ_{max}/nm) 449, 478, 595, 654, 717; HR-MS calcd for $C_{43}H_{36}BF_2N_4O_3$ $(M + H)^+$ m/z 705.2849, observed 705.2850.

Compound 10. A solution of BF_2-oxasmaragdyrin **2** (40 mg, 0.068 mmol) in $CHCl_3$ was shielded from light and cooled to 0 °C under inert atmosphere. A solution of $AgBF_4$ (13.2 mg, 0.068 mmol) in acetonitrile was added, and the mixture was stirred. After 8 h, the reaction was stopped. The solvent was evaporated in a vacuum, the residue was purified by chromatography on a basic alumina column, and the greenish band which eluted with petroleum ether/dichloromethane (60:40) gave the desired product **10** as a green solid in 33% (13 mg) yield: mp > 300 °C, ^{1}H NMR (400 MHz, $CDCl_3$, δ in ppm) −3.83 (m, 4H, -NH), 2.83 (s, 12H), 7.74 (d, 8H, ^3J(H,H) = 7.76 Hz), 8.39 (d, 8H, ^3J(H,H) = 7.80 Hz), 9.15 (d, 4H, ^3J(H,H) = 2.81 Hz), 9.35 (d, 4H, ^3J(H,H) =4.44 Hz), 9.64 (s, 4H), 10.34 (s, 4H), 10.35 (s, 4H); ^{19}F NMR (282.2 MHz, $CDCl_3$, δ in ppm) −148.72; ^{11}B NMR (96.3 MHz, $CDCl_3$, δ in ppm) −12.01; ^{13}C NMR (100 MHz, $CDCl_3$, δ in ppm) 21.90, 107.40, 120.94, 121.47, 122.53, 124.37, 125.23, 126.41, 128.55, 130.19, 131.00, 134.61, 136.51, 138.19, 139.87, 150.14; UV−vis (in $CHCl_3$, λ_{max}/nm) 466, 594, 645, 761; HR-MS calcd for $C_{74}H_{53}B_2F_4N_8O_2$ $(M + H)^+$ m/z 1183.4414, observed 1183.4430.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Characterization data for all new compounds and crystal data (CIF) for compound **5**. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: ravikanth@chem.iitb.ac.in.

Notes

The authors declare no competing financial interest.

dx.doi.org/10.1021/jo400540u | J. Org. Chem. 2013, 78, 6285−6290

■ ACKNOWLEDGMENTS

We thank Council of Scientific and Industrial Research (CSIR), Government of India for financial support, and H.K. thanks CSIR for fellowship.

■ REFERENCES

(1) Pareek, Y.; Ravikanth, M.; Chandrashekar, T. K. *Acc. Chem. Res.* **2012**, *45*, 1801−1816.
(2) Sessler, J. L.; Davis, J. M. *Acc. Chem. Res.* **2001**, *34*, 989−997.
(3) Sessler, J. L.; Tomat, E. *Acc. Chem. Res.* **2007**, *40*, 371−379.
(4) Narayanan, S. J.; Sridevi, B.; Chandrashekar, T. K. *Org. Lett.* **1999**, *1*, 587−590.
(5) Sridevi, B.; Narayanan, S. J.; Rao, R.; Chandrashekar, T. K. *Inorg. Chem.* **2000**, *39*, 3669−3677.
(6) Kumar, R.; Misra, R.; Prabhuraja, V.; Chandrashekar, T. K. *Chem.—Eur. J.* **2005**, *11*, 5695−5707.
(7) Gokulnath, S.; Prabhuraja, V.; Sankar, J.; Chandrashekar, T. K. *Eur. J. Org. Chem.* **2007**, 191−200.
(8) Misra, R.; Kumar, R.; Chandrashekar, T. K.; Suresh, C. H.; Nag, A.; Goswami, D. *J. Am. Chem. Soc.* **2006**, *128*, 16083−16091.
(9) Rao, M. R.; Ravikanth, M. *Eur. J. Org. Chem.* **2011**, 1335−1345.
(10) Rao, M. R.; Ravikanth, M. *J. Org. Chem.* **2011**, *76*, 3582−3587.
(11) Misra, R.; Kumar, R.; Chandrashekar, T. K.; Suresh, C. H. *Chem. Commun.* **2006**, 4584−4586.
(12) Osuka, A.; Shimidzu, H. *Angew. Chem., Int. Ed.* **1997**, *36*, 135−137.
(13) Oberhammer, H. *J. Mol. Struct.* **2002**, *605*, 177−185.
(14) Wagner, R. W.; Johnson, T. E.; Li, F.; Lindsey, J. S. *J. Org. Chem.* **1995**, *60*, 5266−5273.