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A Bifunctional Metal Probe with Independent Signal Outputs and Regulable Detection Limits

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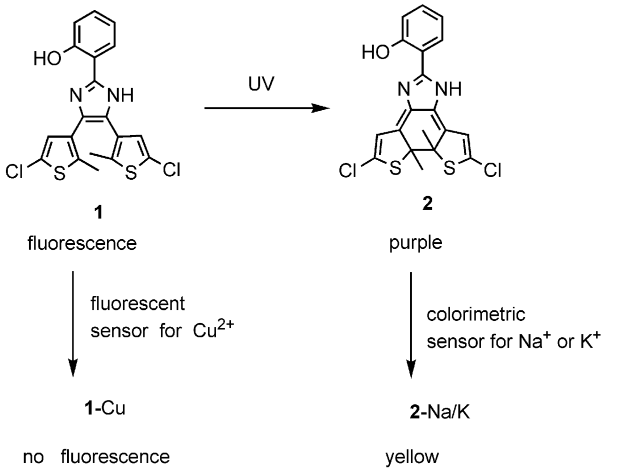
A bifunctional metal detection system with independent signal outputs and regulable detection limits was developed by using a photochromic diarylethene with an imidazole unit as the ligand. The sensor can be used for the detection of Cu^{2+} by fluorescence recognition and for the detection of Na^+ or K^+ by colorimetric recognition. Moreover, the amount of component of the probe can be modulated and manipulated by photomodulation, which results in changes in the upper detectable limits; this enlarges the window of detectable limits for metal ions.

Introduction

The design of metal sensors is of significant importance because sensors can provide in situ and real-time information for a number of applications including environment monitoring, industrial process control, metalloneurochemistry, and biomedical diagnostics.[1] A widely used protocol for metal sensors is to design a ligand that can selectively and sensitively recognize metal ions with a detectable signal output such as fluorescence[2,3] or colorimetry.[4] On the basis of this strategy, many successful sensors for transition-metal ions such as[5,6] Zn^{2+}, Hg^{2+}, Cu^{2+}, and alkali cation such as[7] Na^+, K^+, and Li^+ have been developed. Currently, modular systems that combine one or several receptors and reporter units are of particular interest,[8] as such a constitution not only allows tuning sensitivity and selectivity by choice of the functional subunits but also allows to independently quantify the respective guests.[9] Herein, we report a bifunctional metal sensor based on photochromic diarylethene **1**. With such a system, two recognition events with independent signals can be performed simultaneously by a simple phototrigger. The concept of a bifunctional metal sensor is outlined in Scheme 1.



Scheme 1. The concept of a bifunctional metal sensor.

Results and Discussion

Fluorescent Probe for Cu^{2+}

Both absorption and fluorescence of **1** in acetonitrile showed that the maximum absorption and emission of **1** were at $\lambda_{max} = 318$ nm ($\varepsilon = 3.0 \times 10^4$ L mol^{-1} cm^{-1}) and $\lambda_{max} = 445$ nm, respectively. Compound **1** showed strong fluorescence emission, and a fluorescence quantum yield of $\phi_f = 0.83$ (in CH_3CN) was obtained by using coumarin 307 ($\phi_f = 0.58$, in CH_3CN) as a reference.

Addition of Cu^{2+} (0.01 M in methanol) to a solution of **1** produced a decrease in intensity of the 318 nm band in the absorption spectra with a concomitant increase in a new one at 370 nm, which may be attributed to a complex formed between **1** and Cu^{2+} (Figure 1). Formation of a 1:1 complex was determined from the absorption spectra changes, and the binding constant ($K_b = 3.73 \times 10^4$) was estimated from the change in the spectral intensities.[10]

The investigation of fluorescence showed that the emission of **1** (25 μM) was quenched completely with the addition of Cu^{2+} (66 μM). As presented in Figure 1, the emission at 445 nm decreased significantly, and the fluorescence

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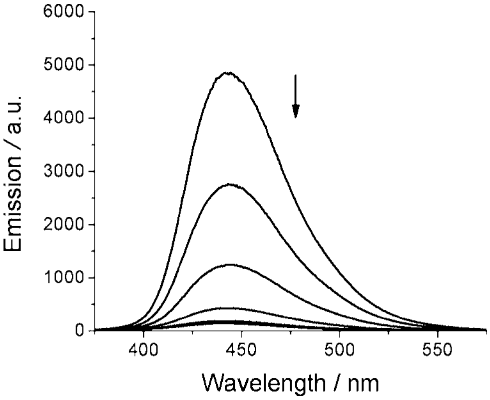


Figure 1. Fluorescence response of **1** (25 µM CH_3CN) to Cu^{2+}. Spectra shown are for [Cu^{2+}] of 0, 16, 33, 50, and 66 µM. λ_{ex} = 316 nm.

quantum yield decreased from 0.83 to 0.01 when the amount of Cu^{2+} was varied from 0 to 1.1 equivalents. The fluorescence quenching of **1** upon the addition of Cu^{2+} may result from ligand-to-metal charge transfer (LMCT), in which the electronic charge is transferred from the ligand towards the coordinating metal. A control experiment showed that the fluorescence of **1** was quenched slightly by methanol, and the addition of 66 µM methanol to a solution of **1** produced only a 5% decrease in fluorescence intensity. The initial integrated fluorescence response (F_i) over the final integrated emission (F_f) is represented in Figure 2.

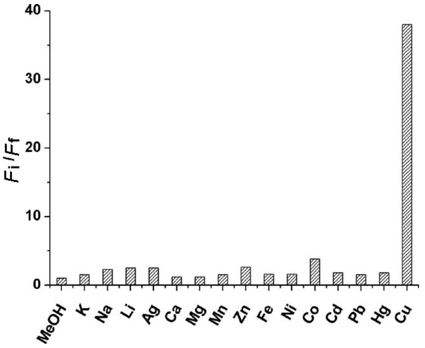
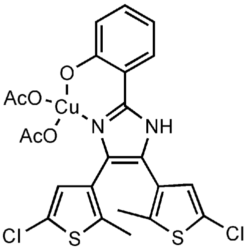


Figure 2. Fluorescence responses of **1** to various ions in CH_3CN. Bar represents the initial integrated fluorescence response (F_i) over the final integrated emission (F_f).

The selectivity of **1** was explored by monitoring the fluorescence emission of **1** with other metal ions (66 µM). As shown in Figure 2, a large decrease in the emission of **1** (F_i/F_f = 38) was obtained by binding with Cu^{2+}, but no, or a very small, decrease in emission ($F_i/F_f < 3$) was detected by binding with other metal ions (K^+, Na^+, Li^+, Ag^+, Ca^{2+}, Mg^{2+}, Mn^{2+}, Zn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cd^{2+}, Pb^{2+}, and Hg^{2+}) under the same conditions. Further investigation showed that no obvious interference was observed in fluorescence quenching when a competition experiment was conducted in which ligand **1** was exposed to a solution of Cu^{2+} in the presence of other metal ions. With 25 µM of **1**, the upper detectable limit for Cu^{2+} is 66 µM; in this case, more than 90% of the fluorescence of **1** was quenched.

Many fluorescent molecule sensors for metal ions are efficiently quenched by paramagnetic Cu^{2+} ions.[11] The quenching process is induced by coordination of Cu^{2+} either directly to the donor atoms of the chromophore or to the chelating groups covalently attached to the latter.[12] It is suggested therefore that the quenching process of ligand **1** is triggered by coordination of ligand **1** to Cu^{2+}, resulting from LMCT. Such a charge transfer is indicted by an absorption change from 318 to 370 nm when the ligand is transferred from free ligand **1** to complex **1**-Cu^{2+}. The binding site where Cu^{2+} coordinates to ligand **1** probably occurs at two donor sites: the OH group of phenol and the N atom of imidazole; the latter is more basic and therefore a better donor than the NH group of imidazole to coordinating complex (Scheme 2). To confirm the binding site, the complex was analyzed by ^1H NMR spectroscopy. By comparing the ^1H NMR spectrum of the complex with that of ligand **1**, it was found that all the signals arising from the aromatic protons shift downfield by 0.16–1.82 ppm, except for the proton in the thiophene ring, for which the chemical shift is less than 0.03 ppm when the ligand binds to Cu^{2+}.



Scheme 2. Fluorescence quenching of ligand **1** by coordination with Cu^{2+}.

Colorimetric Probe for Na^+ and K^+

Photocyclization of **1** is illustrated in Scheme 1. Upon irradiation with UV light, the absorption of **1** at 318 and 230 nm decreased and two new bands appeared at 545 and 340 nm (Figure 3), which corresponds to **2**. Accompanying photocyclization, the color of the solution changed from colorless to purple. The photocyclization of **1** to **2** was achieved only after 90 s of irradiation of **1** (25 µM, 30 W UV light) in acetonitrile, and the conversion was ca. 90%. Compound **2** showed no fluorescence. It is worth noting that both photocyclization and photoreversion were inhibited by the addition of Cu^{2+} and Na^+ or K^+, respectively. No new absorption or color change was observed when a colorless solution of **1** binding with Cu^{2+} was irradiated with UV light, and the yellow solution of **2** binding with Na^+ or K^+ could not be reverted back to a colorless solution of **1** with visible-light ($\lambda \geq 450$ nm) irradiation. This is probably due to the LMCT process leading to photoinduced electron transfer from the ligand to the metal ion, which resulted in the inhibition of the photocyclization process, and the lack of a spectral change upon irradiating complex **2**-Na with light ≥450 nm as being due to the poor absorption at these wavelengths.

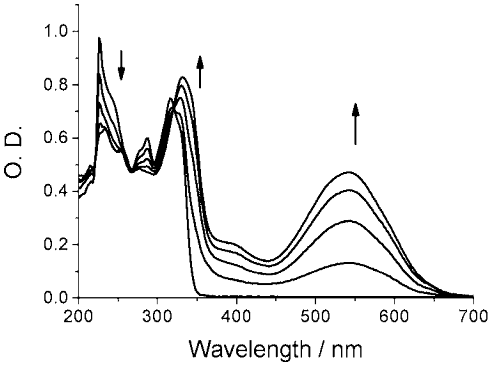


Figure 3. The absorption changes of **1** (25 μM in CH_3CN) with UV-light irradiation.

Addition of Na^+ (80 μM in methanol) to a solution of **2** produced a decrease in intensity of the 550 nm band in the absorption spectrum with a concomitant increase in a new band at 440 nm (Figure 4), which can be attributed to the formation of a complex between **2** and Na^+. This process is accompanied by a strong color change from purple to yellow, which is clearly visible to the naked eye. By comparison of the absorption of complex **2**-Na with that of **2**, it was found that the sensor exhibited an almost 110 nm hypsochromic shift in the absorption spectrum upon binding with Na^+. The hypsochromic shift process is probably induced by coordination of Na^+ directly to the donor atoms (N and O) of the imidazole unit, which reduced its ability to act as an electron donor and caused a shift in the absorption spectrum to a shorter wavelength. The formation of a 1:1 complex was determined from the absorption spectra changes, and the binding constant ($K_b = 5.8 \times 10^4$) was estimated from the change in the spectral intensities. Similar results were obtained when **2** formed a complex with K^+ (75 μM in methanol), and the binding constant was 6.5×10^4.

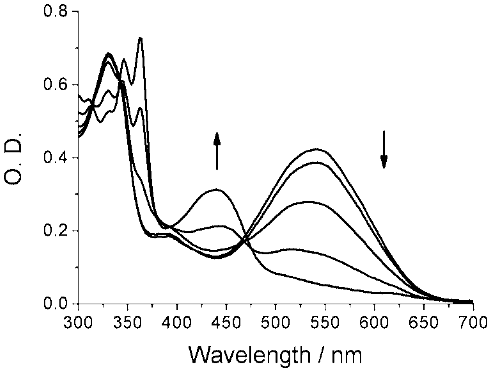


Figure 4. The absorption changes of **2** (ca. 22 μM in CH_3CN) binding with Na^+ (0, 20, 40, 60, 80 μM).

The selectivity of **2** was explored by monitoring the color change of **2** with other metal ions. It was found that no color change was observed when **2** bonded with Ca^{2+}, Mg^{2+}, Mn^{2+}, Fe^{2+}, Ba^{2+}, Li^+, Cd^{2+}, and Pb^{2+}, and no new absorption band was detected except for a slight decrease in absorption at 550 nm (Figure 5) under the same conditions. The color changed from purple to grey when **2** bonded with Zn^{2+}, Ni^{2+}, Hg^{2+}, Ag^+, Co^{2+}, and Cu^{2+}. Spectral investigation showed that the absorption at 550 nm disappeared and a new absorption was detected when **2** bonded with Zn^{2+}, Ni^{2+}, Hg^{2+}, Ag^+, Co^{2+}, and Cu^{2+} under the same conditions. As shown in Figure 6, the absorption of 550 nm experiences a redshift when **2** bond with Zn^{2+}, Ni^{2+}, Co^{2+}, and Cu^{2+} and the absorption disappeared when **2** bonded with Hg^{2+} and Ag^+. The absorption around 440 nm was detected only when **2** bonded with Na^+ and K^+. These results indicate that the selectivity of **2** for the Na^+ and K^+ probe is high. Further investigation showed that no obvious interference was observed with regard to color changes of the solution when a competition experiment was conducted in which **2** was exposed to a solution of Na^+ or K^+ in the presence of other metal ions.

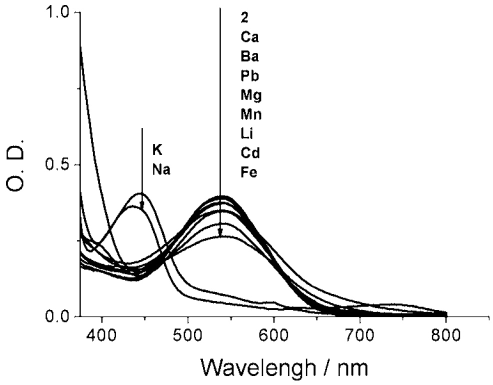


Figure 5. Absorption changes of **2** (ca. 22 μM in CH_3CN) binding with Ca^{2+}, Ba^{2+}, Pb^{2+}, Mg^{2+}, Mn^{2+}, Li^+, Cd^{2+}, Fe^{2+}, Na^+, and K^+ (80 μM).

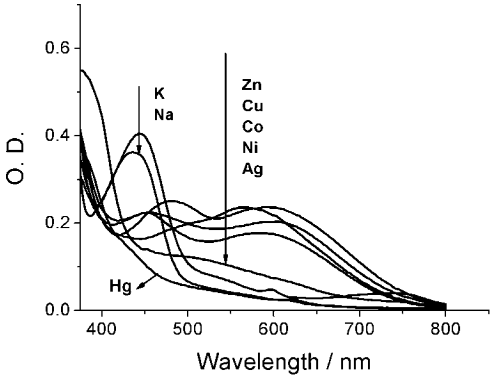


Figure 6. Absorption changes of **2** (ca. 22 μM in CH_3CN) binding with Zn^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, Ag^+, Hg^{2+}, Na^+, and K^+ (80 μM).

Bifunctional Metal Probe Performed Simultaneously

Two recognition events with independent signals was investigation. Upon irradiation of **1** (25 μM) with UV light for 40 s, the solution color changed from colorless to purple, and the fluorescence of **1** decreased by 60%. The mixture, containing ca. 40% of **1** (10 μM) and ca. 60% of **2** (15 μM), was employed as a bifunctional sensor system for the detection of both Cu^{2+} and Na^+ or K^+. It was found that 90% of the fluorescence of **1** (10 μM) was quenched, and the intensity of the absorption of complex **2**-Na at 440 nm did not increase when Cu^{2+} (30 μM) together with Na^+ (50 μM) or K^+ (46 μM) were added to the mixture. Further investigation found that the mixture employed as a bifunctional sensor system for the detection of both Cu^{2+} and Na^+ or K^+ could be modified and manipulated by controlling the irradiation time. Upon irradiation of **1** for 20 s (containing ca. 65% of **1** and ca. 35% of **2**) and 70 s (containing ca. 20% of **1** and ca. 80% of **2**), respectively, different upper detectable limits were found. With irradiation for 20 s, the upper detectable limits for Cu^{2+} and Na^+ were 50 and 30 μM, respectively, and with irradiation for 70 s, the upper detectable limits for Cu^{2+} and Na^+ were 20 and 60 μM, respectively. It is known[13] that alteration of the detection limits for species is related to alterations in selectivity of the sensor; in this paper, however, primary investigation showed that the selectivity of the sensor for both Cu^{2+} and Na^+ or K^+ does not significantly change the range of the upper detectable limits. The findings suggest that the detection limits for metal ions can be regulated by photomodulation.

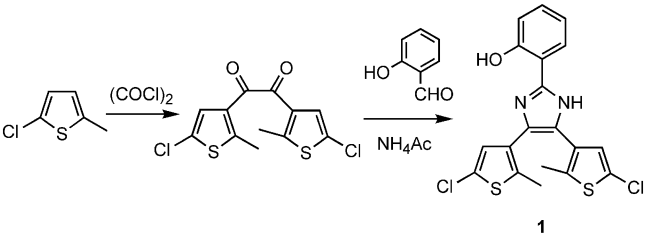
Conclusions

A bifunctional metal probe prepared by using a photochromic diarylethene as a modular system was developed. In such a system, both Cu^{2+} and Na^+ or K^+ can be detected independently by fluorescence and colorimety, respectively. By photomodulation, the composition of the sensor can be manipulated and detectable limits can thus be modulated easily. This provides a promising approach for the development of molecular sensors that exhibit multichannel detections and enlarges the window of detectable limits. Application of such an advanced sensor would be particularly interesting in the field of clinical or environmental science.

Experimental Section

General Information: ^1H NMR spectra were recorded at 400 MHz with TMS as an internal reference and [D$_6$]DMSO as solvent with a Bruker Avance 400 spectrometer. HRMS spectra were recorded with a GC-TOF MS spectrometer. UV absorption spectra and fluorescence spectra were measured with an absorption spectrophotometer (Hitachi U-3010) and a fluorescence spectrophotometer (F-2500), respectively. All chemicals for synthesis were purchased from commercial suppliers, and solvents were purified according to standard procedures. Reactions were monitored by TLC (silica gel, 60F-254). Column chromatography was performed on silica gel (Merck, 70–230 mesh). A low-pressure mercury lamp (30 W) and a xeon light (500 W), with different wavelength filters, were used as light sources for photocoloration and photobleaching, respectively.

Synthesis of Diarylethene 1: Target compound **1** was prepared according to the synthetic route presented in Scheme 3. Diketone was obtained starting from commercially available 2-methylthiophene, which was chlorinated at the 5-position with NCS in AcOH,[14] followed by acylation with oxalyl chloride in DCM. Treatment of the diketone with salicylaldehyde in the presence of NH_4Ac afforded target compound **1** in a yield of 70%. The details of the procedure are as follows: To a solution of diketone (100 mg, 0.31 mmol) in acetic acid (10 mL) was added substituted salicylaldehyde (0.37 mmol) and NH_4Ac (143 mg, 1.86 mmol), and the mixture was heated at reflux until the starting material disappeared (TLC detection). The mixture solution was then slowly poured into $NaHCO_3$ solution (10%, 50 mL), and the product was extracted with $CHCl_3$ (3 × 20 mL). The combined organic phase was washed with water and dried with $MgSO_4$. After evaporation of the solvent, the crude product was purified by flash column chromatography (petroleum ether/ethyl acetate, 20:1) to afford target compound **1** (92 mg, 70%). ^1H NMR ([D$_6$]DMSO): δ = 13.06 (s, 1 H), 12.66 (s, 1 H), 7.94 (d, J = 7.7 Hz, 1 H), 7.27 (t, J_1 = 7.2 Hz, J_2 = 7.1 Hz, 1 H), 7.17 (s, 1 H), 6.97–6.92 (m, 2 H), 6.83 (s, 1 H), 2.21 (s, 3 H), 2.04 (s, 3 H) ppm. HRMS (GC-TOF): calcd. for $C_{19}H_{14}Cl_2N_2OS_2$ 420.0016; found 420.0016. $C_{19}H_{14}Cl_2N_2OS_2$ (420): calcd. C 54.16, H 3.35; found C 54.32, H 3.29.



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Scheme 3. Synthesis of photochromic diarylethene **1**.

Source of Metal Ions and Preparation of Metal Ions in Methanol: All metal ions for binding experiments used acetate salts as sources except for Fe^{2+}, Li^+, and Ag^+. Both Fe^{2+} and Li^+ used $Fe(ClO_4)_2$ and $LiClO_4$ as sources, and Ag^+ used $AgNO_3$ as a source. Metal ions in methanol were obtained by dissolution of the metal salts (0.1 mmol) in methanol (10 mL). Metal ions in methanol were added to the ligand solution by syringe.

Acknowledgments

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[1] a) M. H. Lim, S. J. Lippard, *Acc. Chem. Res.* **2007**, *40*, 41–51; b) P. Jiang, Z. Guo, *Coord. Chem. Rev.* **2004**, *248*, 205–221; c) A. W. Czarnik, *Fluorescent Chemosensors for Ion and Molecule Recognition*, ACS Symposium Series 538, American Chemical Society, Washington, DC, **1993**. pp. 130–146.

[2] a) S. Fakih, M. Podinovskaia, X. Kong, X. H. L. Collins, U. E. Schaible, R. C. Hider, *J. Med. Chem.* **2008**, *51*, 4539–4552; b) M. A. Palacios, V. Z. Wang, V. A. Montes, G. V. Zyryanov, P. Anzenbacher, *J. Am. Chem. Soc.* **2008**, *130*, 10307–10314; c) S. Nath, U. Maitra, *Org. Lett.* **2006**, *8*, 3239–3242; d) F. Song, A. L. Garner, K. Koide, *J. Am. Chem. Soc.* **2007**, *129*, 12354–12355; e) M. Wang, D. Zhang, G. Zhang, Y. Tang, S. Wang, D. Zhu, *Anal. Chem.* **2008**, *80*, 6443–6448; f) L. Liu, D. Zhang, G. Zhang, J. Xiang, D. Zhu, *Org. Lett.* **2008**, *10*, 2271–2274; g) H. Lu, W. Xu, D. Zhang, C. Chen, D. Zhu, *Org. Lett.* **2005**, *7*, 4629–4632.

[3] a) Z. Wang, D. Zhang, D. Zhu, *J. Org. Chem.* **2005**, *70*, 5729–5732; b) I. Stoll, J. Eberhard, R. Brodbeck, W. Eisfeld, J. Mattay, *Chem. Eur. J.* **2008**, *14*, 1155–1163; c) M. Burnworth, S. J. Rowan, C. Weder, *Chem. Eur. J.* **2007**, *13*, 7828–7836; d) P.

Pallavicini, Y. A. Diaz-Fernandez, F. Foti, C. Mangano, S. Patroni, *Chem. Eur. J.* **2007**, *13*, 178–187; e) J. Wang, X. Qian, J. Qian, Y. Xu, *Chem. Eur. J.* **2007**, *13*, 7543–7552; f) P. Bosch, F. Catalina, T. Corrales, C. Peinado, *Chem. Eur. J.* **2005**, *11*, 4314–4325.

[4] a) Q. Chu, D. A. Medvetz, Y. Pang, *Chem. Mater.* **2007**, *19*, 6421–6429; b) J. Loe, Z. Wang, J. Liu, Y. Lu, *J. Am. Chem. Soc.* **2008**, *130*, 14217–14226; c) X. Peng, Y. Wu, J. Fan, M. Tian, K. Han, *J. Org. Chem.* **2005**, *70*, 10524–10531; d) C. Zhang, K. S. Suslick, *J. Am. Chem. Soc.* **2005**, *127*, 11548–11549; e) G. Qing, T. Sun, Z. Chen, X. Yang, X. Wu, Y. He, *Chirality* **2009**, *21*, 363–373.

[5] a) E. M. M. W. M. van Dongen, L. M. Dekkers, K. Spijker, E. W. Meijer, L. W. J. Klomp, M. Merkx, *J. Am. Chem. Soc.* **2006**, *128*, 10754–10762; b) Y. Zhang, X. Guo, W. Si, L. Jia, X. Qian, *Org. Lett.* **2008**, *10*, 473–476; c) Y. Chen, D. X. Zeng, *ChemPhysChem* **2004**, *5*, 564–566; d) Y. Zhao, Z. Lin, C. He, H. Wu, C. Duan, *Inorg. Chem.* **2006**, *45*, 10013–10015; e) J. Wang, X. Qian, *Org. Lett.* **2006**, *8*, 3721–3724; f) S. V. Wegner, A. Okesli, P. Chem, C. He, *J. Am. Chem. Soc.* **2007**, *129*, 3474–3475.

[6] a) X. Chen, S. Nam, M. Jung Jon, Y. Kim, S. Kim, S. Park, J. Yoon, *Org. Lett.* **2008**, *10*, 5235–5238; b) J. Liu, Y. Lu, *J. Am. Chem. Soc.* **2007**, *129*, 9838–9839; c) F. Lu, L. Gao, L. Ding, L. Jiang, Y. Fang, *Langmuir* **2006**, *22*, 841–845; d) L. Zeng, E. W. Miller, A. Pralle, E. Y. Isacoff, C. J. Chang, *J. Am. Chem. Soc.* **2006**, *128*, 10–11; e) J.-S. Wu, W.-M. Liu, X.-Q. Zhuang, F. Wang, P.-F. Wang, S.-L. Tao, X.-H. Zhang, S.-K. Wu, S.-T. Lee, *Org. Lett.* **2007**, *9*, 33–36.

[7] a) S. Nath, U. Maitra, *Org. Lett.* **2006**, *8*, 3239–3242; b) B. Witulski, M. Weber, U. Bergstrasser, J.-P. Desvergne, D. M. Bassani, H. Bouas-Laurent, *Org. Lett.* **2001**, *3*, 1467–1470; c) T. Gunnlaugsson, M. Nieuwenhuyzen, L. Richard, V. Thoss, *Tetrahedron Lett.* **2001**, *42*, 4725–4728; d) H. He, M. A. Mortellaro, M. J. P. Leiner, R. J. Fraatz, J. K. Tusa, *J. Am. Chem. Soc.* **2003**, *125*, 1468–1469.

[8] a) P. D. Beer, *Chem. Soc. Rev.* **1989**, *18*, 409–450; b) Y. Q. Li, J. L. Bricks, U. Resch-Genger, M. Spieles, W. Rettig, *J. Phys. Chem. A* **2006**, *110*, 10972–10984; c) A. S. Batsanov, D. Herault, J. A. K. Howard, L. G. F. Patrick, M. R. Probert, A. Whiting, *Organometallics* **2007**, *26*, 2414–2419.

[9] a) K. Rurack, A. Koval′chuck, J. L. Bricks, J. L. Slominshii, *J. Am. Chem. Soc.* **2001**, *123*, 6205–6206; b) A. P. de Silva, N. D. McClenaghan, *J. Am. Chem. Soc.* **2000**, *122*, 3965–3966; c) G. McSkimming, J. H. R. Tucker, H. Bouas-Laurent, J.-P. Desvergne, *Angew. Chem. Int. Ed.* **2000**, *39*, 2167–2169.

[10] J. R. Long, R. S. Drago, *J. Chem. Educ.* **1982**, *59*, 1037–1039.

[11] a) O. Oter, K. Ertekin, C. Kirilmis, M. Koea, *Anal. Chim. Acta* **2007**, *584*, 308–314; b) S. H. Kim, J. S. Kim, S. M. Park, S.-K. Chang, *Org. Lett.* **2006**, *8*, 371–374; c) B. R. White, J. A. Holcombe, *Talanta* **2007**, *71*, 2015–2020.

[12] a) Z.-C. Wen, R. Yang, H. He, Y. B. Jiang, *Chem. Commun.* **2006**, 106–108; b) R. Martinez, F. Zapata, A. Caballero, A. Espinosa, A. Tarraga, P. Molina, *Org. Lett.* **2006**, *8*, 3225–3238; c) P. Comba, R. Kraoner, A. M. Okhir, K. Naing, E. Schatz, *Eur. J. Inorg. Chem.* **2006**, 4442–4448.

[13] S. Shinkai, H. Kinda, O. Manabe, *J. Am. Chem. Soc.* **1982**, *104*, 2933–2934.

[14] Y. Chen, D. X. Zeng, M. Fan, *Org. Lett.* **2003**, *5*, 1435–1437.

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