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A Bipyridine-Based “Naked-Eye” Fluorimetric Cu^{2+} Chemosensor

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A series of six 2,2′-bipyridine-3,3′-diols with different substituents have been synthesized and characterized. The designed ligands show fluorescence in the visible part of the spectra, but only the luminescence of the less sterically hindered molecules is quenched in the presence of Cu^{2+} ions. Selectivity and sensitivity of the chemosensors have been tested by absorption and luminescence spectroscopy in aqueous solutions, with a dynamic working range of 0.7–30 μM and a limit of detection of 0.04 ppm (mg L^{-1}).

Introduction

The design and synthesis of new colorimetric and fluorimetric chemosensors has widely attracted the interest of chemists, biologists, biochemists, and environmentalists in recent years.[1,2] Of particular interest is the synthesis of simple molecule units that can recognize important ions like toxic metal ions (e.g., Pb^{2+}, Hg^{2+}) or essential trace elements present in plants, animals, and humans (e.g., Ca^{2+}, Cu^{2+}, Zn^{2+}). The use of small suitable molecules as chemosensors could be a starting point to detect the presence of ions before using more sophisticated analytical techniques such as inductively coupled plasma mass spectroscopy (ICP-MS), atomic absorption spectroscopy, or high-performance liquid chromatography mass spectrometry, which require a laborious sample pretreatment and cannot be used in situ.[3]

2,2′-Bipyridine units with different substituents in their structure have been extensively used in coordination chemistry due to their ability to form robust and stable chelate bonds.[4] The interactions of these kind of ligands with metal ions can cause a shift in the absorbance spectra[5] or a quenching[6] or increase in the luminescence intensity,[7] thus favoring the use of these molecules as colorimetric or fluorimetric chemosensors. Furthermore, bipyridine molecules can be easily functionalized with adequate recognition groups to increase the selectivity of the receptor at the same time as their fluorescence properties can be tuned to increase their sensitivity, with both properties being essential requisites for molecular chemosensors.

Copper is a widely used material in electronics and in industry as a conductor material in electrical networks. Although copper is an essential element, in high concentrations it can be poisonous to living organisms, and the development of selective sensors for copper ions is therefore of particular interest.[8]

In this work, we have synthesized a series of new symmetrically substituted 2,2′-bipyridine-3,3′-diols ligands [$BP(OH)_2$] that differ both in their electronic properties and the degree of steric hindrance around the molecular recognition site. With this aim, both electron-withdrawing (-Ph, -NO_2) and electron-donating groups (-CH_3) have been introduced *ortho* to the hydroxy groups. Figure 1 illustrates the structures of the studied ligands **1a**–**f**.

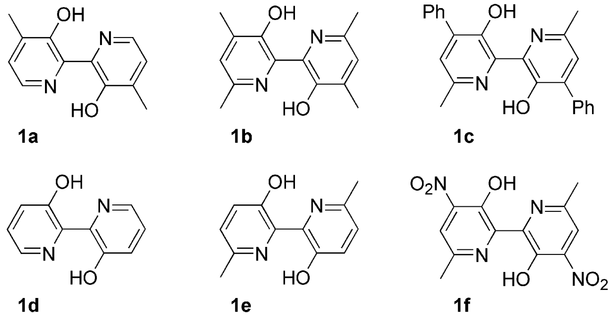

Figure 1. 2,2′-Bipyridine-3,3′-diols synthesized and tested as Cu^{2+} chemosensors.

The high planarity of the $BP(OH)_2$ ligands in the ground state, as a consequence of strong intramolecular hydrogen bonds between the nitrogen and the OH groups,[9] contributes interestingly to the physical properties to this family of ligands. $BP(OH)_2$ and its derivatives have been extensively studied in the field of photophysics, as these compounds are known to be efficient dye lasers and solar energy concentrators, and to undergo excited-state intramolecular double-proton transfer in solution.[10]

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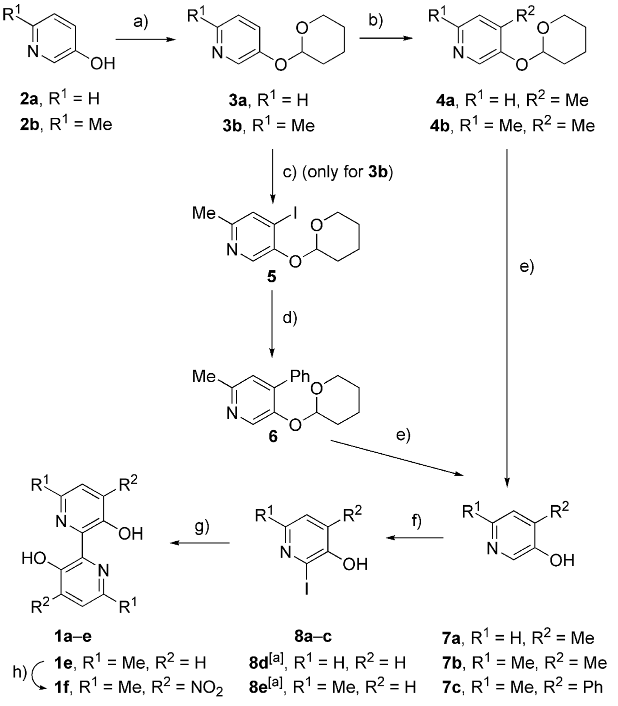
Results and Discussion

The synthetic route to the target 2,2′-bipyridine-3,3′-diols **1a**–**f** is presented in Scheme 1. Commercially available pyridinols **2a**,**b** were transformed into their corresponding tetrahydropyran derivatives **3a**,**b** by a high-yielding Mitsunobu reaction.[11] Lithiation at the *para* position to the pyridine nitrogen atom is greatly facilitated by the tetrahydropyran group.[12] Subsequent reaction of the corresponding lithium derivatives with an electrophile (MeI or iodine) rendered the 4-substituted products **4a**,**b** and **5**. The introduction of iodine in this position allows the transformation of **5** into polyaryl derivatives following a Suzuki coupling protocol: **5** was allowed to react with phenylboronic acid in the presence of a Pd^0 catalyst to yield aryl derivative **6**. Cleavage of the tetrahydropyran protecting group of **4a**,**b** and **6** under aqueous acidic conditions straightforwardly afforded 4-substituted pyridinols **7a**–**c**.



Reagents and conditions: (a) 2-hydroxytetrahydropyrane (100 mol-%), DIAD (110 mol-%), PPh_3 (110 mol-%), r.t., 4 h, THF. (b) *n*BuLi (165 mol-%,-78 °C, 1 h, THF), MeI (165 mol%, -78 °C, 2 h, THF). (c) *n*-BuLi (165 mol%, –78 °C, 1 h, THF), I_2 (165 mol-%, –78 °C, 2 h, THF). (d) $PhB(OH)_2$ (140 mol-%), $Pd(PPh_3)_4$ (5 mol-%), 90 °C, 1 h, MeOH. (e) 1 M HCl_{aq} (110 mol-%), r.t., 1 h, dioxane. (f) I_2 (100 mol-%), Na_2CO_3 (230 mol-%), 0 °C, 2 h, H_2O. (g) $Pd(OAc)_2$ (10 mol-%), nBu_4NI (10 mol-%), DIPEA (100 mol-%), 115 °C, 4 h, DMF. (h) HNO_3 (1000 mol-%), 50 °C, 24 h, AcOH. [a]**8d**–**e** are commercially available products.

Scheme 1. Synthetic route for the preparation of the $BP(OH)_2$ ligands **1a**–**f**.

Regioselective iodination[13] of **7a**–**c** at the *ortho* position to the pyridine nitrogen atom yielded the corresponding 2-iodopyridinols **8a**–**c**, which were direct precursors of the target 2,2′-bipyridine-3,3′-diols. The palladium-mediated homocoupling reaction[14] of **8a**–**c** (and also commercially available **8d**,**e**) afforded the bipyridinols **1a**–**e** in good yields. Finally, the *ortho* nitration of **1e** with HNO_3 yielded the nitro derivative **1f**. The synthetic strategy here described for 2,2′-bipyridine-3,3′-diols represents a good alternative to the synthetic methods previously reported in the literature for these kinds of compounds, namely, the palladium(0)-mediated coupling between iodopyridine and its corresponding Grignard or tin derivatives,[15] the copper(I) thiophene-2-carboxylate (CuTC)-mediated Ullmann homocoupling,[16] or the reductive Ni^{II}–Zn-mediated homocoupling of pyridine halides.[17]

UV/Vis spectroscopy measurements were carried out for a 2.5×10^{-5} M solution of the different bipyridinols in acetonitrile. We observed typical ligand-centered electronic π–π* transition bands with a maximum absorption wavelength at 342 nm for **1d**, 349 nm for **1a**, 351 nm for **1e**, 342 nm for **1b**, 376 nm for **1c**, and 398nm for **1f**. In the case of **1d** and **1a**, a new band is formed that corresponds to the metal-to-ligand charge transfer (MLCT),[18] and a decrease in the π–π* band is observed when small aliquots from an aqueous 10^{-3} M Cu^{2+} solution are added (Figure 2).

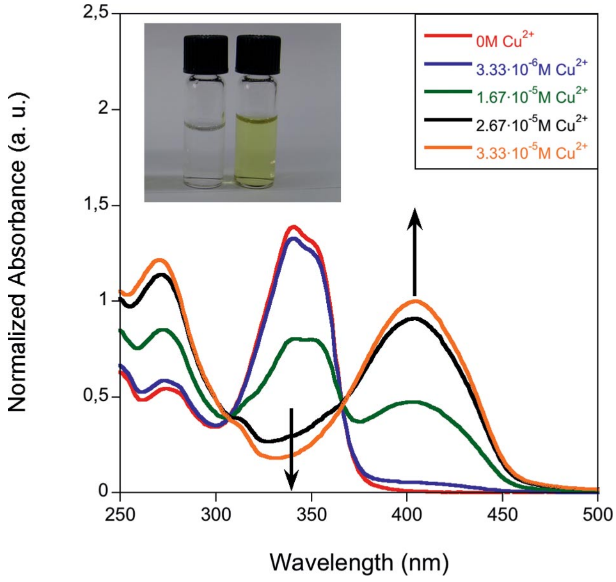


Figure 2. UV/Vis absorption spectra of a 2.5×10^{-5} M solution of **1a** in acetonitrile when a 10^{-3} M aqueous Cu^{2+} solution is added. A color change is observed from transparent to yellow when a Cu^{2+} solution is added to a solution of **1a** (final concentrations: 10^{-4} M Cu^{2+}, 10^{-4} M **1a**).

The emission spectra of 1.25×10^{-5} M solutions of the 2,2′-bipyridine-3,3′-diols in acetonitrile were measured using an excitation wavelength that corresponds to the maximum absorption wavelength of each molecule. An intense luminescence emission was observed at 469 nm for **1d**, 484 nm for **1e**, 475 nm for **1b**, 466 nm for **1a**, 537 nm for **1c**, and 600 nm for **1f** when excited at the maximum absorption wavelength. Luminescence of the less sterically hindered 2,2′-bipyridine-3,3′-diols (**1d** and **1a**) was completely quenched when increasing amounts of Cu^{2+} were added from a stock aqueous solution of $CuCl_2$ (10^{-3} M). On the other hand, no luminescence quenching was observed when other metal ions (Pb^{2+}, Hg^{2+}, Zn^{2+}, Fe^{2+}, Cd^{2+}) were added. In Figure 3 we can observe a luminescence quenching of a 10^{-4} M solution of **1d** in acetonitrile when a 10^{-2} M Cu^{2+} aqueous solution was added.

Figure 3. Observed decrease in luminescence of a 10^{-4} M solution of **1d** when small aliquots of a 10^{-3} M Cu^{2+} aqueous solution were added (from left to right: 0, 5×10^{-5}, 7.5×10^{-5}, 10^{-4}, 1.5×10^{-4}, and 10^{-3} M Cu^{2+}).

Luminescence of **1e**, **1b**, and **1c** did not change upon the addition of aqueous solutions of the metals. Different luminescence behavior was observed for **1f**, which apparently was quenched by all the metals. Further experiments showed that **1f** shows luminescence quenching by the addition of water, which was the solvent used to prepare the metal solutions.

The analysis of the spectroscopic data was done by using the method of continuous variations,[19] which resulted in a 1:1 complexation mode. Binding constants were analyzed with the software package SpecFit, thereby resulting in a binding constant of $(1.44\times10^{7})\pm1.4$ for **1d** and $(3.09\times10^{5})\pm1.2$ for **1a**. The limit of detection was calculated from the luminescence titration values, with a minimum concentration of copper detected of 0.04 ppm for **1d** and 0.1 ppm for **1a**, with a dynamic working range of 0.7–30 and 1.7–30 μM, respectively. The most significant photophysical properties of the 2,2′-bipyridine-3,3′-diols are listed in Table 1.

Table 1. Photophysical parameters for the 2,2′-bipyridine-3,3′-diols described above.

	Abs. λ_{max} [nm][a]	ε [$dm^3 mol^{-1} cm^{-1}$]	Em. λ_{max} [nm][b]	τ [ns][c]	τ_{Cu} [ns][d]
1d	342	16858	469	1.62	1.60
1e	351	16730	484	1.30	1.38
1a	349	18898	475	2.44	2.42
1b	342	17085	466	2.56	2.59
1c	376	15034	537	1.03	1.06
1f	398	12744	600	1.01	1.04

[a] Absorption maximum wavelengths. [b] Emission maximum wavelengths. [c] Emission lifetime measured in CH_3CN. [d] Emission lifetime measured in CH_3CN with a 10^{-3} M aqueous Cu^{2+} solution (100 mL).

The fluorescence quantum yield of 3,3′-dihydroxy-2,2′-bipyridine has been reported before in the literature (Φ = 0.3 ± 0.03, at room temperature and using trimethylpenthane as solvent).[20] Furthermore, the quantum yields of $BP(OH)_2$ compounds with alkyl chain substituents are very similar to the quantum yield of 3,3′-dihydroxy-2,2′-bipyridine.[21]

Time-resolved luminescence spectra were measured for all the molecular receptors ([Receptor] = 2.5×10^{-5} M). The lifetime values of the molecules are in the range of the nanosecond timescale. Addition of Cu^{2+} to a solution of **1a** and **1d** resulted in a strong decrease in signal amplitude when we compared the emission decays measured at constant acquisition time (720 s), but no change in fluorescence lifetime was observed, thereby indicating that the decrease in fluorescence is due to static quenching.

As presented in Figure 4, the total fluorescence intensity of **1a** and **1d** is completely quenched only when Cu^{2+} is present. Cu^{2+} is well known for its high fluorescence quenching, which is due to its paramagnetic properties through electron or energy transfer.[22] Furthermore, luminescence intensity is not significantly affected by a representative selection of transition-metal ions and other alkali and alkaline-earth metal ions. These results are in good agreement with the Irving–Williams series, which predicts a higher affinity for the Cu^{2+} ions due to the increase in the electrostatic effect.

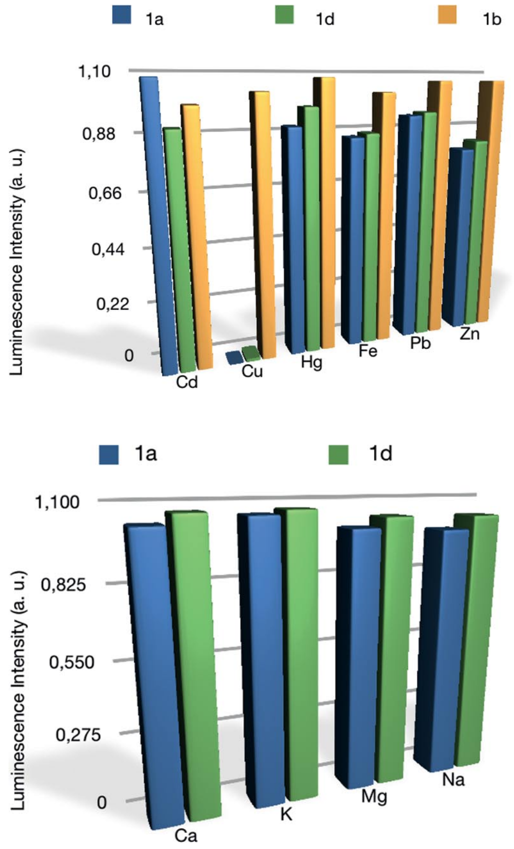


Figure 4. Fluorescence intensity change of **1a**, **1d**, and **1b** in CH_3CN with different metal ions (top). ([Receptor] = 1.25×10^{-5} M, [Metal] = 3×10^{-5} M). Fluorescence intensity of **1a** and **1d** in the presence of alkali and alkaline earth ions (bottom) ([Receptor] = 1.25×10^{-5} M; [Metal] = 3×10^{-5} M).

We believe that the Cu^{2+} ion is linked to the 2,2′-bipyridine-3,3′-diols through one nitrogen atom from the bipyridine and an oxygen atom from the hydroxy group. Two factors might account for this chelation mode between bipyridine-3,3′-diols and Cu^{2+}: (1) The formation of a six-membered ring, which increases the stability of hydrogen bonds formed between the amino and the hydroxy groups of the bipyridine, over a five-membered ring; and (2) the steric hindrance of having two hydroxy groups in the 3,3′-position (Figure 5).[23]

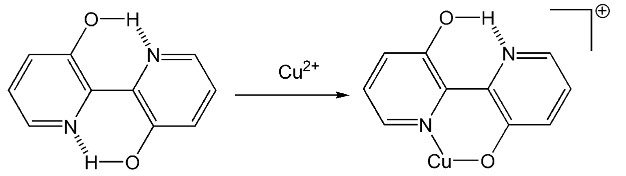


Figure 5. Chelation mechanism of Cu^{2+} with **1d**, including the possible intramolecular hydrogen bonding that increases the stability of the formed complex.

Conclusion

To conclude, we have demonstrated that bipyridine molecules are able to sensitize Cu^{2+} in solution. Moreover, methyl moieties act as sterically hindered groups, which prohibits the coupling between the bipyridine and the Cu^{2+}. The fluorescence of these molecules is completely quenched in the presence of this metal ion and the high selectivity towards copper ions makes these ligands excellent candidates for the measurement of the presence of Cu^{2+} in solution-based processes.

Experimental Section

All syntheses were carried out using chemicals as purchased from commercial sources unless otherwise noted. When required, dried and deoxygenated solvents supplied by a Sigma–Aldrich solvent purification system (SPS-200-6) were used. Air- and moisture-sensitive compounds were prepared under an argon atmosphere using standard Schlenk techniques.

General Procedure for the Mitsunobu Reaction with 3-Hydroxypyridines 3a,b: Diisopropyl azodicarboxylate (11.58 mmol) was added dropwise at 0 °C to a solution of the corresponding hydroxypyridine (10.53 mmol), 2-hydroxytetrahydropyran (11.58 mmol), and Ph_3P (11.58 mmol) in anhydrous THF (10 mL). After being left stirring for 2 h at r. t., the solvent was removed from the solution in vacuo and the residue was dissolved in cyclohexane (50 mL) and left overnight at room temp. Most of the Ph_3PO and hydrazinodicarboxylate crystallized and was filtered off. After evaporation of the filtrate, the crude material was purified by means of column chromatography on silica.

General Procedure for the Lithiation/Electrophilic Addition Reaction of 3-(Tetrahydropyranyloxy)pyridines 4a,b, 5: A 2.5 M solution of *n*BuLi in hexanes (43.00 mmol) was added dropwise to a solution of the corresponding 3-(tetrahydropyranyloxy)pyridine (26.00 mmol) in THF (430 mL) at –78 °C. After being stirred for 30 min at this temperature, the electrophile (43.00 mmol) was added dropwise as a 1 M solution in THF. After being stirred for 1 h at –78 °C, 10% NH_4Cl (15 mL) was added. The solution was extracted with Et_2O (3 × 20 mL). The organic phase was dried with Na_2SO_4, filtered, and evaporated in vacuo. The products were purified by flash column chromatography in AcOEt/hexanes.

Suzuki Coupling Reaction: Synthesis of 4-Phenyl-2-methyl-5-(tetrahydropyranyloxy)pyridine (6): A mixture of **5** (0.78 g, 2.44 mmol), phenylboronic acid (0.42 g, 3.42 mmol), 2 M aqueous Na_2CO_3 solution (7.30 mL, 14.60 mmol), and $[Pd(PPh_3)_4]$ (0.14 g, 0.12 mmol, 5%mol^{-1}) in MeOH (20 mL) was heated for 1 h at 90 °C with stirring under an Ar atmosphere. After cooling to room temp. the reaction mixture was evaporated and CH_2Cl_2 (25 mL) and water (10 mL) were added to the residue. The organic layer was separated, washed with water (3 × 15 mL), dried ($MgSO_4$), filtered, and the solvents evaporated. The product was purified by column chromatography over silica gel (Combiflash AcOEt/hexane 1:4), which provided compound **6** in 76% yield as a brown oil (0.51 g, 1.89 mmol). IR (film): $\tilde{\nu}$ = 2941.0, 1595.4, 1499.5, 1482.8, 1442.0 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.50–1.88 (m, 6 H), 2.57 (s, 3 H), 3.58 (m, 1 H), 3.80 (td, *J* = 11.1, 2.9 Hz, 1 H), 5.36 (t, *J* = 2.9 Hz, 1 H), 7.15 (s, 1 H), 7.37–7.62 (m, 5 H), 8.46 (s, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 18.4 (CH_2), 23.6 (CH_3), 25.1 (CH_2), 30.1 (CH_2), 62.0 (CH_2), 97.7 (CH), 124.1 (CH), 128.1 (CH), 128.1 (CH), 129.2 (CH), 136.1 (C), 138.6 (CH), 139.3 (C), 148.3 (C), 152.0 (C) ppm. HRMS: calcd. for $C_{17}H_{20}NO_2$: 270.1494; found 270.1486.

General Procedure for the Deprotection of 3-(Tetrahydropyranyloxy)pyridines 4a,b, 6: A 5 M solution of aqueous HCl (20.00 mmol) was added dropwise to a solution of the corresponding 3-(tetrahydropyranyloxy)pyridine **4a**,**b** or **6** (19.00 mmol) in dioxane (10 mL) at room temp. After 1 h of being stirred at this temperature, K_2CO_3 (21.00 mmol) was added and the mixture was stirred for 1 h. Then the mixture was filtered and the solvent was removed in vacuo to obtain the corresponding hydroxypyridines **7a–c**.

General Procedure for the Iodination of 4-Substituted 3-Hydroxypyridines 8a–c: The corresponding hydroxypyridine **7a**–**c** (13.75 mmol) and sodium carbonate (31.63 mmol) were dissolved in water (200 mL). Iodine (13.75 mmol) was added with stirring at 0 °C for 2 h. Then, aqueous HCl was added until the pH reached 3. The solution was extracted with CH_2Cl_2 (3 × 20 mL) and the organic phases were washed with 0.1 M Na_2SO_3 (13.00 mmol). The organic phase was dried with Na_2SO_4, filtered, and evaporated in vacuo. The products were purified by flash column chromatography.

General Procedure for the Pd^0-Mediated Homocoupling of 4-Substituted 3-Hydroxy-2-iodopyridines 1a–e: A mixture of the corresponding iodopyridinol **8a**–**e** (1.30 mmol), *N*,*N*-diisopropylethylamine (DIPEA; 1.30 mmol), $Pd(OAc)_2$ trimer (0.04 mmol), and nBu_4NI (0.13 mmol) in DMF (0.13 mL) was stirred at 115 °C for 4 h under an Ar atmosphere. After cooling to room temp., 2 M aqueous HCl (1.30 mmol) and CH_2Cl_2 (10 mL) were added and the mixture was stirred at room temp. for 1 h. Then the volatiles were removed in vacuo. The products were purified by flash column chromatography in CH_2Cl_2/hexanes.

3,3′-Dihydroxy-4,4′-dimethyl-2,2′-bipyridine (1a): By following the general procedure, from **8a** (1.00 g, 4.26 mmol), $[\{Pd(OAc)_2\}_3]$ (0.10 g, 0.15 mmol), DIPEA (0.74 mL, 4.25 mmol), and nBu_4NI (0.79 g, 2.12 mmol), compound **1a** was obtained in 51% yield as a yellow solid (0.24 g, 2.17 mmol); m.p. 183–184 °C. IR (film): $\tilde{\nu}$ = 2922.5, 2848.1, 2450.7, 1742.2, 1466.2, 1423.0, 1375.2 cm^{-1}. ^{1}H NMR (400 MHz, CD_2Cl_2): δ = 2.38 (s, 3 H), 7.21 (dd, *J* = 4.8, 0.7 Hz, 1 H), 7.97 (d, *J* = 4.8 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, CD_2Cl_2): δ = 15.5 (CH_3), 125.9 (CH), 135.1 (CH), 136.6 (C), 138.5 (C), 155.1 (C) ppm. HRMS: calcd. for $C_{12}H_{12}N_2O_2$: 216.0899; found 216.0910.

3,3′-Dihydroxy-4,4′,6,6′-tetramethyl-2,2′-bipyridine (1b): By following the general procedure, from **8b** (1.55 g, 6.22 mmol), $[\{Pd(OAc)_2\}_3]$ (71 mg, 0.11 mmol), DIPEA (1.08 mL, 6.22 mmol), and nBu_4NI (0.23 g, 0.62 mmol), compound **1b** was obtained in 52% yield as a yellow solid (0.41 g, 3.24 mmol); m.p. 238–240 °C. IR (film): $\tilde{\nu}$ = 2923.3, 2512.1, 1748.1, 1603.6, 1580.6, 1467.1, 1439.5, 1375.8 cm^{-1}. ^{1}H NMR (400 MHz, CD_2Cl_2): δ = 2.33 (s, 3 H), 2.50 (s, 3 H), 7.03 (s, 2 H) ppm. ^{13}C NMR (100 MHz, CD_2Cl_2): δ = 15.5 (CH_3), 22.5 (CH_3), 125.5 (CH), 136.9 (C), 137.3 (C), 143.8 (C), 152.9 (C) ppm. HRMS: calcd. for $C_{14}H_{17}N_2O_2$: 245.1290; found 245.1296.

3,3′-Dihydroxy-6,6′-dimethyl-4,4′-diphenyl-2,2′-bipyridine (1c): By following the general procedure, from **8c** (0.40 g, 1.29 mmol), [{Pd(OAc)$_2$}$_3$] (15 mg, 0.02 mmol), DIPEA (0.22 mL, 1.29 mmol), and *n*Bu$_4$NI (48 mg, 0.13 mmol), compound **1c** was obtained in 51% yield as an orange solid (0.12 g, 0.33 mmol); m.p. 214–215 °C. IR (film): ṽ = 3052.3, 2919.4, 2323.6, 1736.6, 1570.0, 1479.2, 1433.7, 1374.4 cm^{-1}. ^{1}H NMR (400 MHz, CD_2Cl_2): δ = 2.59 (s, 6 H), 7.27 (s, 2 H), 7.47 (m, 2 H), 7.53 (m, 4 H), 7.75 (m, 4 H) ppm. ^{13}C NMR (100 MHz, CD_2Cl_2): δ = 22.5 (CH_3), 124.9 (CH), 128.3 (CH), 128.3 (CH), 129.3 (CH), 136.2 (C), 138.5 (C),138.9 (C), 144.1 (C), 152.0 (C) ppm. HRMS: calcd. for $C_{24}H_{21}N_2O_2$ [M + 1]: 369.16; found 369.1603.

3,3′-Dihydroxybipyridine (1d):[24] By following the general procedure, from **8d** (0.20 g, 0.90 mmol), [{Pd(OAc)$_2$}$_3$] (19 mg, 0.03 mmol), DIPEA (0.16 mL, 0.90 mmol), and *n*Bu$_4$NI (0.17 g, 0.45 mmol), compound **1d** was obtained in 32% yield as a yellow solid (27 mg, 0.14 mmol). Physical and spectroscopic data were in agreement with those reported.[24]

3,3′-Dihydroxy-6,6′-dimethylbipyridine (1e):[25] By following the general procedure, from **8e** (7.00 g, 29.49 mmol), [{Pd(OAc)$_2$}$_3$] (0.63 g, 0.94 mmol), DIPEA (5.18 mL, 29.49 mmol), and *n*Bu$_4$NI (5.56 g, 14.74 mmol), compound **1e** was obtained in 68% yield as a yellow solid (2.14 g, 9.87 mmol). Physical and spectroscopic data were in agreement with those reported.[25]

Nitration Reaction of Bipyridinol 1e To Afford 1f: Bipyridinol **1e** (0.50 g, 2.31 mmol) was dissolved in acetic acid (10 mL) and the mixture was cooled to 15 °C. Then, 90% nitric acid (1.59 mL, 23.12 mmol) was added over 3 min. After stirring for an additional 20 min, the mixture was heated at 50 °C. After 24 h, the mixture was cooled and neutralized with 10% aqueous NaOH and extracted with AcOEt (3 × 10 mL) The combined organic phases were dried with Na_2SO_4, filtered, and the solvent was removed under reduced pressure. Purification by flash chromatography (silica 12 g, CH_2Cl_2) afforded compound **1f** in 76% yield as an orange solid (0.54 g, 1.77 mmol); m.p. 298–300 °C. IR (film): ṽ = 3063.2 2324.2, 1579.3, 1525.1, 1444.9, 1357.9 cm^{-1}. ^{1}H NMR (400 MHz, CD_2Cl_2): δ = 2.69 (s, 6 H), 7.75 (s, 2 H) ppm. ^{13}C NMR (100 MHz, CD_2Cl_2): δ = 22.4 (CH_3), 119.3 (CH), 141.3 (C), 144.2 (C); 145.6 (C), 147.7 (C) ppm. HRMS: calcd. for $C_{12}H_9N_4O_6$ [M – 1]: 305.0522; found 305.0519.

Optical, Electrochemical, and Spectroscopic Measurements: UV/Vis and fluorescence spectra were recorded in a quartz cell (1 cm path length) with a Shimadzu UV spectrophotometer 1700 and an Aminco-Browman Series 2 luminescence spectrophotometer, respectively. Lifetime measurements were done with a Lifespec-red picosecond-fluorescence-lifetime spectrophotometer from Edinburgh Instruments. NMR spectra were recorded with Bruker Avance 400 and 500 Ultrashield spectrometers in $CDCl_3$ unless otherwise noted. IR spectra were recorded with a Tensor-27 FTIR Bruker spectrometer. Mass spectra were obtained with Bruker Autoflex (MALDI-TOF) and Waters LCT Premier (ESI, HRMS) instruments. Melting points were measured with a Büchi melting point B-540 apparatus.

Supporting Information (see also the footnote on the first page of this article): Detailed descriptions of experimental procedures and characterization of compounds **1a**–**f**, **2a**,**b**, **3a**,**b**, **4a**,**b**, **5**, **6**, **7a**–**c**, and **8a**–**e**. Also available are UV/Vis and fluorescence spectra showing changes upon titration of **1a** and **1d** with solutions of transition-metal cations.

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