

SYNTHESIS AND ION SENSING PROPERTIES OF NEW COLORIMETRIC AND FLUORIMETRIC CHEMOSENSORS BASED ON BITHIENYL-IMIDAZO-ANTHRAQUINONE CHROMOPHORES

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1. Experimental Section

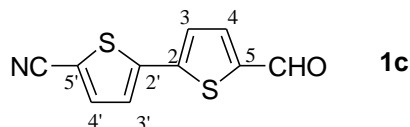
1.1. Synthesis general

Progress of the reaction was monitored by thin layer chromatography (0.25 mm thick precoated silica plates: Merck Fertigplatten Kieselgel 60F254), while purification was effected by silica gel column chromatography (Merck Kieselgel 60; 230-400 mesh). Light petroleum refers to solvent boiling in the range 40-60 °C. 2-Bromo-5-cyanothiophene, 2-bromo-5-formylthiophene, 2-formylthiophene boronic acid and 5-formyl-2,2'-bithiophene were purchased from Aldrich and used as received. The synthesis of 5'-ethoxy-5-formyl-2,2'-bithiophene **1b** has been described elsewhere.¹

NMR spectra were obtained on a Varian Unity Plus Spectrometer at an operating frequency of 300 MHz for ¹H NMR and 75.4 MHz for ¹³C NMR using the solvent peak as internal reference. The solvents are indicated in parenthesis before the chemical shift values (δ relative to TMS). Mps were determined on a Gallenkamp apparatus and are uncorrected. Infrared spectra were recorded on a BOMEM MB 104 spectrophotometer. UV-vis absorption spectra (200 – 800 nm) were obtained using a Shimadzu UV/2501PC spectrophotometer. Mass spectrometry analyses were performed at the C.A.C.T.I. - Unidad de Espectrometria de Masas of the University of Vigo, Spain. Elemental analysis was carried out on a Leco CHNS-932.

1.2. Procedure for the synthesis of aldehyde **1c** through Suzuki cross-coupling

2-Bromo-5-cyanothiophene (1.0 mmol) was coupled with 2-formylthiophene boronic acid (1.4 mmol), in a mixture of DME (15 mL) and aqueous 2M Na₂CO₃ (1 mL) and Pd(PPh₃)₄ (3 mol %) at 80 °C under a argon atmosphere. The reaction was followed by TLC until completion (12 h). After cooling the mixture was filtered. Ethyl acetate (50 mL) and a saturated solution of NaCl (20 mL) were added and the phases were separated. The organic phase was washed with water (3 x 50 mL) and with a solution of NaOH (10%) (1 x 20 mL). The organic phase was dried (MgSO₄), filtered and solvent removal gave the crude coupled compound which was purified by column chromatography on silica with increasing amounts of diethyl ether in light petroleum as eluent, affording the pure product **1c**.



5'-cyano-5-formyl-2,2'-bithiophene 1c. Brown solid (61%). Mp: 179.5-180.8 °C. UV (EtOH): λ_{\max} nm (ϵ /M⁻¹ cm⁻¹) 454.5 (29730), 300.0 (6000), 277.0 (10390). IR (KBr) ν 2219 (CN), 1657 (CO), 1432, 1286, 1221, 1060, 884, 810, 754 cm⁻¹. ¹H NMR (CDCl₃) δ 7.32 (d, 1H, $J=3.9$ Hz, 3'-H), 7.37 (d, 1H, $J=3.9$ Hz, 3-H), 7.59 (d, 1H, $J=3.9$ Hz, 4-H), 7.72 (d, 1H, $J=3.9$ Hz, 4'-H), 9.93 (s, 1H, CHO). ¹³C NMR (CDCl₃) δ 110.05 (C5'), 113.50 (CN), 125.63 (C3), 126.38 (C3'), 136.82 (C4), 138.33 (C4'), 142.68 (C2'), 143.45 (C2), 143.83 (C5), 182.47 (CHO). MS (EI) m/z (%): 220 (9), 219 (M⁺ + 1, 17), 218 (M⁺, 91), 217 (100), 146 (51), 118 (6), 85 (53), 83 (84). HRMS: (EI) m/z (%) for C₁₀H₅NOS₂; calcd 218.9813; found 218.9817.

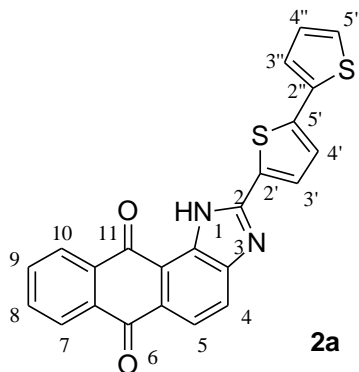
1.3. General procedure for the synthesis of compounds 2a-c

i) Preparation of the imines

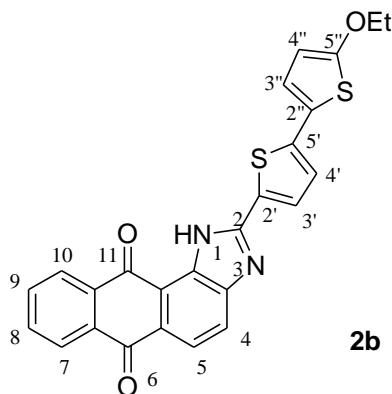
The aldehydes **1a-c** (0.20 mmol) and 1,2-diaminoanthraquinone (0.24 mmol) were dissolved separately in ethanol (4 mL/mmol). The ethanolic solution of aldehyde and formic acid (0.04 mL/mmol of aldehyde) was added to the solution of 1,2-diaminoanthraquinone heated at reflux. The reaction mixture was heated under reflux overnight.

ii) Cyclisation of the imines

After cooling, the ethanolic solution was evaporated and the crude imine was dissolved in a small volume of acetic acid (5 mL/mmol of imine). To this solution, lead tetraacetate was added (0.20 mmol) and the mixture was stirred overnight at room temperature. Addition of water to the reaction mixture gave a solid which was isolated by filtration and purified by recrystallization from diethyl ether/chloroform.

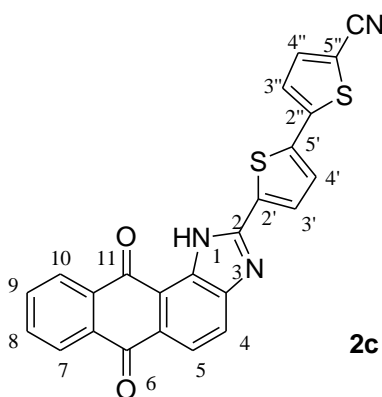


2-(2',2''-bithienyl)-1H-anthra[1,2-d]imidazole-6,11-dione 2a. Dark red solid (92%). Mp: 249.1-251.6 °C. UV (CH₃CN): λ_{max} nm ($\epsilon/M^{-1} \text{ cm}^{-1}$): 262 (25741); 288(sh) (14776); 342 (18609); 446 (18224). IR (KBr) ν 1657 (CO br), 1579, 1530, 1488, 1424, 1326, 1289, 1156, 1063, 1007, 926, 832, 807, 714 cm^{-1} . ¹H NMR (DMSO-d₆) δ 7.14 (m, 1H, 4''-H), 7.43 (d, 1H, $J=3.9$ Hz, 3'-H), 7.47 (dd, 1H, $J=3.4$ and 1.2 Hz, 3''-H), 7.61 (dd, 1H, $J=4.9$ and 1.2 Hz, 5''-H), 7.90-7.93 (m, 2H, 8-H and 9-H), 7.89-8.06 (m, 2H, 4-H and 5-H), 8.17-8.23 (m, 2H, 7-H and 10-H), 8.46 (d, 1H, $J=3.6$ Hz, 4'-H), 13.47 (s, 1H, NH). ¹³C NMR (DMSO-d₆) δ 118.42, 121.20, 124.04, 125.14, 125.41, 126.19, 126.75, 126.81, 127.87, 128.65, 130.79, 131.27, 133.01, 133.11, 134.23, 134.41, 135.73, 140.58, 149.10, 182.24, 183.06. MS (FAB) m/z (%): 413 ([M+H]⁺, 22), 412 (M⁺, 9), 307 (39), 289 (13), 288 (10), 155 (31), 154 (100). HRMS: (FAB) m/z (%) for C₂₃H₁₂N₂O₂S₂; calcd 413.0418; found 413.0415.



2-(5''-Ethoxy-2',2''-bithienyl)-1H-anthra[1,2-d]imidazole-6,11-dione 2b. Dark red solid (67%). Mp: 227.2-230.3 °C. UV (CH₃CN): λ_{max} nm ($\epsilon/M^{-1} \text{ cm}^{-1}$): 263 (15143); 363 (8137); 450 (8945). IR (liquid film) ν 3383 (NH), 1667 (CO br), 1583, 1503, 1468, 1376, 1291, 1154, 1046, 1006, 930, 894, 839, 809, 793, 719 cm^{-1} . ¹H NMR (DMSO-d₆) δ 1.34

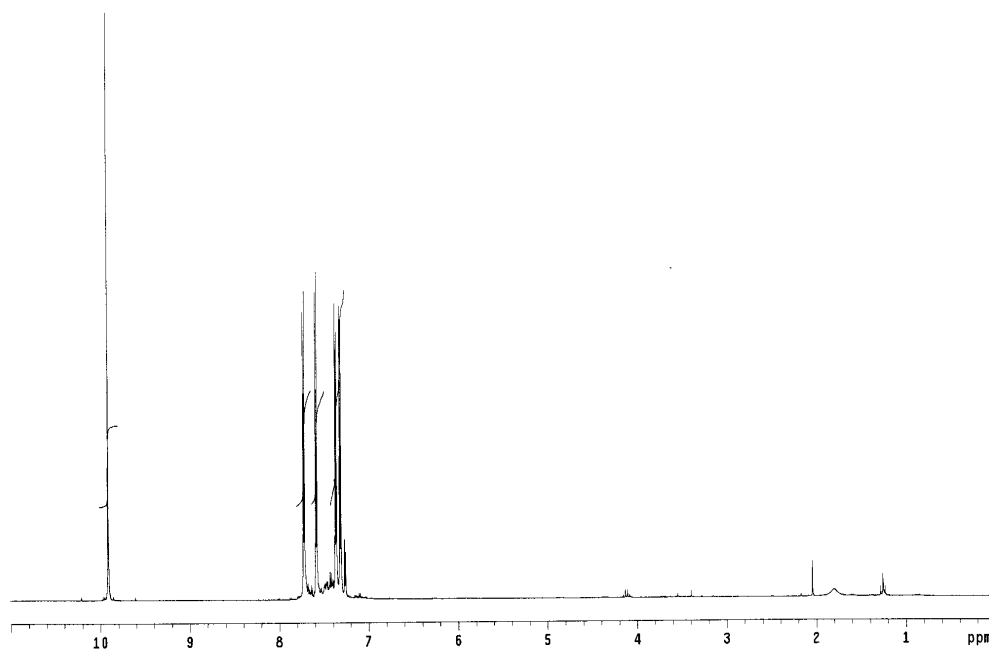
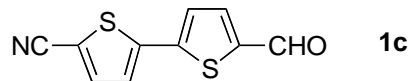
(t, 3H, $J = 6.9$ Hz, OCH_2CH_3), 4.12 (q, 2H, $J = 6.9$ Hz, OCH_2CH_3), 6.30 (d, 1H, $J = 4.2$ Hz, 4''-H), 7.08 (d, 1H, $J = 3.9$ Hz, 3''-H), 7.16 (d, 1H, $J = 3.9$ Hz, 3'-H), 7.87-7.89 (m, 2H, 8-H and 9-H), 7.94-8.01 (m, 2H, 4-H and 5-H), 8.14-8.19 (m, 2H, 7-H and 10-H), 8.37 (br s, 1H, 4'-H), 13.32 (s, 1H, NH). ^{13}C NMR (DMSO-d_6) δ 14.44, 69.37, 106.04, 121.18, 121.69, 123.29, 123.65, 124.01, 126.13, 126.70, 127.71, 129.12, 131.92, 132.92, 134.15, 141.45, 149.17, 152.54, 164.89, 182.11, 182.99. MS (FAB) m/z (%): 457 ($[\text{M}+\text{H}]^+$, 50), 456 (M^+ , 31), 426 (13), 307 (29), 289 (17), 155 (32), 154 (100). HRMS: (FAB) m/z (%) for $\text{C}_{25}\text{H}_{16}\text{N}_2\text{O}_3\text{S}_2$; calcd 457.0681; found 457.0681.



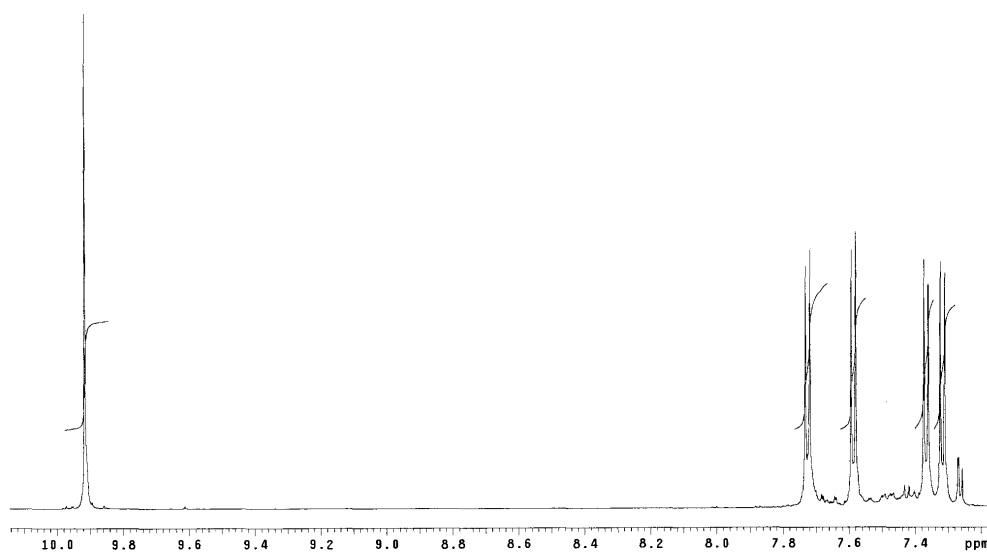
2-(5''-Cyano-2',2''-bithienyl)-1H-anthra[1,2-d]imidazole-6,11-dione 2c. Dark brown solid (68%). Decomposition at $T > 320$ °C. UV (CH_3CN): λ_{max} nm ($\epsilon / \text{M}^{-1} \text{cm}^{-1}$): 261 (26830); 346 (16645); 410 (15290); 448(sh) (13115); 531 (7675). IR (liquid film) ν 3490 (NH), 2215 (CN), 1663 (CO br), 1584, 1565, 1529, 1490, 1376, 1325, 1187, 1156, 1062, 1006, 965, 846, 795, 716 cm^{-1} . ^1H NMR (DMSO-d_6) δ 7.64 (d, 1H, $J = 3.9$ Hz, 3'-H), 7.70 (d, 1H, $J = 3.9$ Hz, 3''-H), 7.93-7.96 (m, 2H, 8-H and 9-H), 8.00 (d, 1H, $J = 3.6$ Hz, 4'-H), 8.08-8.10 (m, 2H, 4-H and 5-H), 8.21-8.27 (m, 2H, 7-H and 10-H), 8.56 (d, 1H, $J = 3.9$ Hz, 4''-H), 13.64 (s, 1H, NH). MS (FAB) m/z (%): 438 ($[\text{M}+\text{H}]^+$, 13), 437 (M^+ , 12), 307 (44), 289 (18), 155 (31), 154 (100). HRMS: (FAB) m/z (%) for $\text{C}_{24}\text{H}_{11}\text{N}_3\text{O}_2\text{S}_2$; calcd 438.0371; found 438.0377.

2. ^1H and ^{13}C NMR spectra of compounds **1c** and **2a-c**

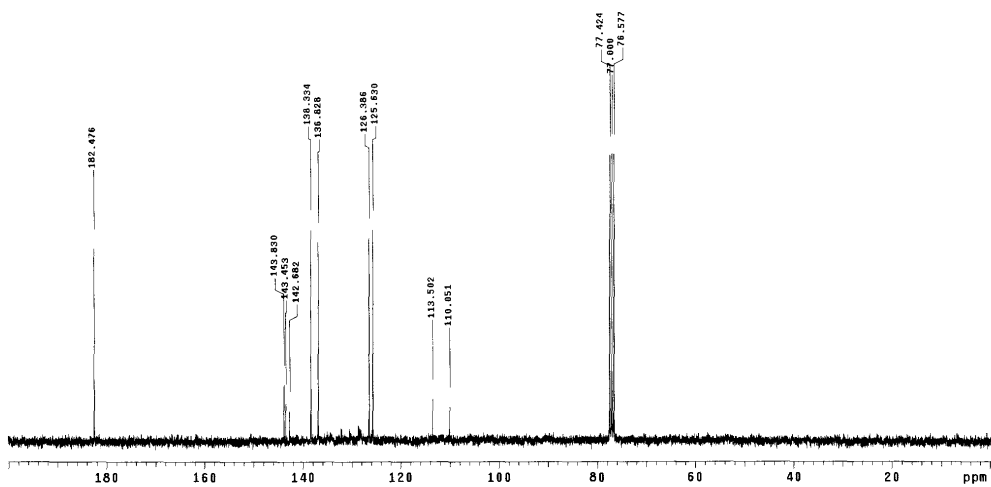
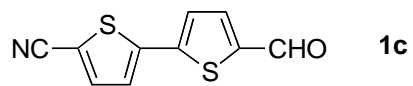
^1H NMR data for compound **1c**



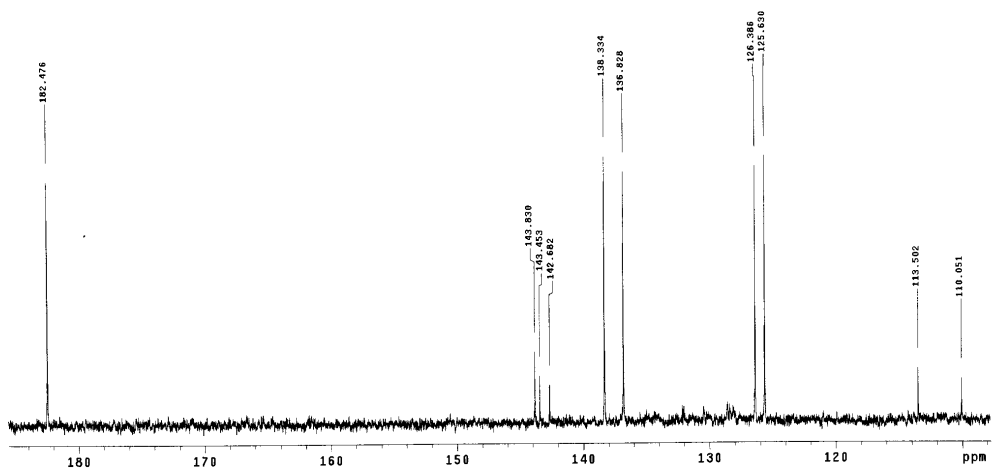
Expansion of aromatic zone



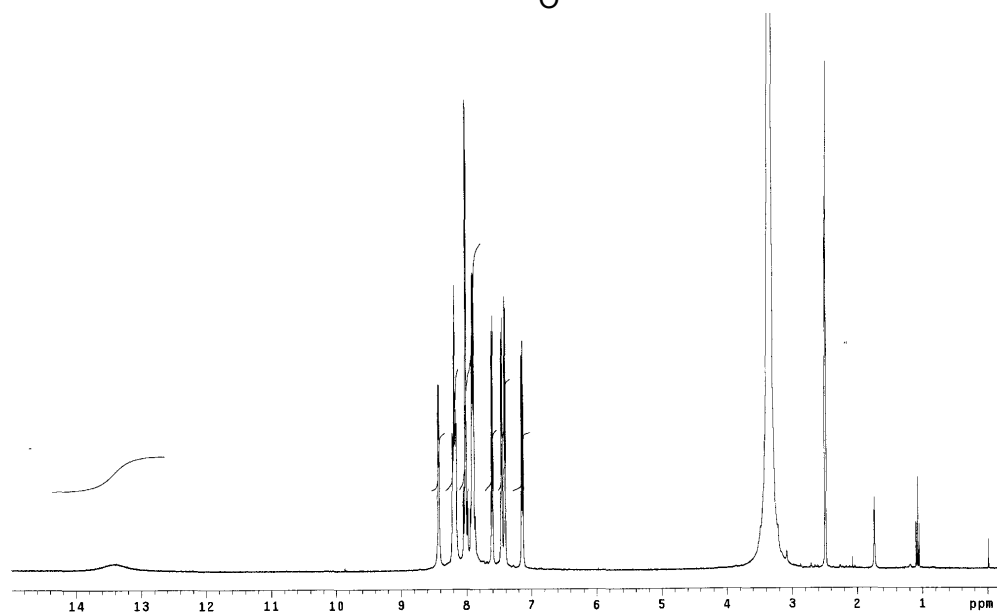
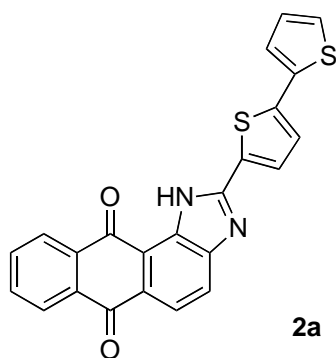
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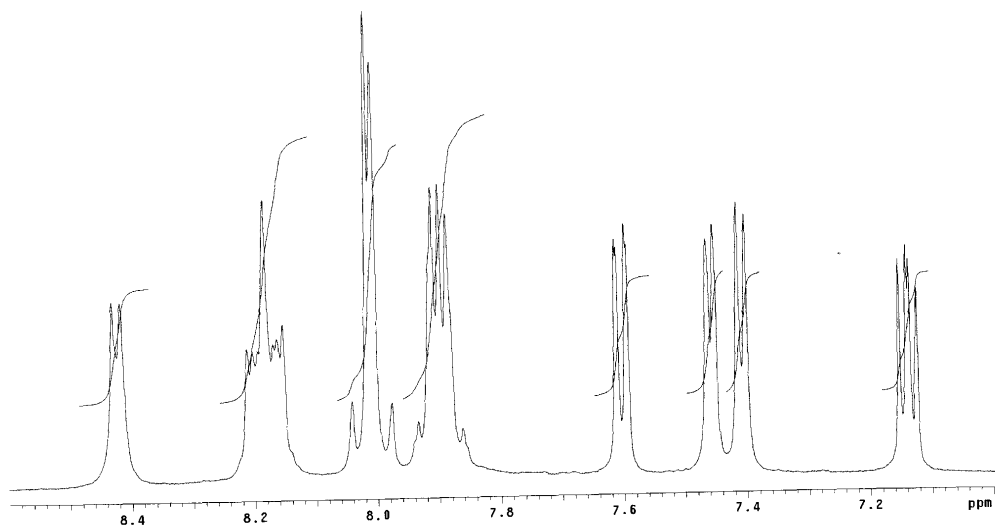
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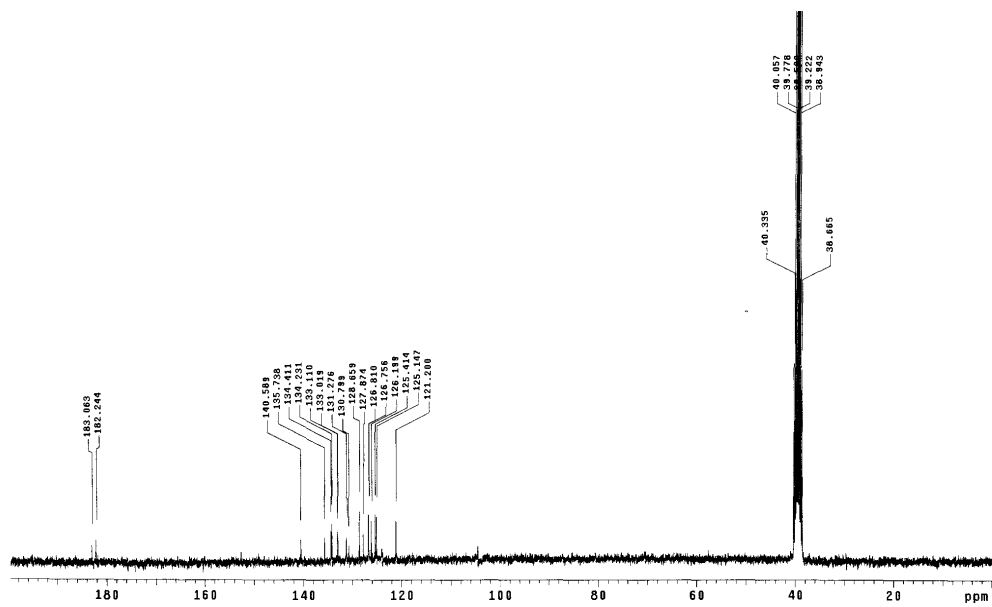
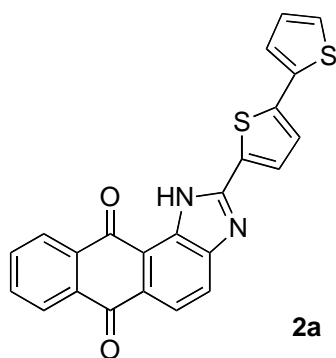
¹H NMR data for compound **2a**



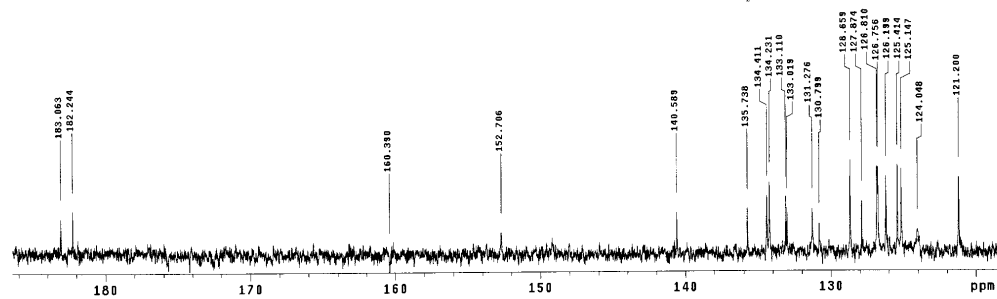
Expansion of aromatic zone



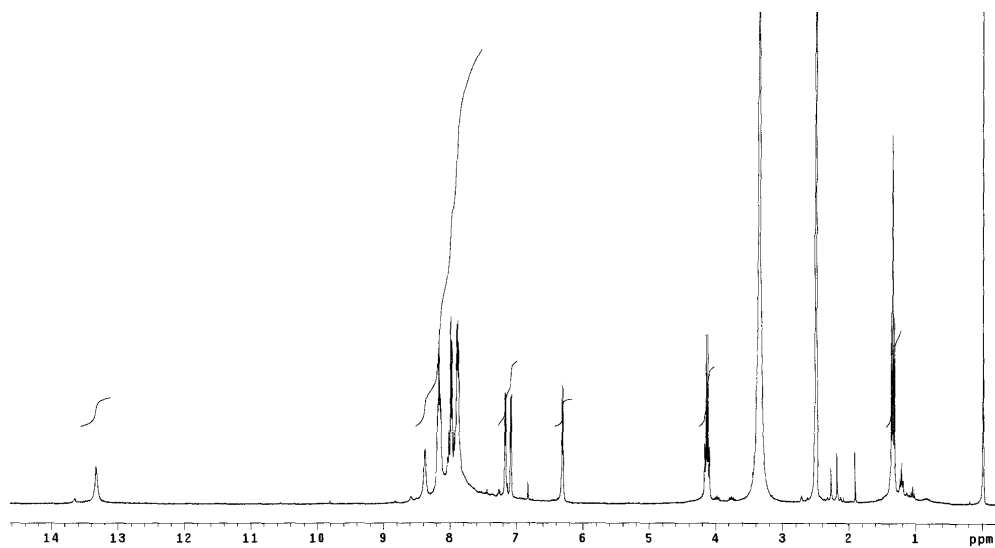
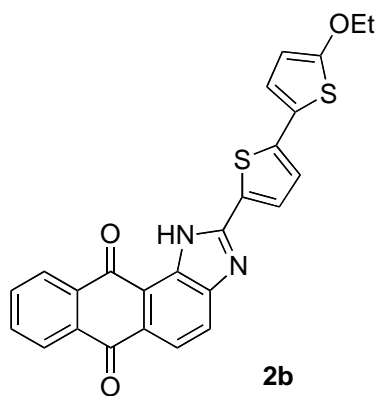
¹³C NMR data for compound **2a**



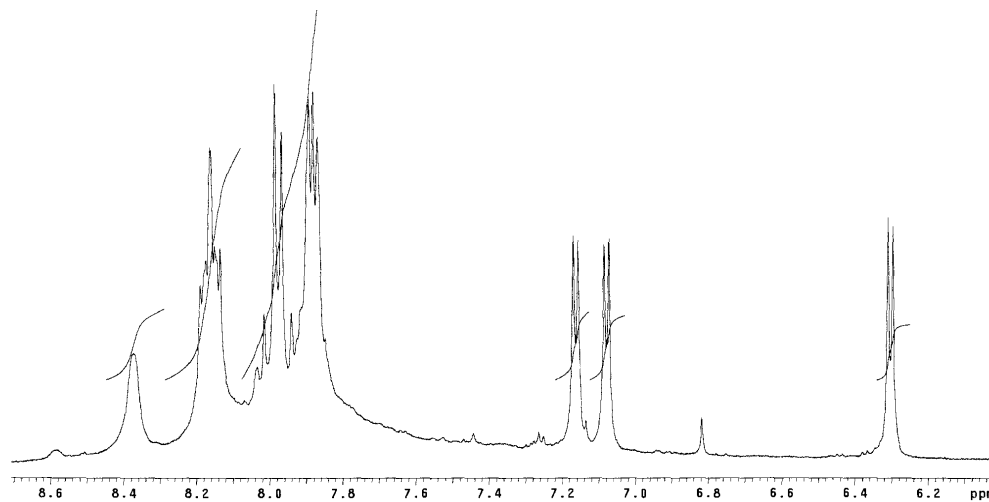
Expansion of aromatic zone



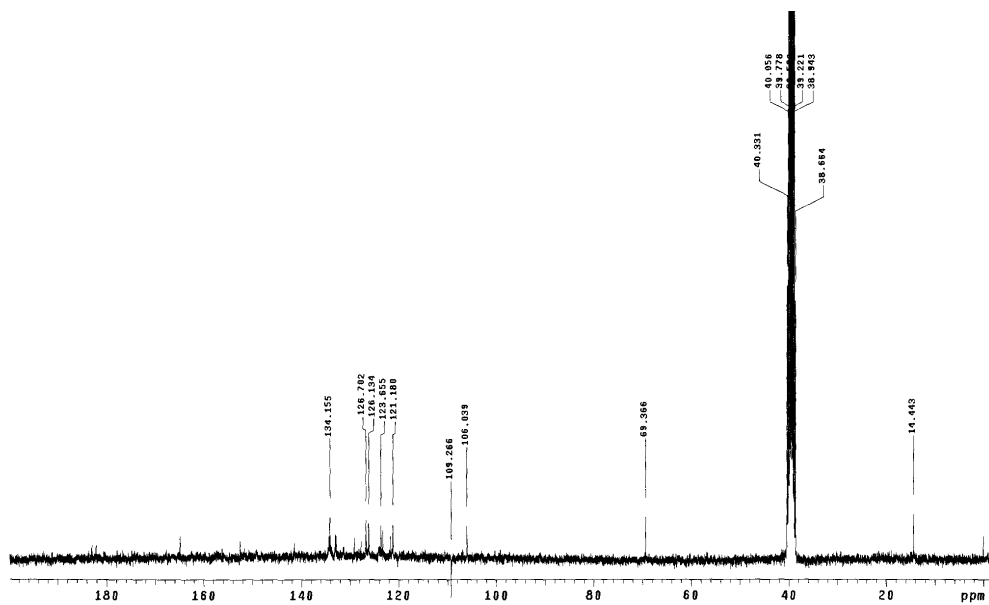
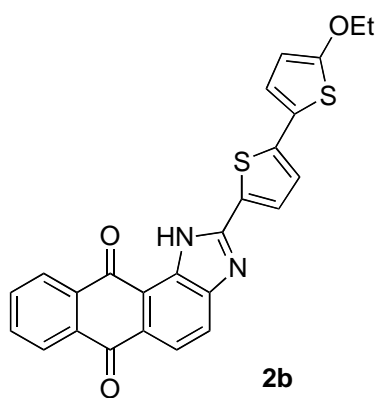
¹H NMR data for compound **2b**



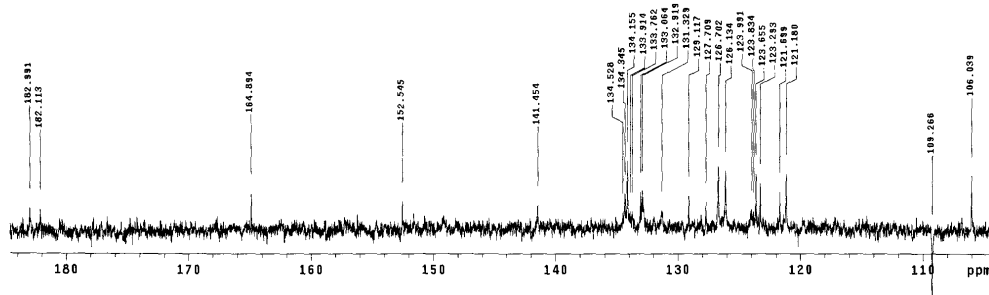
Expansion of aromatic zone



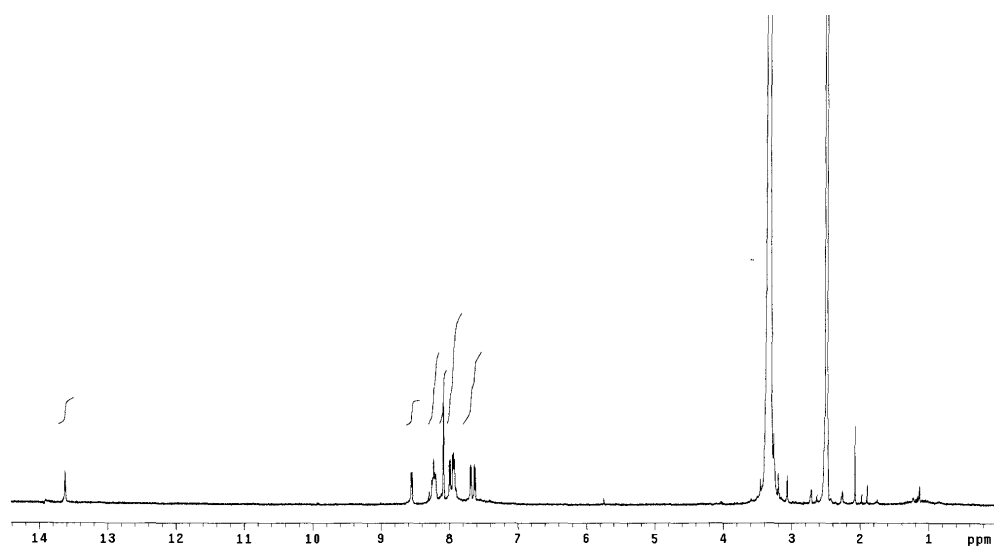
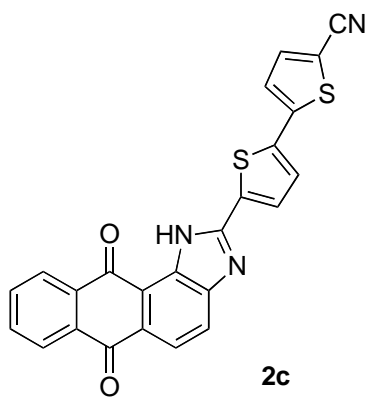
¹³C NMR data for compound **2b**



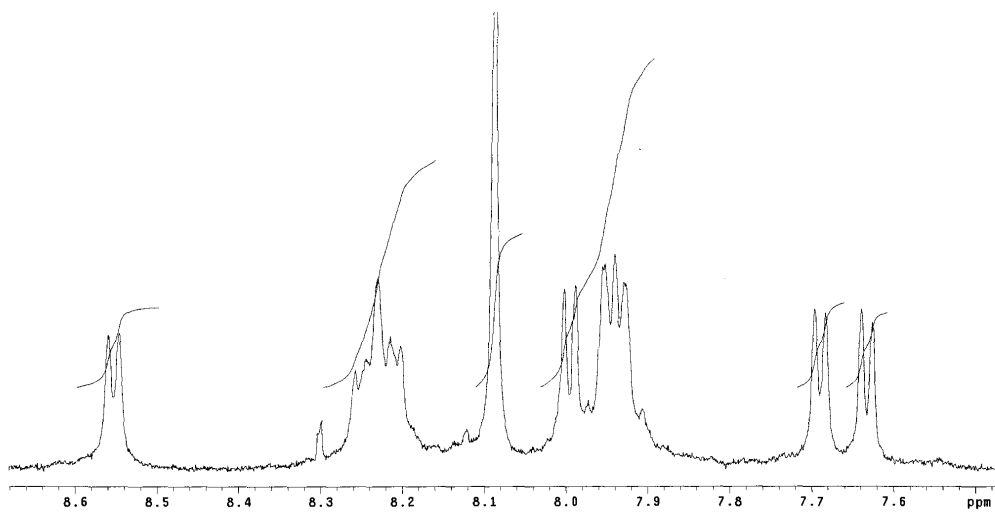
Expansion of aromatic zone



^1H NMR data for compound **2c**



Expansion of aromatic zone



3. Spectrophotometric and spectrofluorimetric studies of compounds **2a-c**

3.1. General

UV/Vis spectra were performed using a Perkin Elmer Lambda 35 spectrophotometer and fluorescence spectra on a Perkin Elmer LS45. The linearity of the fluorescence emission vs. concentration was checked in the concentration range used (10^{-4} - 10^{-6} M). A correction for the absorbed light was performed when necessary. All spectrofluorimetric titrations were performed as follows: stock solutions of compounds **2a-c** (*ca.* 10^{-3} M) were prepared with CH_3CN UVA-sol and used in the preparation of titration solutions by appropriate dilution. Titration of the compounds **2a-c** was carried out by addition of microliter amounts of standard solutions of the ions (cations or anions) in acetonitrile. All anions (F^- , Cl^- , Br^- and I^-) were used as their tetrabutylammonium salts. The acidity of the acetonitrile solutions was adjusted by addition of HBF_4 , methanesulphonic acid, triethylamine and tetrabutylammonium hydroxide. Luminescence quantum yields were measured using as standard a solution of quinine sulfate in sulfuric acid (0.1 M) ($\Phi_{\text{F}} = 0.54$).² $\text{Cu}(\text{CF}_3\text{SO}_3)_2$, $\text{Zn}(\text{CF}_3\text{SO}_3)_2$, and $\text{Hg}(\text{CF}_3\text{SO}_3)_2$ were purchased from Alfa Aesar and used without further purification.

3.2. Proton sensing ability of compounds **2a-c**

UV-vis absorption spectra of **2a-c** in CH_3CN solution upon addition of increasing amounts of methanesulphonic acid. Inset: equivalents of acid $[2]/[\text{H}^+]$.

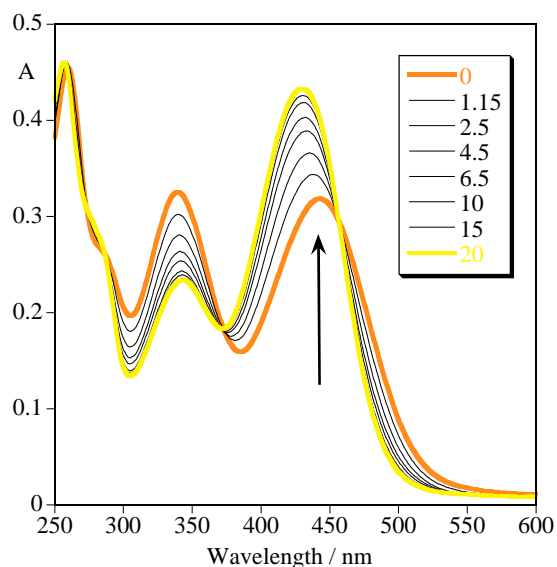


Figure S1. UV-vis spectral changes of **2a** in CH_3CN (1.75×10^{-5} M) with addition of acid.

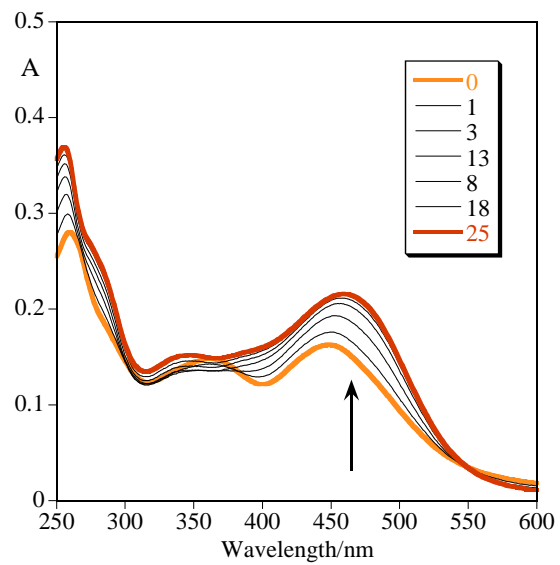


Figure S2. UV-vis spectral changes of **2b** in CH_3CN ($1.80 \times 10^{-5} \text{ M}$) with addition of acid.

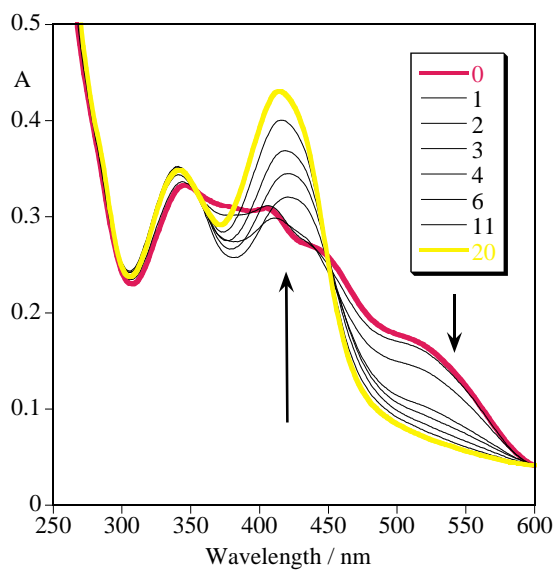


Figure S3. UV-vis spectral changes of **2c** in CH_3CN ($2.00 \times 10^{-5} \text{ M}$) with addition of acid.

3.3. Basic anions (CN^- , CH_3COO^- and H_2PO_4^-) sensing ability of compound **2a**

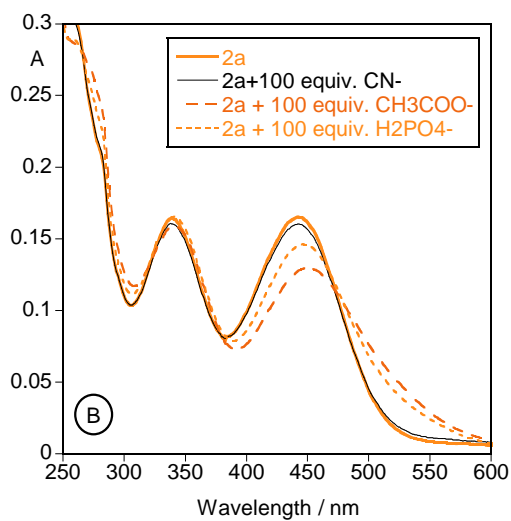


Figure S4. Spectral changes of **2a** in CH_3CN (1.00×10^{-5} M) with the addition of cyanide, acetate and dihydrogen phosphate anions.

3.4. Halide ion (Cl^- , Br^- and I^-) sensing ability of compounds **2a-c**

UV-vis spectrum of **2a-c** in CH_3CN solution upon addition of 20 equivalents of halide ions ($[(\text{Bu})_4\text{N}]\text{Cl}$; $[(\text{Bu})_4\text{N}]\text{Br}$ and $[(\text{Bu})_4\text{N}]\text{I}$).

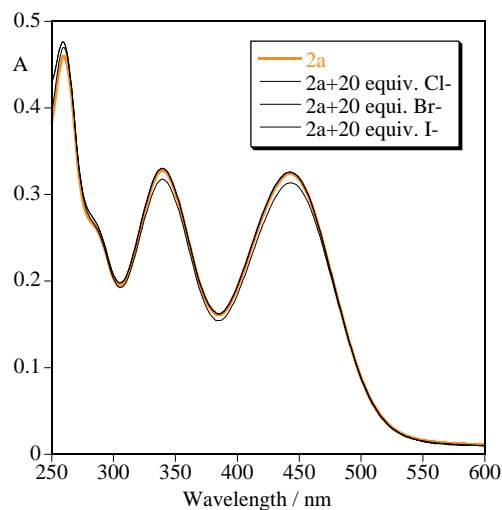


Figure S5. UV-vis spectral changes of **2a** in CH_3CN (1.75×10^{-5} M) with addition of halide ions.

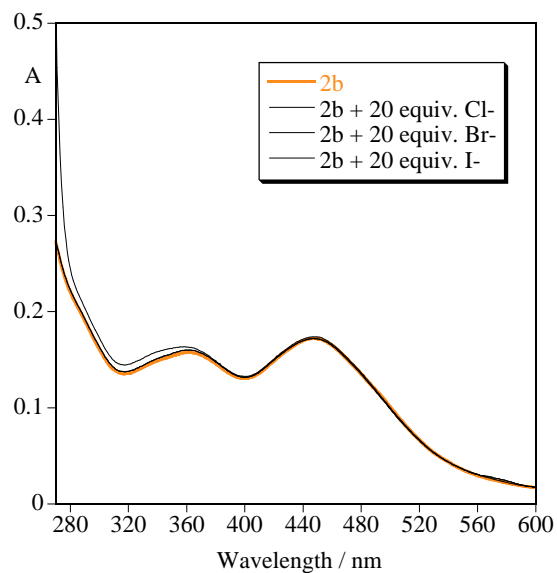


Figure S6. UV-vis spectral changes of **2b** in CH_3CN (1.80×10^{-5} M) with addition of halide ions.

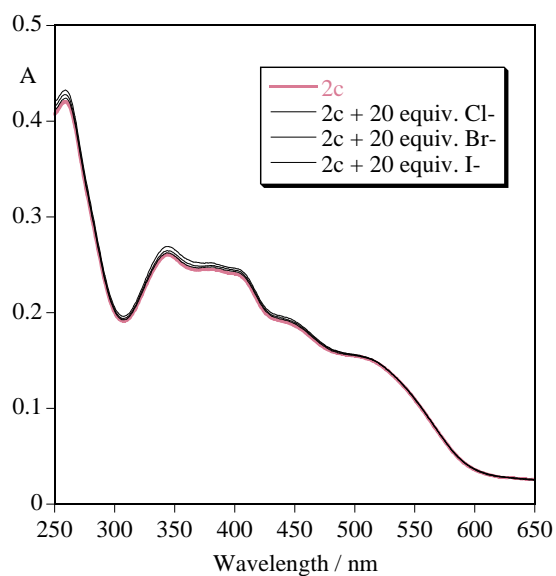


Figure S7. UV-vis spectral changes of **2c** in CH_3CN (2.00×10^{-5} M) with addition of halide ions.

3.5. Fluoride ion sensing ability of compounds 2a-c

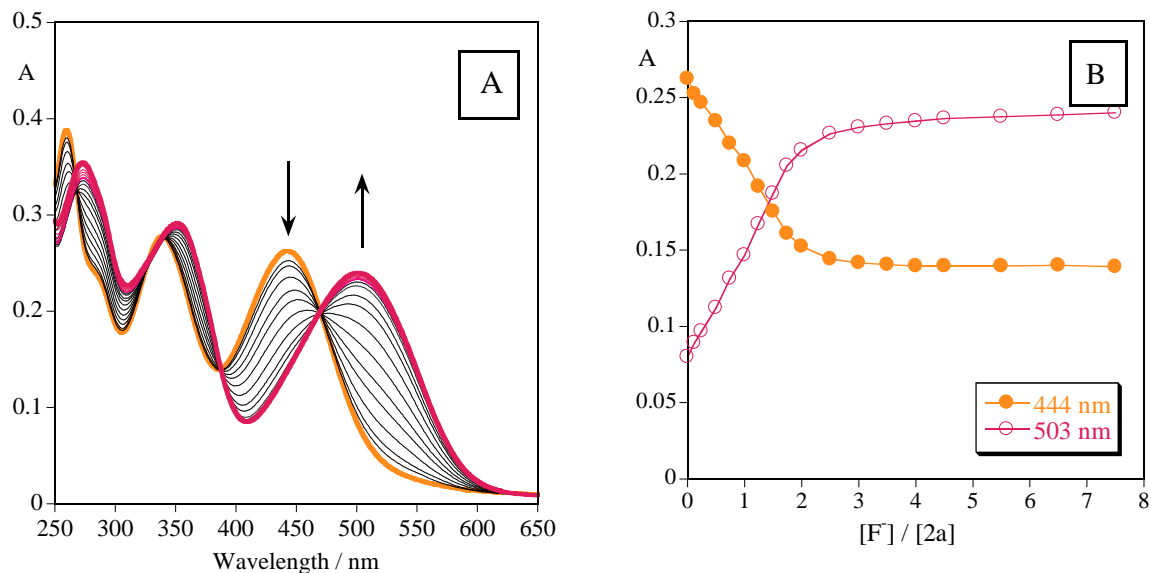


Figure S8. Spectrophotometric titration of an CH₃CN solution of **2a** with a standard CH₃CN solution of [(Bu)₄N]F (A) and (B) titration profile of **2a** in CH₃CN with fluoride; Absorptions at 444 nm and 503 nm; [2a] = 1.75 × 10⁻⁵ M.

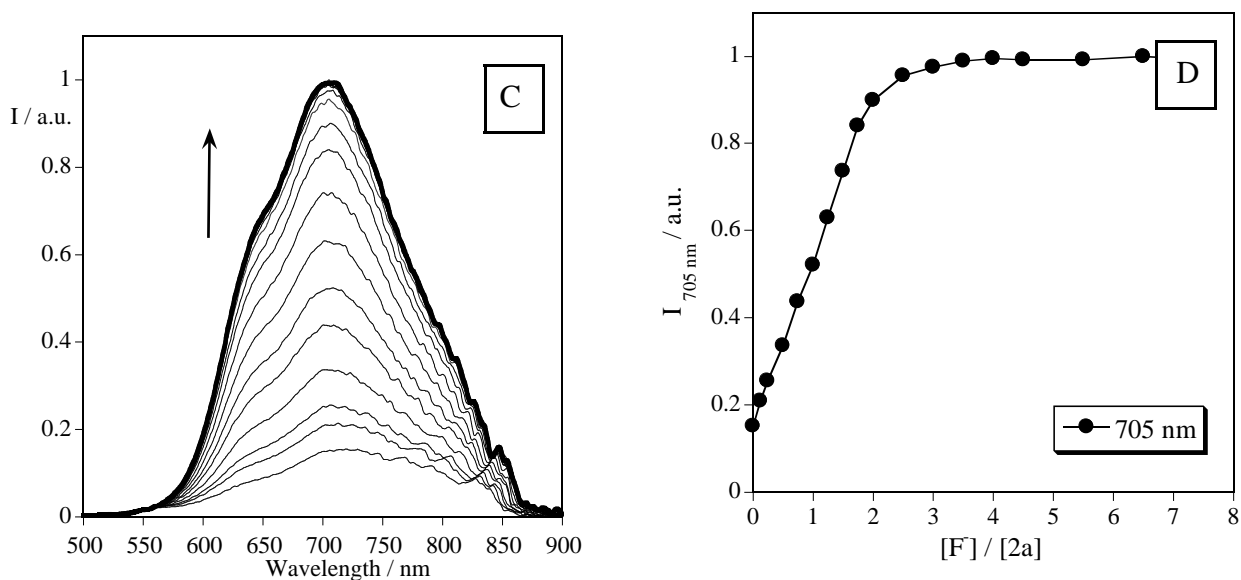


Figure S9. Fluorimetric titration of an CH₃CN solution of **2a** with a standard CH₃CN solution of [(Bu)₄N]F (C) and (D) Maximum of emission at 705 nm as a function of fluoride added; [2a] = 1.75 × 10⁻⁵ M, λ_{exc} = 450 nm, T = 25°C.

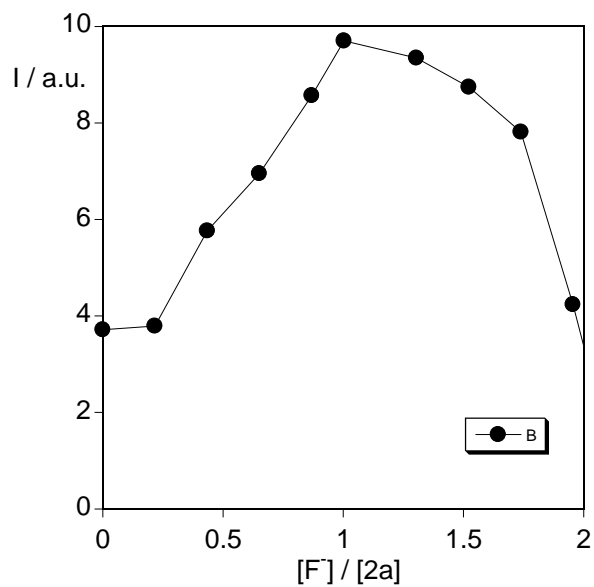


Figure S10. Stoichiometric study for the interaction between fluoride ion and compound **2a**. The total concentration $[F^-] + [2a] = 2.0 \times 10^{-5} \text{ M}$.

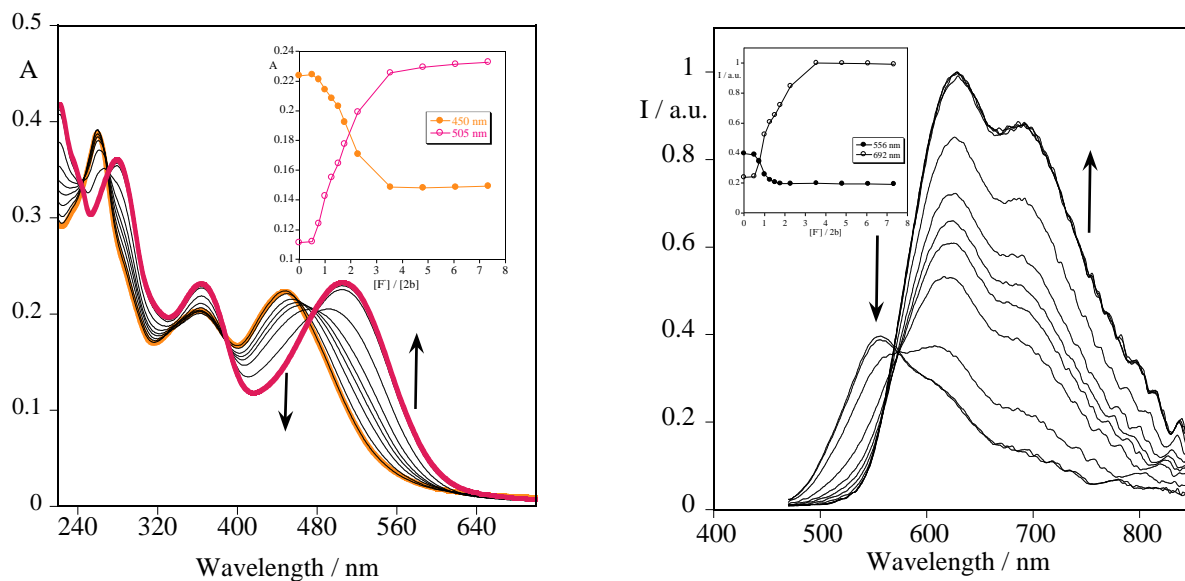


Figure S11. UV-vis and fluorescence emission spectra of **2b** in CH_3CN upon addition of increasing amount of $[(\text{Bu})_4\text{N}]\text{F}$; $[2b] = 1.60 \times 10^{-5} \text{ M}$, $\lambda_{\text{exc}} = 450 \text{ nm}$, $T = 25^\circ\text{C}$.

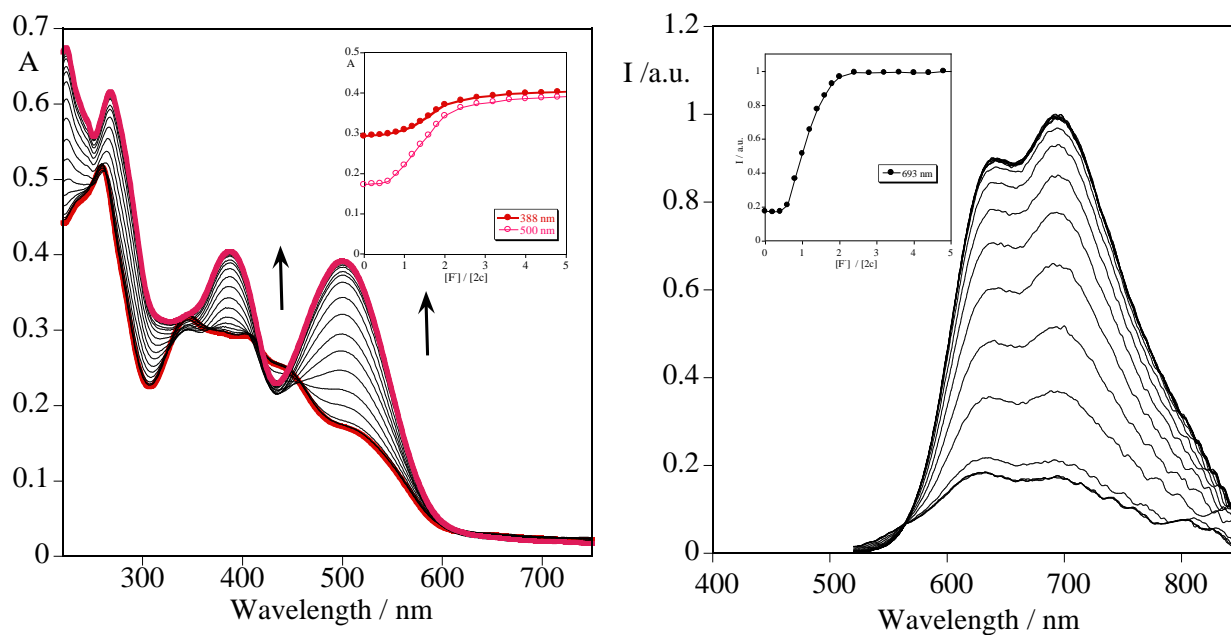


Figure S12. Uv-vis and fluorescence emission spectra of **2c** in CH_3CN upon addition of increasing amount of $[(\text{Bu})_4\text{N}]\text{F}$. ($[\mathbf{2c}] = 2.00 \times 10^{-5} \text{ M}$, $\lambda_{\text{exc}} = 450 \text{ nm}$, $T = 25^\circ\text{C}$)

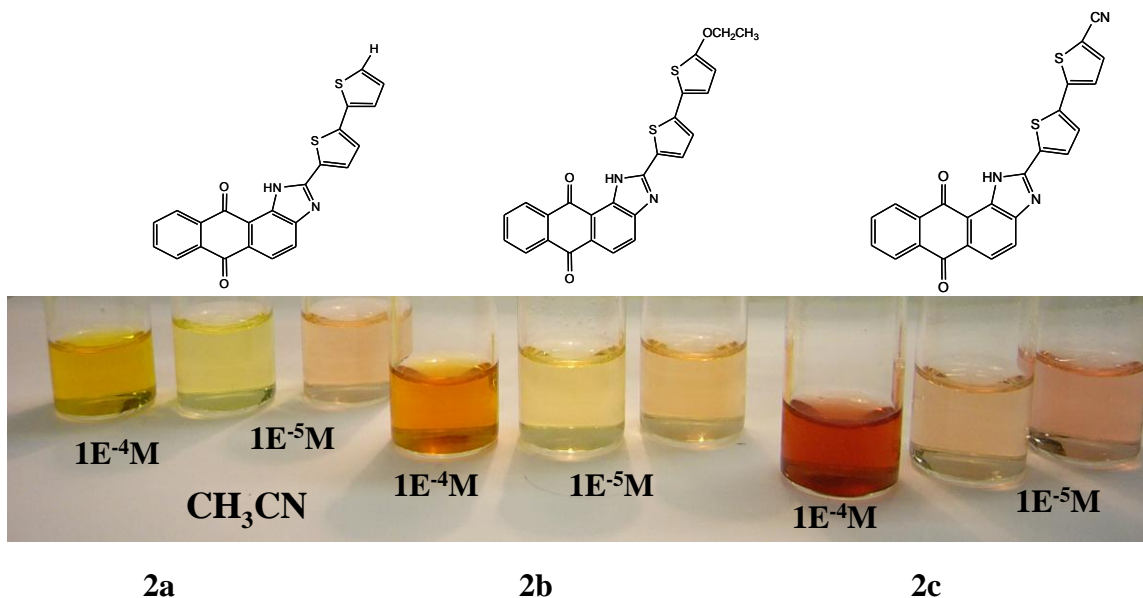


Figure S13. Colorimetric effect in systems **2a-c** after interaction with fluoride ion in acetonitrile.

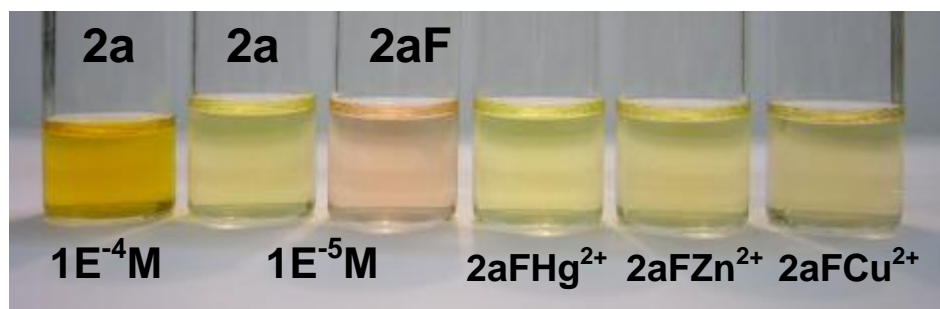


Figure S14. Colorimetric effect in compound **2a** after interaction with fluoride ion, fluoride and mercury(II), fluoride and zinc(II) and fluoride and copper(II).

3.6. UV-vis and emission titration of 2a-c with metal ions, after fluoride ion addition.

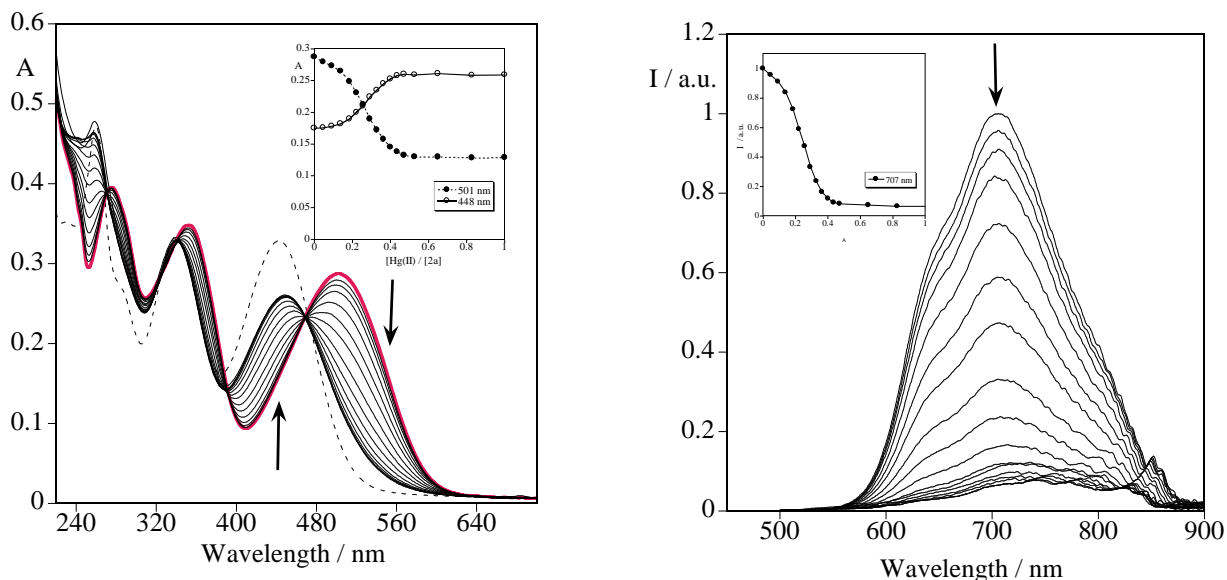


Figure S15. UV-vis and emission titration of **2a** in CH₃CN with increasing addition of Hg(CF₃SO₃)₂ after addition of [(Bu)₄N]F. ($\lambda_{\text{exc}} = 470$ nm). Dotted line: spectra of the free ligand.

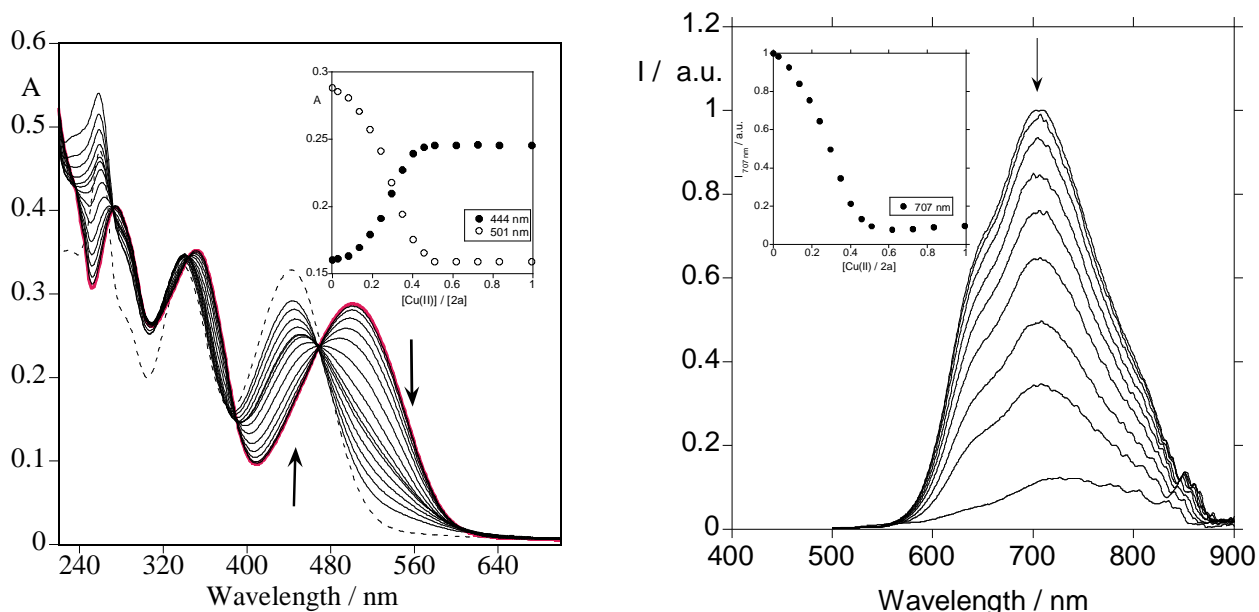


Figure S16. UV-vis and emission titration of **2a** in CH₃CN with increasing addition of Cu(CF₃SO₃)₂ after addition of [(Bu)₄N]F. ($\lambda_{\text{exc}} = 470$ nm). Dotted line: spectra of the free ligand.

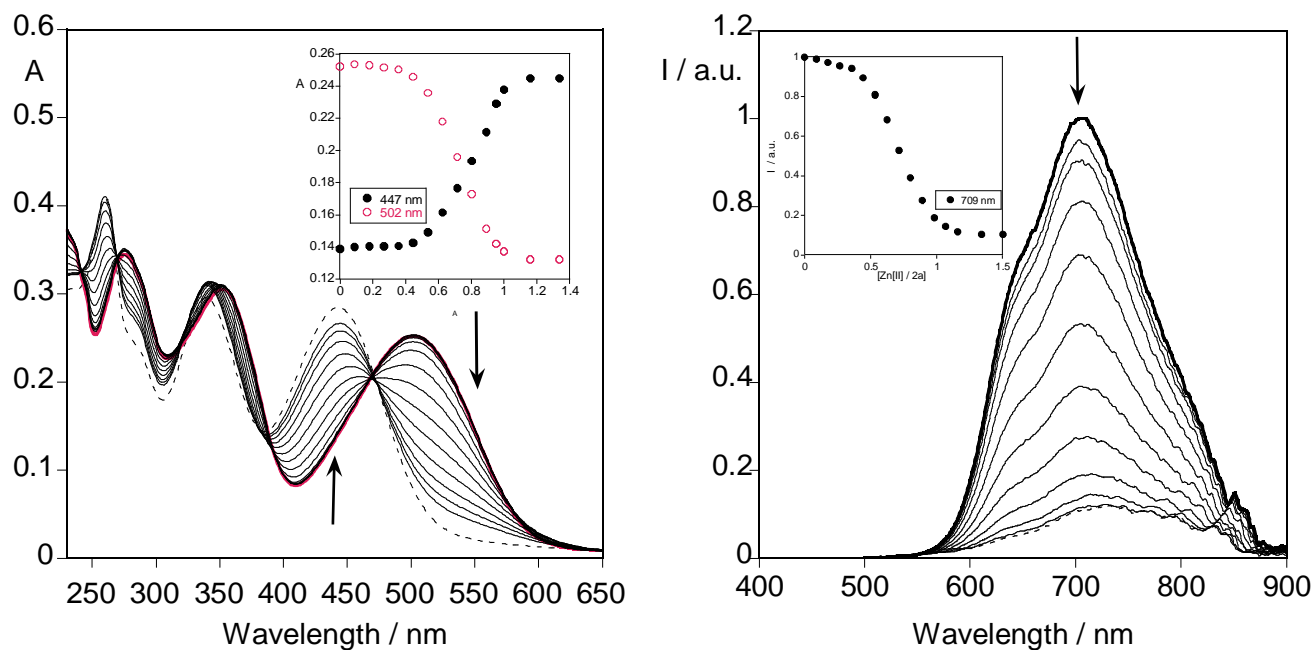


Figure S17. UV-vis and emission titration of **2a** in CH_3CN with increasing addition of $\text{Zn}(\text{CF}_3\text{SO}_3)_2$ after addition of $[(\text{Bu})_4\text{N}]\text{F}$. ($\lambda_{\text{exc}} = 470 \text{ nm}$). Dotted line: spectra of the free ligand.

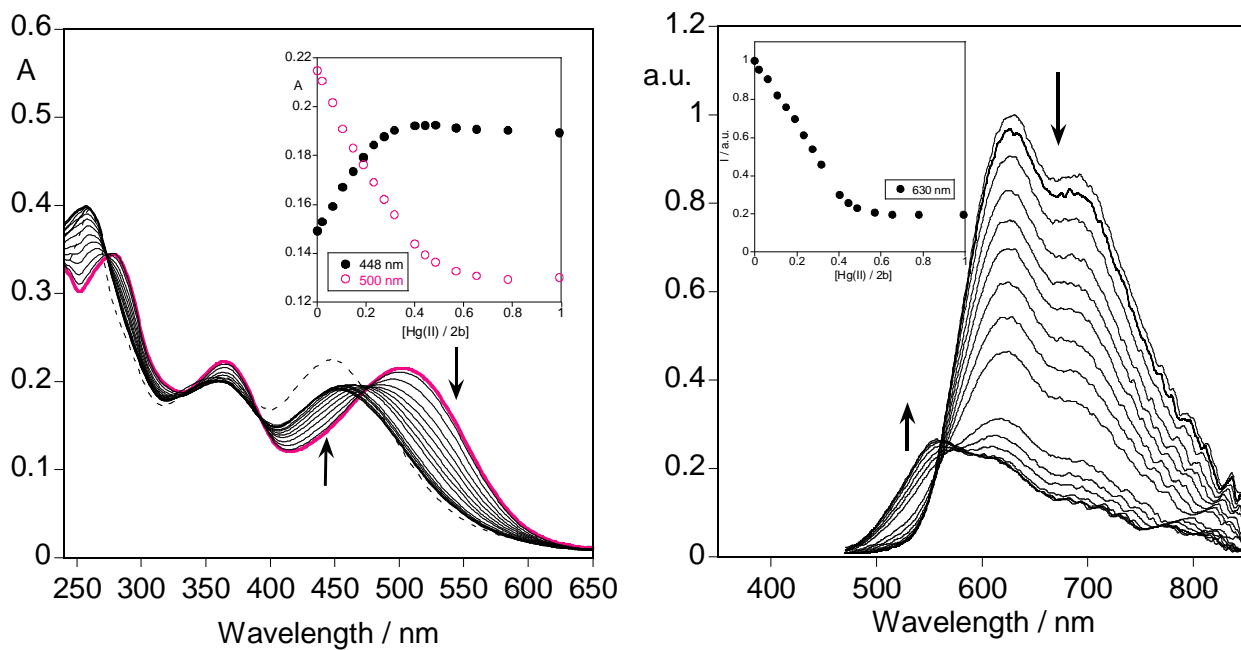


Figure S18. Representative metal ion UV-vis and emission titration of **2b** in CH_3CN with increasing addition of $\text{Hg}(\text{CF}_3\text{SO}_3)_2$ after addition of $[(\text{Bu})_4\text{N}]\text{F}$. ($\lambda_{\text{exc}} = 470 \text{ nm}$). The metal ion titration with $\text{Zn}(\text{CF}_3\text{SO}_3)_2$ and $\text{Cu}(\text{CF}_3\text{SO}_3)_2$ are similar.

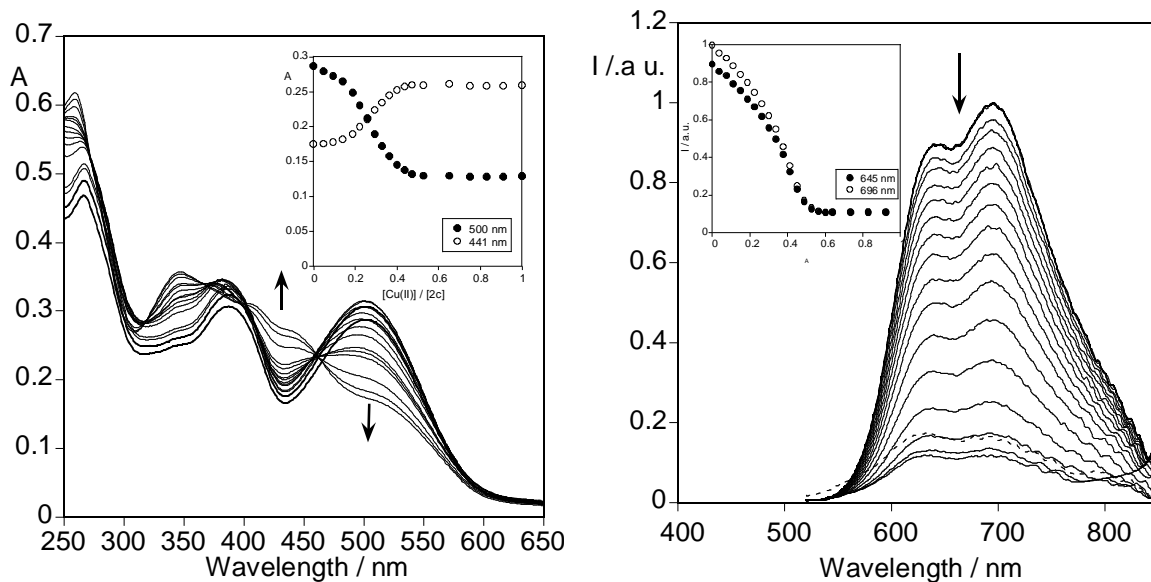


Figure S19. Representative metal ion UV-vis and emission titration of **2c** in CH₃CN with the increase addition of Cu(CF₃SO₃)₂ after addition of [(Bu)₄N]F. ($\lambda_{\text{exc}} = 470 \text{ nm}$) The metal ion titration with Zn(CF₃SO₃)₂ and Hg(CF₃SO₃)₂ are similar.

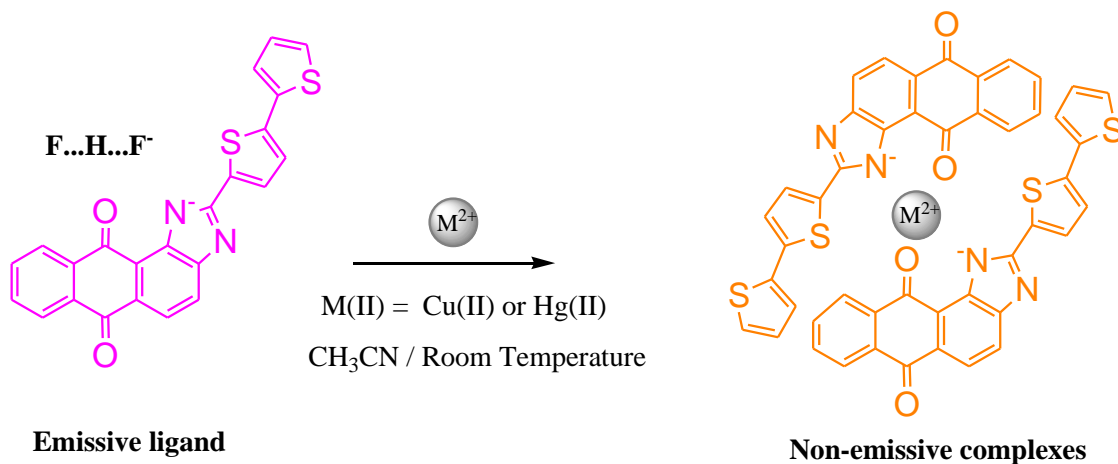


Figure S20. Schematic representation of the complexes of Cu(II) and Hg(II) formed with ligand **2a**. Similar complexes can be proposed for **2b** and **2c**.

4. References

1. Raposo, M. M. M.; Kirsch, G. *Tetrahedron* **2003**, 59(26), 4891.
2. a) Berlan, I. B. *Handbook of Fluorescence Spectra of Aromatic Molecules*, 2nd ed.; Academic Press: New York, **1971**.; b) Melhuish, W. H. *J. Phys Chem.*, **1961**, 84, 229-235