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Chromic and fluorescence response system based on the dihydrophenanthroline-bipyridine skeleton: dynamic redox behavior and metal binding properties

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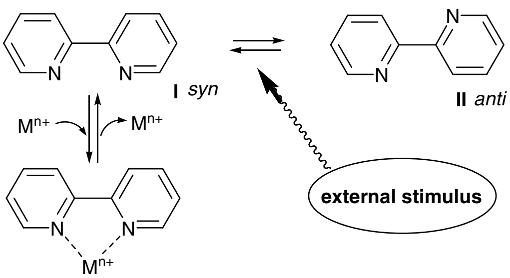
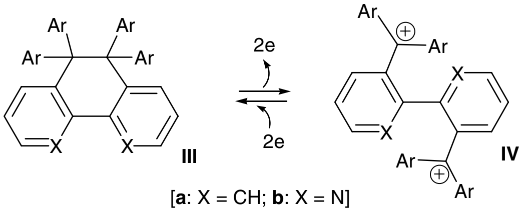
Abstract—The spiro-acridan/acridinium-based dynamic redox pair ($\mathbf{1}/\mathbf{2}^{2+}$) transduces the electrochemical input into UV–vis and fluorescence spectra, whereas the 2,2′-bipyridine units in **1** works as a bidentate ligand for metal ions. X-ray structural analyses of this redox pair and the corresponding Zn-complexes [$\mathbf{1}$-ZnI_2/$\mathbf{2}^{2+}$-$Zn^{2+}(OTf^-)_4$] demonstrate drastic structural changes upon electron-transfer, thus metal binding properties are modified by redox reactions.

2,2′-Bipyridine is the representative nitrogen-based ligand to afford a plethora of metal complexes.[1] To realize bidentate binding, two pyridine nuclei adopt *syn* orientation (I) whereas the *anti*-form (II) with C–H⋯N hydrogen bonds[2] is energetically favored for the metal-free state due to lack of dipole/electrostatic repulsion (Scheme 1).[3] When the *syn*/*anti* equilibrium is biased to prefer, or even fixed, to adopt one state by applying external stimuli, metal-binding properties could be modified to induce controllable binding/release of the metal ion (M^{n+}). On the other hand, when M^{n+} is strongly bound to these molecules, sensitivity toward the external stimuli might be modified by the presence/absence of M^{n+}.



Scheme 1.

We previously reported the electrochromic behavior of dihydrophenanthrene-biphenyl-type redox pair (IIIa/IVa, X = CH) (Scheme 2),[4] which undergoes drastic structural changes upon electron transfer accompanied by C–C bond formation/breaking (‘dynamic redox properties’).[5] When the 2,2′-bipyridine skeleton is replaced for the biphenyl unit, the newly designed redox pair (IIIb/IVb, X = N) would exhibit *syn*/*anti* geometrical switching by electric potential: the neutral donor IIIb must adopt *syn*-orientation due to the ethano-bridge whereas the dication IVb strongly prefers *anti*-form by coordination of pyridine lone pairs to the cationic centers.



Scheme 2.

Keywords: Dynamic redox system; Bipyridine; Metal sensing; Electrochromism; Fluorescence.

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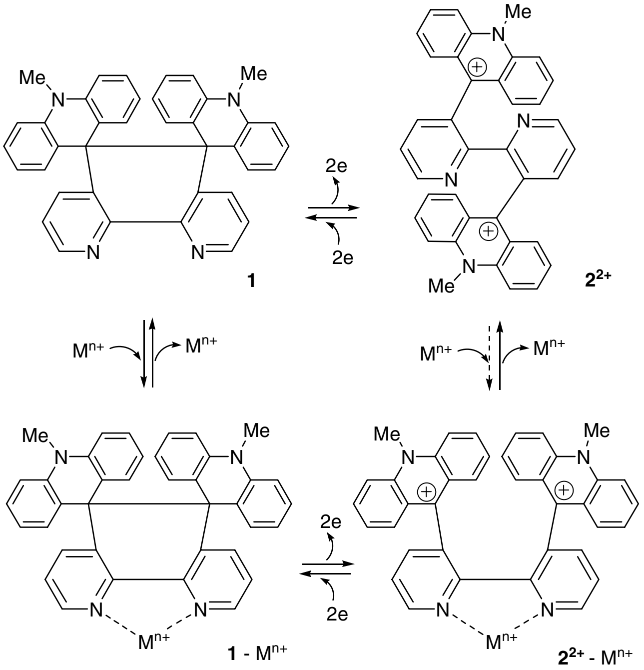
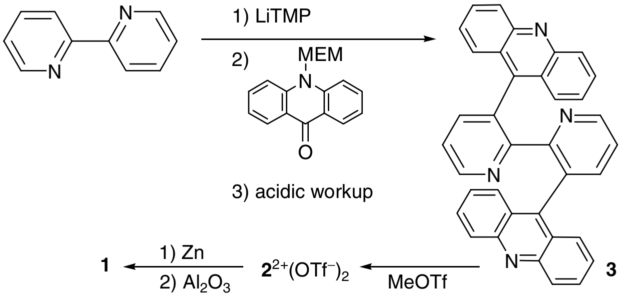


Scheme 3.

We have succeeded in constructing the title 2,2′-bipyridine-based redox pair ($\mathbf{1}/\mathbf{2}^{2+}$) with spiro-acridan/acridinium chromophores[6] shown in Scheme 3, that exhibits UV–vis and fluorescence spectral changes upon electron transfer (two-way-output response systems). Since the spectral properties would be also modified upon the addition of M^{n+}, the present molecules can serve as two-way-input response systems. Here we report preparation, properties, and X-ray structures of the redox pair as well as their metal complexes ($\mathbf{1}$-M^{n+}/$\mathbf{2}^{2+}$-M^{n+}).

3,3′-Dilithio-2,2′-bipyridine was generated by the reaction of 2,2′-bipyridine with lithium 2,2,6,6-tetramethylpiperidide (LTMP),[7] which was then reacted with *N*-methoxyethoxymethyl (MEM)-9-acridone.[8] Acidic workup induced removal of MEM groups and successive dehydration to give 2,2′-bipyridine-3,3′-diylbis(9-acridine) **3** in 33% yield (Scheme 4). Careful treatment of **3** with methyl trifluoromethanesulfonate (MeOTf, 2.1 equiv)[9] gave the desired dication $\mathbf{2}^{2+}$ along with monocationic species, in which only one acridine unit is quaternized. The orange salt of $\mathbf{2}^{2+}(\mathrm{OTf}^-)_2$ was isolated in 43% yield, yet it is more convenient to use the cationic mixture directly for the next step, and reduction by Zn powder produced colorless crystals of dihydrophenanthroline derivative **1**, which was isolated in 16% yield after chromatographic separation (Al_2O_3/$CHCl_3$).



Scheme 4.

According to the X-ray analysis,[10] two acridine moieties in precursor **3** are aligned in parallel with the *syn*-arrangement of the bipyridine unit [<N–C–C–N 57.9(3)°, Fig. S1]. Thus, the presence of two bulky groups at 3,3’-positions is not enough to bias the *syn*/*anti* equilibrium to prefer the *anti*-form. In contrast, the torsion angle of N–C–C–N in $\mathbf{2}^{2+}(\mathrm{OTf}^-)_2$ is 180.0°, the ultimate value for the *anti*-form (Fig. 1b). Slight deformation of the acridinium units into butterfly-shape is indicative of coordination of the pyridine lone pairs to the cationic centers (C9).[11] On the other hand, the bipyridine unit in neutral donor **1** is fixed to *syn*-form [<N–C–C–N 6.9(9)°, Fig. 1a] by forming a C–C bond of 1.629(9) Å between C9 carbons upon

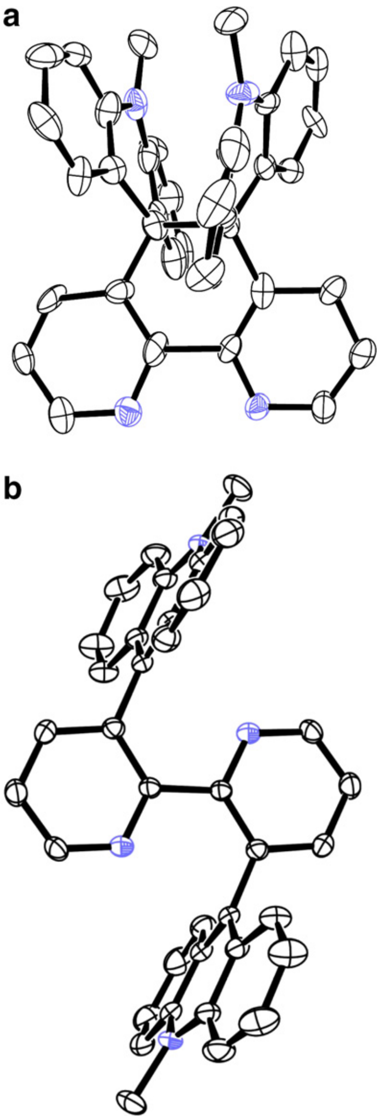


Figure 1. ORTEP drawings of (a) **1** and (b) $\mathbf{2}^{2+}(\mathrm{OTf}^-)_2$ determined by the low-temperature X-ray analyses.

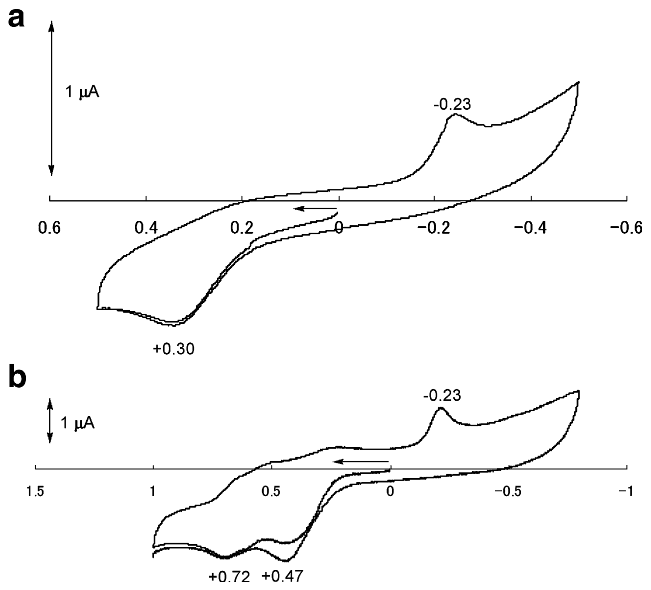


Figure 2. Cyclic voltammograms of (a) **1** and (b)**1**-ZnI_2 complex measured in MeCN containing 0.1 mol dm^{-3} Et_4NClO_4 as a supporting electrolyte.

reduction. These results indicate that the present redox pair (**1**/$\mathbf{2}^{2+}$) undergoes dynamic structural changes, and the *syn*/*anti*-preference of the bipyridine unit could be switched by electric potential.

As shown by the large separation of redox potentials (Fig. 2a), this redox pair exhibits electrochemical bistability. The oxidation potential of **1** (+0.30 V vs SCE in MeCN) and the reduction potential of $\mathbf{2}^{2+}$ (−0.23 V) are close to those of dihydrophenanthrene-biphenyl analogue studied previously (+0.18 and −0.27 V, respectively).[4a] Electrochemical oxidation of colorless donor **1** caused orange coloration with continuous changes of UV–vis spectrum to that of $\mathbf{2}^{2+}$ with several isosbestic points. Although the fluorescence of dication $\mathbf{2}^{2+}$ is not strong,[12] donor **1** is completely non-fluorescent. Thus, the electrolysis induced gradual emerge of green emission around 500 nm. In this way, two-way-output response of the present redox system was demonstrated (Fig. 3), thanks to the chromophoric interconversion between spiro-acridans and acridiniums.[4a]

In accord with the clean electrochemical response, preparative scale interconversion proceeded quantitatively: oxidation of **1** with iodine (3 equiv) gave $\mathbf{2}^{2+}(I_3^-)_2$ in 98% yield, and reduction of $\mathbf{2}^{2+}(I_3^-)_2$ with Zn gave **1** in 100% yield. In the latter reaction, donor **1** was isolated by column chromatography of the crude reduction product. Noteworthy is the differences between the ^1H NMR spectra of the reduction product before and after the chromatographic separation (Fig. S2). It is most probable that the initial reduction product is the zinc complex of donor **1**, which lost the metal ion during chromatography.

In fact, purification by recrystallization enabled us to isolate **1**-ZnI_2 complex, in which bipyridine unit of *syn*-form [<N–C–C–N 8(1)°] binds with a zinc atom

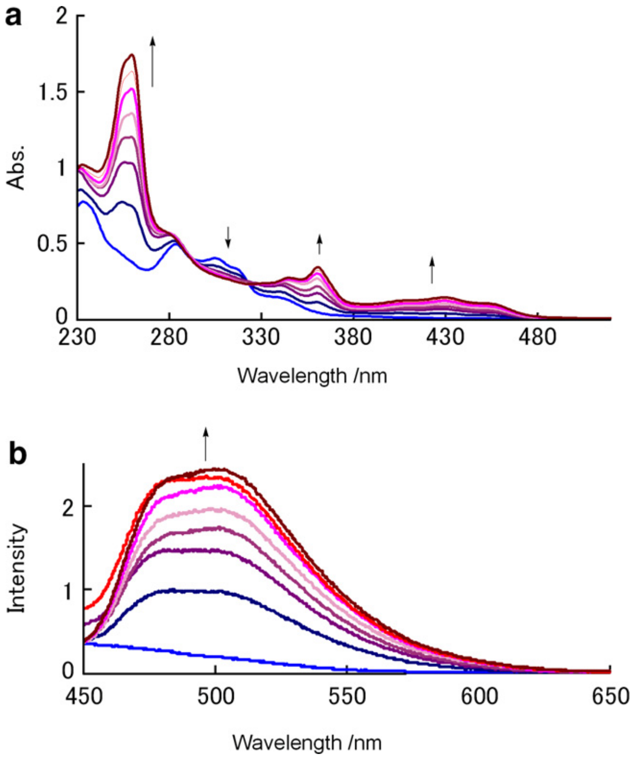


Figure 3. Changes in (a) UV–vis and (b) fluorescence spectra upon constant-current electrochemical oxidation (30 μA, every 5 min) of **1** (3.5 mL, 2.3×10^{-5} mol dm^{-3}) to $\mathbf{2}^{2+}$ in MeCN containing 0.05 mol dm^{-3} n-Bu_4NBF_4 as a supporting electrolyte. UV–vis changes are accompanied by several isosbestic points (292 and 322 nm).

[Zn–N, 2.056(8) and 2.074(8) Å], as determined by the X-ray structural analysis (Fig. 4a). As shown in Figure 5, the UV–vis spectrum of isolated **1** changed gradually upon the addition of $Zn^{2+}(OTf^-)_2$ with isosbestic points. In this way, donor **1** was proven to exhibit metal binding properties even in the diluted solution of 10^{-5} mol dm^{-3}. On the other hand, UV–vis and fluorescence spectra of $\mathbf{2}^{2+}$ showed only negligible changes upon the addition of $Zn^{2+}(OTf^-)_2$, suggesting that complexation is reluctant or even prohibited in dication $\mathbf{2}^{2+}$ due to *anti*-geometrical preference as well as repulsion between positive charges. Fortunately, we could obtain the single crystal of Zn^{2+} complex of dication $\mathbf{2}^{2+}$ by air-oxidation of **1**-$Zn^{2+}(OTf^-)_2$ complex generated in chloroform. The X-ray structure shown in Figure 4b clearly shows that the bipyridine unit in $\mathbf{2}^{2+}$-$Zn^{2+}(OTf^-)_4$ complex adopts *syn*-orientation [<N–C–C–N 32(1)°], and the two acridinium units are forced to overlap each other. The steric and electrostatic repulsion must be the major reason for instability of $\mathbf{2}^{2+}$-M^{n+}, and voltammetric analysis indicates release of zinc ion[15] upon two-electron oxidation of **1**-ZnI_2 complex in MeCN (Fig. 2b).[16] In this way, it is shown that the metal-binding properties could be modified by electrochemical input.

In summary, we have constructed a novel dynamic redox pair containing 2,2′-bipyridine skeleton (**1**/$\mathbf{2}^{2+}$), which transduces electrochemical input into two-kinds

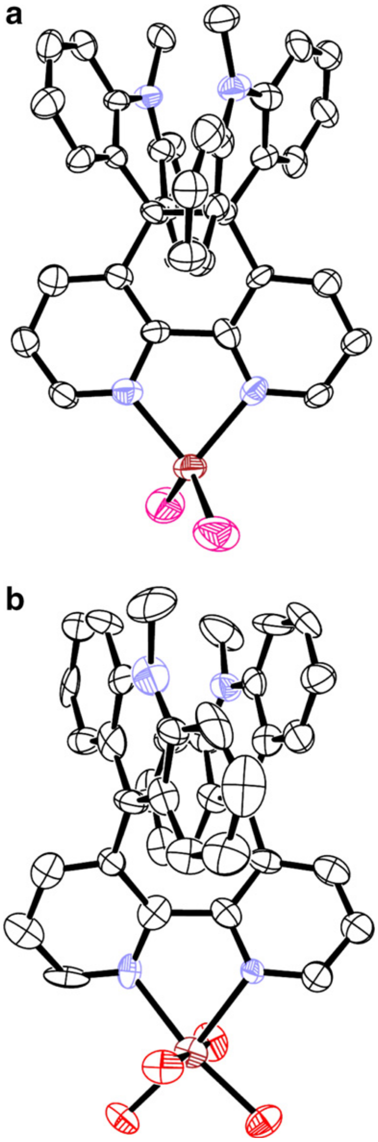


Figure 4. ORTEP drawings of (a) **1**-ZnI$_2$ and (b) **2**$^{2+}$-Zn^{2+}(OH$_2$)$_4$-(OTf$^-$)$_4$·4H$_2$O determined by the low-temperature X-ray analyses.

of spectral outputs (UV–vis and fluorescence). Due to the drastic change of geometry upon electron transfer, *syn*/*anti*-preference of the bipyridine moiety could be also switched, thus modifying the metal binding properties. On the other hand, metal-ion addition induces spectral change of the donor, showing that the present pair could also serve as a prototype of multi-input response system through metal-ion sensing.

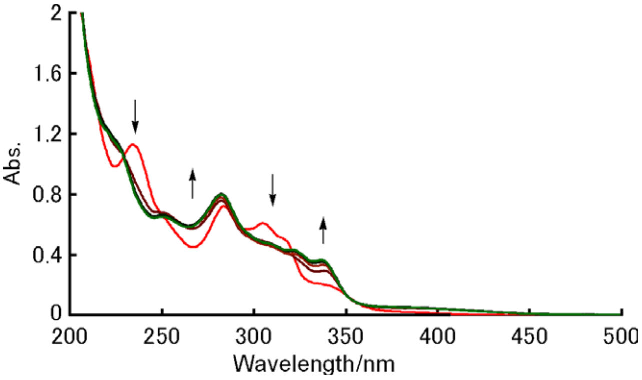


Figure 5. Changes in UV–vis spectrum of **1** (red line, 3.5 mL, 3.3×10^{-5} mol dm^{-3}) upon addition of Zn(OTf$^-$)$_2$ (0.25, 0.50, 0.74, 1.0, and 2.0 equiv) in CH$_2$Cl$_2$/MeCN = 1:1, which are accompanied by several isosbestic points (229, 250, 290, 320, and 355 nm).

Acknowledgment

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Supplementary data

Crystallographic data (excluding structure factors) for the structures in this Letter has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 637945–637949. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44 (0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

Selected spectral data for new compounds. ORTEP drawing of **3** (Fig. S1) and ^{1}H NMR spectra of **2**$^{2+}$(I$_3^-$)$_2$, **1**-ZnI$_2$, and **1** (Fig. S2), which are available in PDF format. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2007.03.167.

References and notes

1. Recent reviews (a) Ye, B.-H.; Tong, M.-L.; Chen, X.-M. *Coord. Chem. Rev.* **2005**, *249*, 545; (b) Balzani, V.; Bergamini, G.; Marchioni, F.; Ceroni, P. *Coord. Chem. Rev.* **2006**, *250*, 1254.
2. (a) Reddy, D. S.; Craig, D. C.; Desiraju, G. R. *J. Am. Chem. Soc.* **1996**, *118*, 4090; (b) Ohkita, M.; Suzuki, T.; Nakatani, K.; Tsuji, T. *Chem. Commun.* **2001**, 1454; (c) Ohkita, M.; Kawano, M.; Suzuki, T.; Tsuji, T. *Chem. Commun.* **2002**, 3054.
3. Jaime, C.; Font, J. *J. Org. Chem.* **1990**, *55*, 2637.
4. (a) Suzuki, T.; Migita, A.; Higuchi, H.; Kawai, H.; Fujiwara, K.; Tsuji, T. *Tetrahedron Lett.* **2003**, *44*, 6837; (b) Suzuki, T.; Nishida, J.; Tsuji, T. *Angew. Chem., Int. Ed.* **1997**, *36*, 1329; (c) Suzuki, T.; Nishida, J.; Tsuji, T. *Chem. Commun.* **1998**, 2193; (d) Suzuki, T.; Yamamoto, R.; Higuchi, H.; Hirota, E.; Ohkita, M.; Tsuji, T. *J. Chem. Soc., Perkin Trans. 2* **2002**, 1937; (e) Suzuki, T.; Tanaka, S.; Higuchi, H.; Kawai, H.; Fujiwara, K. *Tetrahedron Lett.* **2004**, *45*, 8563; (f) Suzuki, T.; Tanaka, S.; Kawai, H.; Fujiwara, K. *Chem. Asian J.* **2007**, *2*, 171.
5. (a) Suzuki, T.; Higuchi, H.; Tsuji, T.; Nishida, J.; Yamashita, Y.; Miyashi, T. In *Chemistry of Nanomolecular Systems, Chapter 1: Dynamic Redox Systems*; Nakamura, T., Matsumoto, T., Tada, H., Sugiura, K., Eds.; Springer-Verlag: Heidelberg, 2003; p 3; (b) Suzuki, T.; Ohta, E.; Kawai, H.; Fujiwara, K.; Fukushima, T. *Synlett (account)* **2007**, 851.

6. Many attempts to prepare dications IVb containing 4-MeOC$_6$H$_4$ or 4-Me$_2$NC$_6$H$_4$ groups as Ar were unfruitful probably due to the insufficinet thermodynamic stability of Ar$_2$C$^+$ units against intermolecular nucleophilic attack by pyridine lone pairs.
7. (a) Mongin, F.; Quéguiner, G. *Tetrahedron* **2001**, *57*, 4059; (b) Zoltewicz, J. A.; Dill, C. D. *Tetrahedron* **1996**, *52*, 14469.
8. Tanaka, T.; Tasaki, T.; Aoyama, Y. *J. Am. Chem. Soc.* **2002**, *124*, 12453.
9. Increased amount of MeOTf did not reduce the amount of monocationic species but produced intractable material without changing the yield of **2**$^{2+}$.
10. Crystal data of **1**·2CHCl$_3$: $C_{40}H_{30}N_4Cl_6$, *M* 779.42, monoclinic *Pc*, $a = 7.506(7)$, $b = 14.00(1)$, $c = 16.69(2)$ Å, $\beta = 94.062(4)°$, $V = 1749.7(2)$ Å^3, D_c $(Z = 2) = 1.479$ g cm^{-3}, $T = 153$ K, $\mu = 5.28$ cm^{-1}. The final *R* value is 0.121 for 3950 independent reflections and 449 parameters. Refinement with the space group of *P*2/*c* did not converge. CCDC 637945. **1**-ZnI$_2$: $C_{38}H_{28}I_2N_4Zn$, *M* 859.85, triclinic $P\bar{1}$, $a = 7.362(4)$, $b = 13.775(8)$, $c = 16.32(1)$ Å, $\alpha = 90.31(1)$, $\beta = 90.14(3)$, $\gamma = 80.49(3)°$, $V = 1632.1(1)$ Å^3, D_c $(Z = 2) = 1.750$ g cm^{-3}, $T = 153$ K, $\mu = 26.79$ cm^{-1}. The final *R* value is 0.086 for 7194 independent reflections and 406 parameters. CCDC 637946. **2**$^{2+}$(OTf$^-$)$_2$: $C_{40}H_{28}F_6N_4O_6S_2$, *M* 838.79, triclinic $P\bar{1}$, $a = 8.477(2)$, $b = 10.020(2)$, $c = 11.076(3)$ Å, $\alpha = 84.365(8)$, $\beta = 81.882(8)$, $\gamma = 78.047(8)°$, $V = 908.8(4)$ Å^3, D_c $(Z = 2) = 1.532$ g cm^{-3}, $T = 153$ K, $\mu = 2.34$ cm^{-1}. The final *R* value is 0.054 for 3976 independent reflections and 1262 parameters. CCDC 637947. **2**$^{2+}$-Zn(OH$_2$)$_4$-(OTf$^-$)$_4$·4H$_2$O: $C_{42}H_{28}F_{12}N_4O_{20}S_4Zn$, *M* 1330.30, monoclinic *P*2$_1$/c, $a = 17.022(5)$, $b = 13.097(4)$, $c = 24.364(8)$ Å, $\beta = 91.158(3)°$, $V = 5430(3)$ Å^3, D_c $(Z = 4) = 1.627$ g cm^{-3}, $T = 153$ K, $\mu = 72.4$ cm^{-1}. The final *R* value is 0.134 for 9310 independent reflections and 748 parameters. CCDC 637948. **3**·C$_2$H$_5$OH: $C_{38}H_{28}N_4O$, M 556.67, monoclinic *C*2/c, $a = 16.841(4)$, $b = 12.939(3)$, $c = 14.308(4)$ Å, $\beta = 117.645(1)°$, $V = 2761.9(1)$ Å^3, D_c $(Z = 4) = 1.339$ g cm^{-3}, $T = 153$ K, $\mu = 0.82$ cm^{-1}. The final *R* value is 0.073 for 3033 independent reflections 193 parameters. CCDC 637949.
11. This molecule is C_i-symmetric in crystal, and non-bonded C···N distance is 2.62 Å and the dihedral angle between two benzene nuclei of the acridinium is 13.4°.
12. 9-Aryl-10-methylacridiniums are known as fluorophores, however, their quantum yields depend drastically on the aryl moiety (Ref. 13). For example, naphthelene-1,8-diylbis(10-methyl-9-acridinium) was shown to be non-fluorescent due to internal charge shift from the electron-donating naphthalene nucleus to the excited acridinium units (Ref. 14) Weaker fluorescence of **2**$^{2+}$ than the dihydrophenanthrene derivative (Ref. 4a) may be accounted for by donation of nitrogen lone pairs to the fluorophores.
13. (a) Huber, C.; Fähnrich, K.; Krause, C.; Werner, T. *J. Photochem. Photobio.* **1999**, *A128*, 111; (b) Jonker, S. A.; Ariese, F.; Verhoeven, J. W. *Recl. Trav. Chim. Pays-Bas* **1989**, *108*, 109.
14. Kawai, H.; Takeda, T.; Fujiwara, K.; Suzuki, T. *Tetrahedron Lett.* **2004**, *45*, 8289.
15. Oxidative demetallation of **1**-ZnI$_2$ complex in MeCN and successful isolation of **2**$^{2+}$-Zn^{2+}(OTf$^-$)$_4$ in chloroform might be considered as inconsistent. However, difference in Lewis acidity of M^{n+} and Lewis basicity of solvents may account for the observation.
16. The more positive value for the oxidation potential of **1**-ZnI$_2$ can be ascribed to the electron-withdrawing effects of metal-bound dihydrophenanthroline unit. Stepwise oxidation processes may be related with the electrostatic repulsion between the face-to-face overlapped acridinium units in **2**$^{2+}$**-**ZnI$_2$ generated just after two-electron oxidation of **1**-ZnI$_2$. Similar stepwise process were also observed during oxidation of some dynamic redox systems, where two cationic parts are forced to locate in proximity (Refs. 4e,f).