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Synthesis and characterization of novel fluorescent BOPIM dyes with large Stokes shift

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ABSTRACT

A novel BOPIM (boron 2-(2-pyridyl)imidazole complex) dye **1** was facilely synthesized by treatment of previously reported 2-(2′-pyridyl)imidazole with $BF_3{\cdot}Et_2O$ under basic condition. The bromination of BOPIM dye **1** by NBS gives an unexpected product 2-(2′-pyridyl)-4,5-dibromoimidazole (**L2**) with no BF_2 group. The desired brominated boron complex **2** was obtained by treating **L2** with $BF_3{\cdot}Et_2O$. The photophysical properties of these two compounds are thoroughly studied in various solvents. Compound **1** formed aggregates in non-polar solvents, inducing abnormal emission in long-wavelength region. Both **1** and **2** show moderate fluorescent intensity and comparatively large Stokes shift, especially for compound **2** (fluorescent quantum yield is more than 0.30, and Stokes shift is over 70 nm in all adopted solvents) due to its p, π-conjugated effect, which makes BOPIM a valuable building block for synthesis of multi-functional materials.

1. Introduction

The development of highly emissive dyes has been under widely research recently for their various applications, especially those dyes with 4-bora-4,4-difluoro-pyrromethene (BODIPY) units due to their exceptional spectral properties (high fluorescent quantum yield and absorption coefficient), photo-stability and chemical stability. Many applications have been found for BODIPY dyes, such as light-emitting devices [1–7], photosensitizer [8], sensors [9–17], fluorescent probes for bio-imaging study [18–21], and molecular switches [22]. An ideal dye should comprise high fluorescent quantum yield, high absorption coefficient, large Stokes shift, high stability, and facile availability. BODIPY dyes meet most of these acquisitions, however, the Stokes shifts for most BODIPY dyes are usually in the range of 400–600 cm^{-1}, which is quite small and results in undesirable quenching of the emission due to the reabsorption by itself. To enlarge BODIPY dyes' Stokes shift, it's important to make the electronic structure of the excited state quite different with that of the ground state [23,24].

A few years ago, Yeh et al. synthesized a new class highly fluorescent derivative of modified BODIPY dye, starting from 2-(2-pyridyl)naphtha[b]imidazole as ligand [25]. Some other solid-emissive BODIPY dyes with modified structures are also synthesized and thoroughly studied [26–31]. These dyes show moderate fluorescent quantum yield, high stability, especially large Stokes's shift (normally larger than 90 nm) compared to typical BODIPY dyes, which make them good candidate for light-emitting materials and fluorescent probes. However, it's difficult to further modify these chromophores. In order to obtain fluorescent dyes which can be easily functionalized, 2-(2-pyridyl)imidazole was chosen as the ligand to chelate BF_2, since imidazole contains two reactive protons. Here we report the synthetically versatile chromophore – fluorescent boron 2-(2′-pyridyl)imidazole complex **1** with previously reported 2-(2-pyridyl)imidazole as ligand [32], and the dibromo derivative **2**. Also, the photophysical properties of compounds **1** and **2** are thoroughly studied in various organic solvents.

2. Results and discussion

The ligand **L1** was synthesized with 45% yield after purification, starting from 2-pyridinecarbox-aldehyde and aqueous glyoxal solution [32]. After treating the ligand with $BF_3{\cdot}Et_2O$ using Et_3N as base, target product **1** was obtained as a pale yellow

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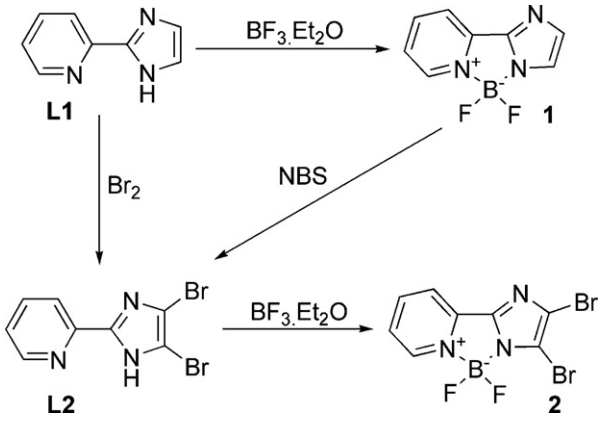
solid (Scheme 1), with moderate yield (18%) after purification by column chromatography.

Compound **1** has two reactive protons on imidazole, which can be further substituted for synthesis of multi-functional materials. With treatment by NBS in chloroform under acidic condition, compound **1** was obviously brominated, which could be followed by TLC and also ^{1}H NMR, since ^{1}H NMR can provide clear evidence for the disappearance of protons on imidazole. After the addition of 2.5 equivalents NBS, the ^{1}H NMR signal referred to protons on imidazole disappears completely, indicating the completion of bromination reaction. However, the Ms analysis gives species of the corresponding ligand with no BF_2 complex (m/z: 300). And ^{19}F NMR gives no signal of any resonance, further proving the absence of BF_2 group. Although BODIPY dyes normally exhibit high chemical- and photo-stability, decomposition also happens in certain chemical conditions, especially under attack of radicals in this case [33,34]. Ligand **L2** could also be synthesized through bromination of **L1** by bromine with excellent yield (82%), following previously reported procedure [35]. And the desired product **2** was obtained by treating **L2** with $BF_3{\cdot}Et_2O$ under basic condition.

^{1}H NMR of these compounds show different resonance patterns as shown in Fig. 1. The ligands **L1** and **L2** exhibit similar resonances, except the proton signals on imidazole. Compared to ligand **L1**, ^{1}H NMR of **1** only shows one resonance for the two protons on imidazole (located at 7.18 ppm), indicating that the chelation with BF_2 makes the chemical environment of the two protons similar with each other. And for compound **2**, the intense p, π-conjugated effect and chelation with boron largely changes the electronic density of protons on C3, C4 of pyridine ring, so that it results in up-field shift for H3, and down-field shift for H4 on pyridine ring.

The photophysical properties of compound **1** were studied in various organic solvents. Typical BODIPY dyes exhibit solvent-dependent properties, but it's not evident for the prepared compound **1** from UV–vis absorption spectra. As depicted in Fig. 2, the absorption spectra are of similar shape with maximum absorption band around 300 nm, attributed to S_0–S_1 transition. The absorption spectra are only barely affected by solvent polarity, with the maximum being slightly shifted hypsochromically (~5 nm), which is consistent with the general behavior of non-pyrrole-based BODIPY chromophores [25]. For compound **2**, obvious red-shift was observed compared to **1**, due to the p, π-conjugated effect which enhances the π system on a large scale. The longest absorptive band was observed at 393 nm in hexane (starting from 446 nm). Similar with typical



Scheme 1. Synthesis of the BF_2 chelate **1** and dibromo derivative **2**.

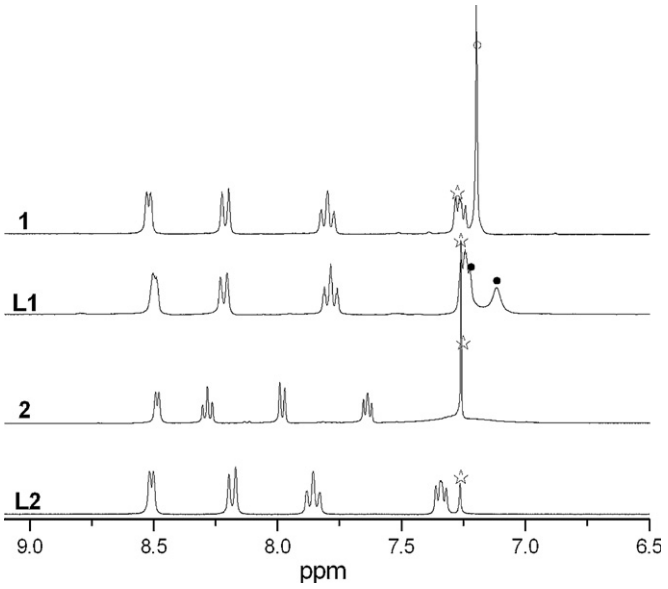


Fig. 1. ^{1}H NMR spectra (☆ $CDCl_3$; ● protons on imidazole of **L1**; ○ protons on imidazole of **1**).

BODIPYs, compound **2** shows solvent-dependent properties. With increasing of the solvent polarity, absorptive band blue-shifts evidently, and the main absorption was located at 487 nm in methanol.

Unlike UV–vis absorption, the fluorescent emission of compound **1** is strongly solvent-dependent as normal BODIPYs [36,37]. The solvent dependence of the long wavelength emission is referenced to an excited state with a large dipole [23]. In polar solvent such as methanol, the maximum emission band is located at 362 nm, however, a broad band around 500 nm clearly rises up. With solvent polarity decreasing, the obvious blue-shifts of emission were observed. In mid-polarity solvents, the main fluorescence bands are of similar patterns, shifting from 352 nm in dioxane to 359 nm in acetonitrile. As the polarity further decreasing, another sequences of emission bands show up in visible region (527, 560 nm) in hexane and cyclohexane, due to the formation of aggregates. Concentration-dependent fluorescent emission in hexane was measured to verify the aggregation-induced fluorescence difference. When the concentration is lower than $1.0 \times 10^{-6}\,M^{-1}$, the main emission is centered at 337 nm, and the emission bands in long-wavelength region are hardly observed. However, obvious red-shift occurs with concentration increasing. When the concentration is higher than $1.0 \times 10^{-4}\,M^{-1}$, this sequence of emission red-shifts to 342 nm. And the fluorescence around 540 nm becomes much more intense. The fluorescence ratio between 540 nm region and 337 nm region increases from 5% ($1.0 \times 10^{-6}\,M^{-1}$) to 30% ($1.0 \times 10^{-4}\,M^{-1}$). The effort to measure fluorescent spectrum in more concentrated solution failed due to the poor solubility in hexane. For compound **2**, however, no aggregate was observed in all the solvents studied, as showing in concentration-dependent fluorescence (Fig. 2F). There is no obvious emission shift with concentration changing. However, the emissive band red-shifts with decreasing of the solvent polarity. The longest emission was observed at 493 nm in dioxane, and the shortest emission band was 463 nm in cyclohexane.

Photophysical data of the boron chelates are shown in Table 1. Compound **1** shows moderate fluorescence quantum yield in mid-

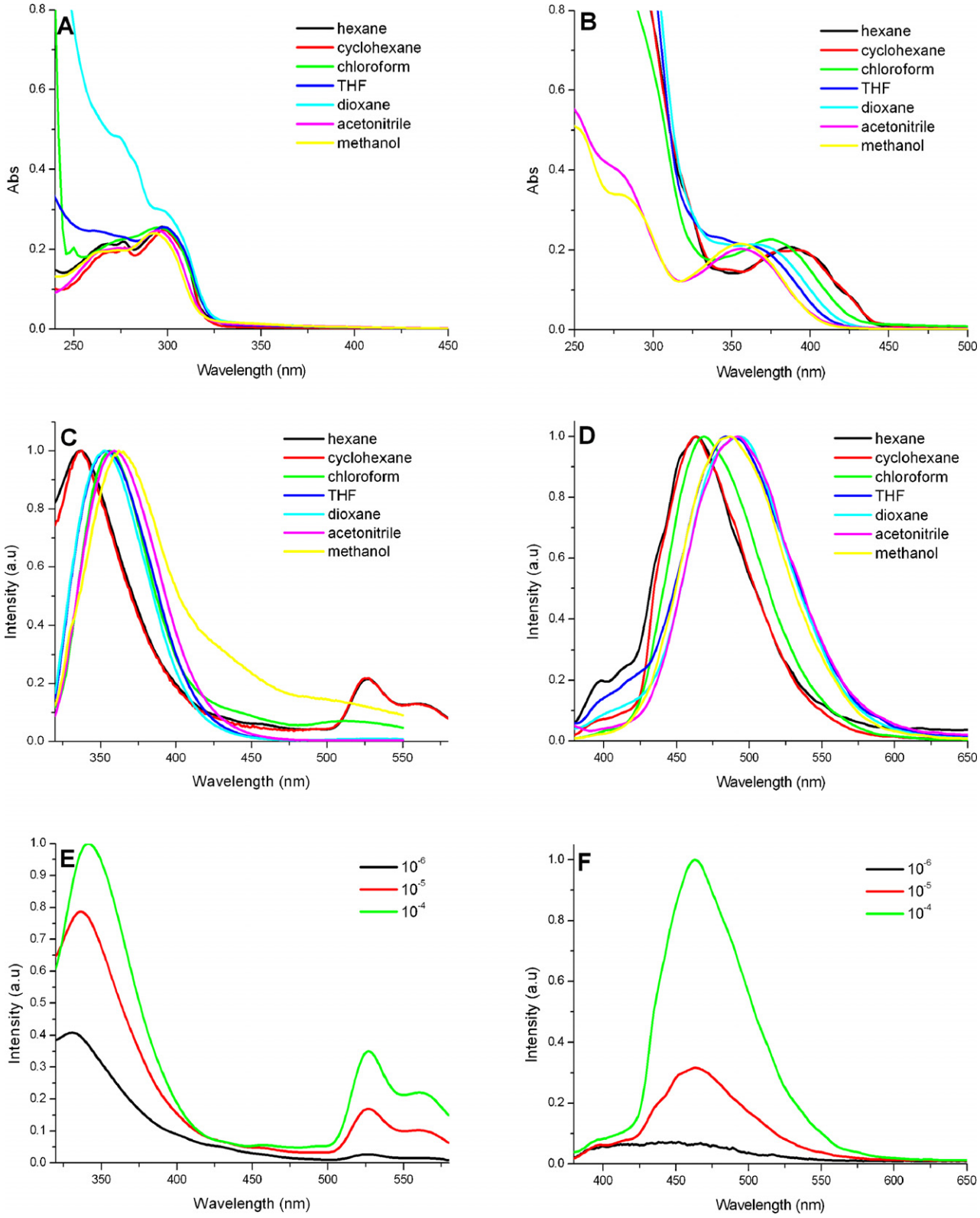


Fig. 2. (A) Absorption spectra of compound **1**, (B) absorption spectra of compound **2**, (C) fluorescent spectra of **1**, (D) fluorescent spectra of **2** in different solvents (1.0×10^{-5} M^{-1}); (E) concentration-dependent fluorescent spectra of **1**, (F) concentration-dependent fluorescent spectra of **2** in hexane (Ex: 365 nm).

polar solvents and the highest (0.44) in THF, but poor fluorescence in extremely high polar solvent (methanol) and non-polar solvents (hexane, cyclohexane). Plus, compound **1** exhibits comparatively large Stokes's shift (over 49 nm) in all solvents, which is much larger than typical BODIPY dyes. However, compound **2** shows excellent fluorescent quantum yields in all the adopted solvents, indicating the enlarged π system highly increased the fluorescent properties. The Stokes shifts turn over 70 nm in all solvents studied, and normally around 120 nm in most solvents. The largest Stokes shift was 136 nm observed in acetonitrile. The large Stokes shift alleviates self-absorption remarkably and prohibits the decreasing of fluorescent intensity.

Table 1
Photophysical properties of compounds **1** and **2** in different solvents.

	Solvent	λ_{abs} nm (M^{-1} cm^{-1})[a]	λ_{em} (nm)	$\Delta\nu$ (nm)[b]	Φ_F (%)[c]
1	Hexane	276 (21,970) 297 (25,700)	337, 527, 560	–	~3
	Cyclohexane	277 (20,430) 298 (24,950)	338, 528, 560	–	~3
	Chloroform	300 (24,860)	356	56	14
	THF	298 (25,640)	353	52	44
	Dioxane	297 (29,940)	352	49	28
	Acetonitrile	295 (24,730)	359	58	28
	Methanol	293 (24,080)	362	66	3
2	Hexane	393 (20,318)	464	71	45
	Cyclohexane	392 (19,995)	463	71	47
	Chloroform	374 (22,702)	469	95	41
	THF	366 (20,843) 344 (21,790)	484	118	32
	Dioxane	366 (21,439)	493	127	35
	Acetonitrile	356 (20,383)	492	136	32
	Methanol	357 (21,632)	487	130	31

[a] Wavelength (absorption coefficient).
[b] Stokes' shift.
[c] Fluorescence quantum yield (determined using anthracene as reference, error: ± 5%).

3. Conclusion

A new class BOPIM derivatives were synthesized and their photophysical properties are studied in various organic solvents. These dyes show hypsochromically solvent-dependent properties, with moderate fluorescent quantum yield and large Stokes shift compared to typical BODIPY dyes. Especially for brominated BOPIM 2, its excellent photophysical properties and facile functionalization make it a valuable building block for synthesis of multi-functional materials.

4. Experimental

4.1. General

All starting materials were obtained from commercial suppliers and used as received. Moisture sensitive reactions were performed under an atmosphere of nitrogen, and the solvents were treated according to standard methods. ^{1}H NMR and ^{13}C NMR were recorded on Bruker 400 NMR or Varian 300 Mercury spectrometers. Chemical shifts are reported in ppm with $CDCl_3$ as reference (7.26 ppm for ^{1}H NMR, and 77.0 ppm for ^{13}C NMR). MS data were recorded on a Waters Quattro Micro API LC-MS spectrometer (Waters, USA) or Applied Biosystems Voyager-DE STR mass spectrometer. UV–vis and fluorescent spectra were obtained on Hitachi U-3010 and F-4500, respectively. The fluorescent quantum yield is calculated using anthracene as reference.

4.2. Synthetic procedure of Boron 2-(2′-pyridyl)imidazole complex 1

In a stirred mixture of 2-(2-pyridyl)imidazole [9] (2.0 g, 13.8 mmol) and Et_3N (8 mL) in anhydrous CH_2Cl_2 (30 mL), $BF_3{\cdot}Et_2O$ (9.0 mL, 70 mmol) was added dropwise at 0 °C. After the addition of $BF_3{\cdot}Et_2O$, the reaction mixture was allowed to warm to room temperature and stir at room temperature overnight. The organic phase was washed with water several times, dried on Na_2SO_4, and evaporated in vacuo. Then the obtained crude residue was subjected to column chromatography on a silica gel column (hexane:EtOAc = 1:1) to provide a pale yellow solid (18%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 8.40 (d, J = 4.80 Hz, 1H), 8.15 (d, J = 8.10 Hz, 1H), 7.70 (m, J = 1 1H), 7.16 (m, 1H), 7.10 (s, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 148.6, 148.3, 146.1, 137.3, 123.3, 120.2. HRMs calcd for $C_8H_7BF_2N_3$ $[M+H]^+$ 194.0697, found 194.0693.

4.3. Treatment of 1 by NBS

Boron 2-(2′-pyridyl)imidazole complex **1** (41.6 mg, 0.21 mmol) was dissolved in a mixture of chloroform and acetic acid (8 mL, 1:1 v/v), followed by addition of NBS (95.4 mg, 0.54 mmol) in chloroform (2 mL). The reaction mixture was stirred at room temperature overnight, then washed with aqueous $Na_2S_2O_3$, K_2CO_3, and then water. The organic phase was collected and dried over anhydrous Na_2SO_4. After removal of the solvent, the crude product was subjected to a silica plug (chloroform) to provide a pale yellow solid (88%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 8.51 (d, J = 5.10 Hz, 1H), 8.18 (d, J = 7.80 Hz, 1H), 7.86 (m, 1H), 7.34 (m, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 148.6, 138.0, 124.0, 120.4. ESI-Ms: m/z: 300 $[M]^+$.

4.4. Synthetic procedure of Boron 2-(2′-pyridyl)-4,5-dibromoimidazole complex 2

In a stirred mixture of compound **L2** (2.4 g, 8 mmol) and Et_3N (5 mL) in anhydrous CH_2Cl_2 (25 mL), $BF_3{\cdot}Et_2O$ (5.6 mL, 44 mmol) was added dropwise at 0 °C. After the addition of $BF_3{\cdot}Et_2O$, the reaction mixture was allowed to warm to room temperature and stir at room temperature overnight. The organic phase was washed with water several times, dried on Na_2SO_4, and evaporated in vacuo. Then the obtained crude residue was subjected to column chromatography on a silica gel column to provide a yellow solid (38%). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.43 (d, J = 5.60 Hz, 1H), 8.23 (t, J = 7.80 Hz, 1H), 7.92 (d, J = 8.00 Hz, 1H), 7.58 (t, J = 6.60 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 145.4, 141.8, 123.9, 117.7. HRMs calcd for $C_8H_5BBr_2F_2N_3$ $[M+H]^+$ 349.8911, found 349.8915.

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