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A turn-on fluorescent chemosensor based on acylhydrazone for sensing of Mg^{2+} with a low detection limit†

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A novel highly selective chemosensor for Mg^{2+} ions based on the naphthalene group as the fluorophore has been designed and synthesized, which shows a fluorescence turn-on response from colorless to green for Mg^{2+} ions in DMSO–H_2O solutions. **L** could perform as an "OFF–ON" molecular switch, which was cyclically controlled by Mg^{2+} and EDTA. Moreover, further study demonstrated that the detection limit for the fluorescence response of **L** to Mg^{2+} was down to 9.2×10^{-10} M, which was lower than with other sensors for Mg^{2+}. Test strips based on **L** were also fabricated, which could act as a convenient and efficient Mg^{2+} test kit. The sensor **L** could detect Mg^{2+} in two different sources of water, distilled and tap water.

Introduction

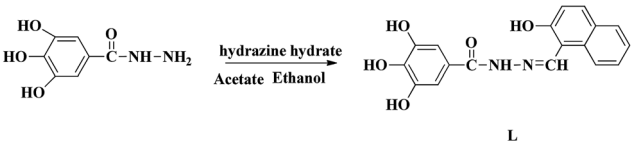
The magnesium ion (Mg^{2+}) plays vital roles in biological systems.[1–3] For plants, magnesium is one of the ingredients for forming chlorophyll and is involved with forming phosphate compounds and phosphate metabolism.[4,5] In the cells of the human body, Mg^{2+} is one of the most abundant cations, and participates in numerous basic biochemical reactions. Magnesium also plays a crucial role in skeletal development and bone remodeling.[6,7] Magnesium ion can influence nervous impulses and tension development in muscle, and modulates, amongst others, ion transport in nerves and mitochondria.[8–10] If the concentrations of magnesium in the cytosol and subcellular regions are abnormal, there is a possibility of the occurrence of a disease, such as diabetes, hypertension, epilepsy and Alzheimer's disease.[11–13] In particular, detection of Mg^{2+} has been of considerable interest and a great amount of effort has been devoted to the design and synthesis of sensitive and selective sensors for Mg^{2+} ion.

Nonetheless, reports about fluorescent sensors for Mg^{2+} are still few compared with those on other important ions, such as Zn^{2+}, Al^{3+}, Hg^{2+} and CN^-.[14–27] Even so, some methodologies for detecting Mg^{2+} are often interfered with by Zn^{2+} and Ca^{2+}. To date, as far as we know, β-diketone, crown ether derivatives, and nanoparticles have been employed for selective detection of Mg^{2+} ions.[28–30] It is worth mentioning that their synthetic processes are intricate. Hence, there is interest in designing a highly selective, sensitive and simple chemosensor that recognizes Mg^{2+} without the interference of other metal ions.[31,32]

Our research group has a longstanding interest in molecular recognition.[33–38] We have successfully developed a simple and efficient optical fluorescent acylhydrazone chemosensor **L** that can detect Mg^{2+} in DMSO–H_2O solution. To the best of our knowledge, acylhydrazone is easy and inexpensive to prepare. The naphthalene group acts as the fluorophore, while the hydroxyl and imine groups in the sensor molecule **L** enhance the coordination capacity. As a result, the addition of Mg^{2+} inhibits the ESIPT process and increases its structural rigidity, which leads to a strong green emission. The mechanism of this process was verified by spectroscopic methods, including ^1H NMR, DFT and mass spectrometry. The fluorescent detection limit of the sensor for Mg^{2+} was 9.2×10^{-10} M, while the corresponding detection limit by the naked eye was determined to be 5.0×10^{-8} M under a UV lamp at 365 nm.

Results and discussion

The molecule **L** was conveniently synthesized *via* the condensation of 3,4,5-trihydroxybenzhydrazide and 2-hydroxy-1-napthaldehyde. The recognition abilities of **L** were investigated by adding perchlorate salts (Fe^{3+}, Hg^{2+}, Ag^+, Ca^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, Cd^{2+}, Pb^{2+}, Zn^{2+}, Cr^{3+} and Mg^{2+}) into DMSO–H_2O solutions (Scheme 1).



L

Scheme 1 Synthesis of receptor **L**.

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Receptor **L** was found to have limited solubility in water, and this compelled us to use this sensor in mixed solvents. The fluorescence emission was examined upon adding various metal ions: Fe^{3+}, Hg^{2+}, Ag^{+}, Ca^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, Cd^{2+}, Pb^{2+}, Zn^{2+}, Cr^{3+} and Mg^{2+} ions in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5). Only compound **L** displayed a weak, single fluorescence emission band at 480 nm when excited at 378 nm in DMSO–H_2O media. Changes in the spectral pattern were observed only with the addition of 20 equivalents of Mg^{2+}, when sensor **L** produced a strong fluorescence band at 480 nm and responded with a dramatic color change, from colorless to green. However, upon addition of other metal ions no significant changes in color were observed (Fig. 1). In addition, the fluorescence emission was also examined upon adding $MnCl_2$ and $CaCl_2$ (Fig S3†). The addition of Mn^{2+} caused no significant spectral change. The absorption spectra of **L** in the presence of other ions were also tested. The results suggested that sensor **L** could display an excellent selectivity for Mg^{2+} over all other ions tested (Fig S4†).

It was well known that fluorescent probes for Mg^{2+} might encounter interference from other cations, particularly Zn^{2+} and Cd^{2+}. Thus, competitive behavior was tested to further elucidate whether the coexistence of competing metal cations interfered with the detection of Mg^{2+}. In the solutions of sensor **L** with Mg^{2+}, when solutions of **L** were added to solutions of other competing cations, it was clear that the receptor **L** was highly selective for the detection of Mg^{2+} in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) (Fig. 2).

As shown in Fig. 3, the fluorescence titration of Mg^{2+} was performed using a 20 μM solution of **L** in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5). With the addition of Mg^{2+} (0.2 M), a gradual increase in the fluorescence intensity of chemosensor **L** at 480 nm was observed as the Mg^{2+} volume increased from 0 to 1.7 equivalents. The solution containing Mg^{2+} also showed a change in fluorescence color from colorless to grass green.

The detection limit is one of the most important parameters in ion sensing. For various practical purposes, it is very important to detect analytes at low concentrations. The naked eye detection limit for Mg^{2+} was determined to be 5.0×10^{-8} M, through use of a UV lamp at 365 nm (Fig. 4). The detection limit for fluorescent spectrum changes was 9.2×10^{-10} M for Mg^{2+}, as calculated on the basis of $3\delta/S$ (where δ is the standard deviation of the blank solution and S is the slope of the

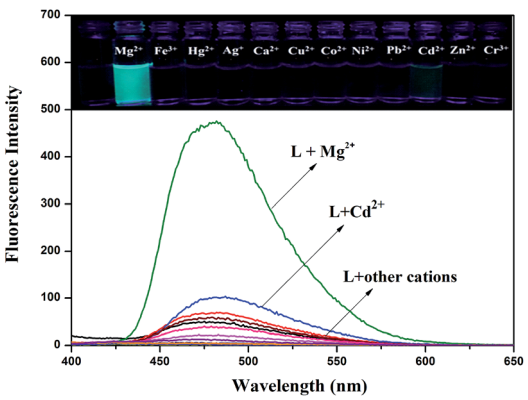


Fig. 1 Fluorescence spectra response of **L** (2.0×10^{-5} M) in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) upon addition of Mg^{2+}. Inset: photograph in the presence of various cations under UV-lamp (365 nm).

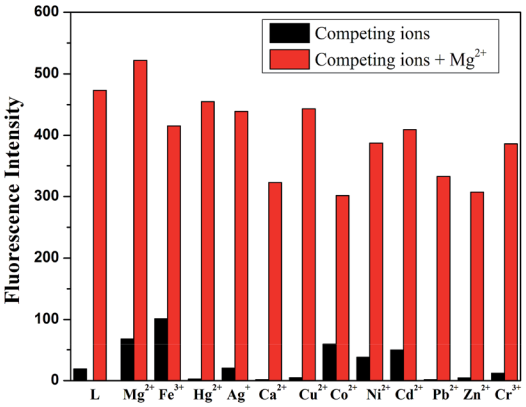


Fig. 2 Fluorescence spectra response of **L** (2.0×10^{-5} M) in the presence of various cations in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) in response to Mg^{2+}.

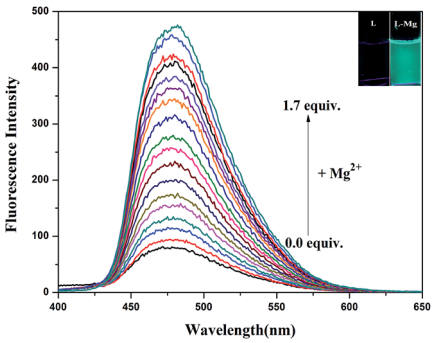


Fig. 3 Fluorescence titration spectra of **L** (2.0×10^{-5} M) in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) upon adding of an increasing concentration of Mg^{2+} (λ_{ex} = 378 nm). Inset: photograph of **L** upon adding of Mg^{2+} under UV-lamp (365 nm).

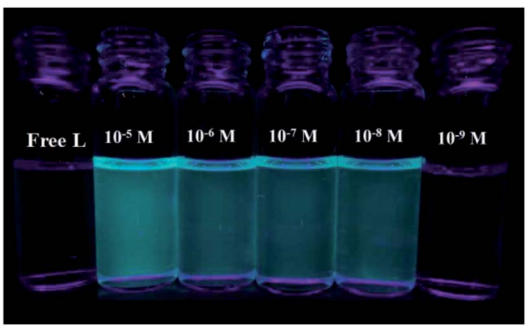


Fig. 4 Naked-eye detection limit under UV light at 365 nm. From left to right the concentration of Mg^{2+}: 10^{-5} M, 5×10^{-6} M, 5×10^{-7} M, 5×10^{-8} M, 5×10^{-9} M.

calibration curve), which indicates the high detection sensitivity (Fig. 5). The result of the analysis is as follows: linear calibration equation: $I = 1.30432C + 53.84714$, $R^2 = 0.997$.

We also made comparisons with other reported magnesium selective sensors, and the detection limit of **L** was much lower.[29–31] Some did not explain the detection limits. This indicated that probe **L** could be used to quantitatively detect Mg^{2+} at extremely low concentrations and in a relatively wide range (Table 1).

The pH dependence of the probe **L** system in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) was also checked by fluorescence emission spectroscopy. Mg^{2+} ion was added to buffered solutions of **L** at different pH values (1–12). The probe **L** was insensitive to H^+ and OH^-. However, the results with the **L**–Mg^{2+} system in DMSO–H_2O media indicated that the reaction of **L** (2.0×10^{-5} M) with Mg^{2+} only occurred effectively in the pH range between 8 and 11, where the fluorescence intensity at 480 nm was enhanced more significantly, which indicated that the sensor **L** and Mg^{2+} ions and formed a magnesium complex in weak alkaline solutions (Fig. S5†).

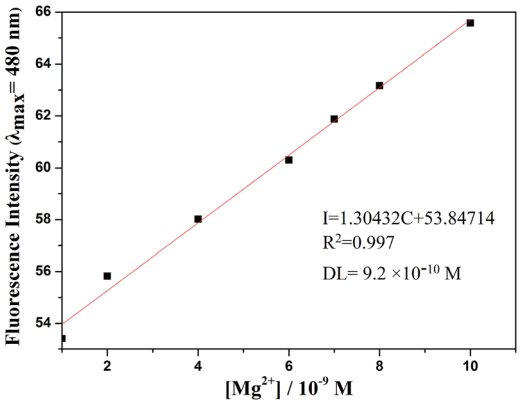
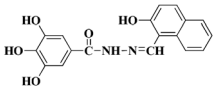
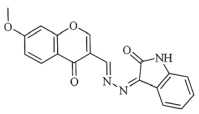
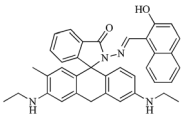
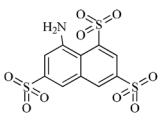


Fig. 5 Fluorescence detection limit spectra of **L** (2.0×10^{-5} M) in DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) solution upon adding of a concentration of Mg^{2+}.

Table 1 Comparison of detection limits

Journal	Structures	Detection limits (fluorometric)	Solvent
This work		9.2×10^{-10} M	DMSO/H_2O (7 : 3, v/v)
39		5.16×10^{-7} M	Ethanol
40		1.44×10^{-6} M	Acetonitrile
41		2.37×10^{-8} M	Deionized water

According to ^{1}H NMR spectra (Fig. 6), the addition of Mg^{2+} made the two proton signals of –OH and –NH at 12.96 (s, 1H) and 11.92 (s, 1H) ppm gradually disappear. Due to coordination of the O atom of the carbonyl group in **L**, the signal of the two hydroxyl atoms at 9.29 (s, 2H) ppm in the benzene ring showed a significant downfield shift. To further investigate the interaction between the sensor **L** and Mg^{2+}, IR spectra were collected, and the stretching vibration peak of (–C=O) in **L** at 1605 cm^{-1} shifted to 1619 cm^{-1} when **L** interacted with Mg^{2+} (Fig. S6†). These phenomena indicate that in **L**–Mg^{2+}, the Mg^{2+} coordinated with the oxygen atoms on the acylhydrazone group.

An obtained mass spectrum confirmed that the sensor **L** ion peak was detected at *m*/*z* 339.08, which corresponded to $[L + H]^+$, and the magnesium complex ion peak appeared at *m*/*z* 439.09, which indicated that after deprotonation, probe **L** reacted with Mg^{2+} and one DMSO to form a stable complex $[L - 2H^+ + Mg^{2+} + 1DMSO + 1H^+]^+$ (Fig. S7†). A job plot analysis showed a 1 : 1 stoichiometry for the **L**–Mg^{2+} complex (Fig. 7). Based on the data in the job plot, ^{1}H NMR spectra and IR spectra, a stable complex between **L** and Mg^{2+} was proposed.

The sensing mechanism was estimated based on the above experiments. In solution, **L** exhibited weak fluorescence owing to ESIPT. The addition of Mg^{2+} broke the intramolecular

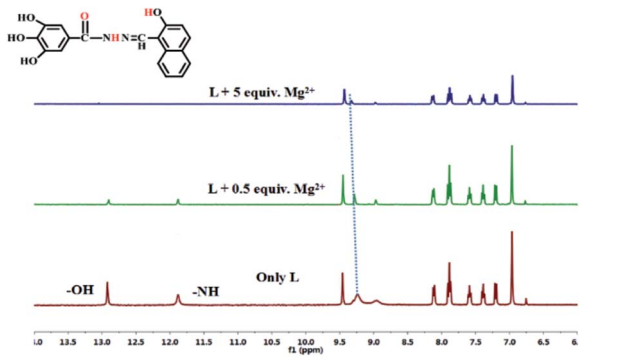


Fig. 6 ^{1}H NMR spectra of free **L** and in the presence of Mg^{2+}.

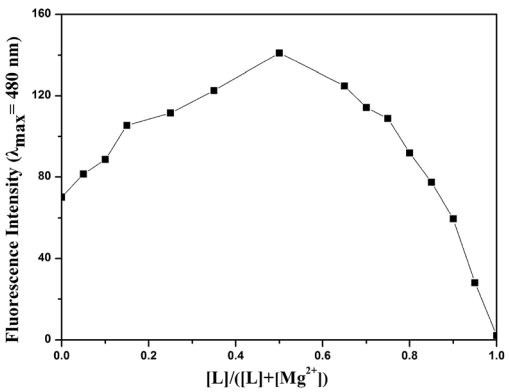


Fig. 7 Job plot of **L** with Mg^{2+}.

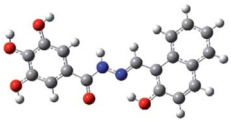
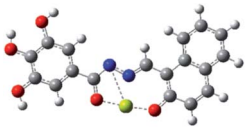
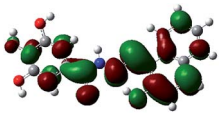
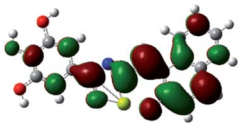
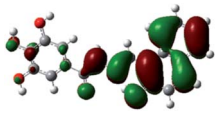
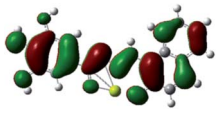
hydrogen bond and deprotonated the secondary amine. Hence, excited state intramolecular proton transfer was inhibited. The sensor **L** showed strong green fluorescence (Scheme 2).

In order to investigate the reversibility of the sensor **L**, the addition of Mg^{2+} to a solution of sensor **L** that had no fluorescence showed increasing fluorescence (That was "ON"). After adding of EDTA to the solution of **L**–Mg^{2+} complex, there was no fluorescence (That was "OFF"). In fact, this "OFF–ON–OFF" switching process could be repeated several times with little fluorescent efficiency loss (Fig. 8).

To further confirm the proposed mechanism of sensor **L** with Mg^{2+}, we performed DFT calculations at the B3LYP/6-311g (2d, p) level of theory. The highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of **L** and the **L** + Mg^{2+} complex were investigated and are shown in Table 2. The HOMO–LUMO energy band gap of **L** + Mg^{2+} complex was 0.12157 au, which was lower than that of **L** (0.13522 au).

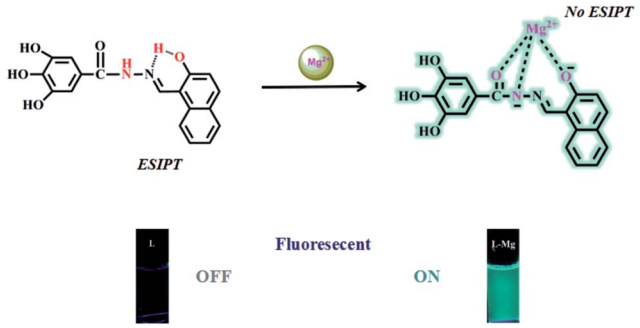
To investigate the practical application of chemosensor **L**, test strips were prepared by immersing filter papers into a DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) solution of **L** (0.1 M) and then drying in air. The test strips containing **L** were utilized to sense Mg^{2+} and other metal ions. As shown in Fig. 9, when the test strips were added to solutions of Mg^{2+} and the other ions, a significant color change was observed only with

Table 2 Density functional theory results for L and L + Mg^{2+} [a]

	L	L + Mg^{2+}
Optimized structure		
Diagrams of LUMOs		
Diagrams of HOMOs		
Energy gaps	0.13522 au	0.12157 au

[a] Blue ball is nitrogen, grey ball is carbon, red ball is oxygen, yellow ball is magnesium, and white ball is hydrogen.

Mg^{2+} solution under a 365 nm UV lamp. Moreover, potentially competitive ions exerted no influence on the detection of Mg^{2+} by the test strips. Therefore, the test strips based on **L** could quickly and conveniently detect Mg^{2+} in solutions. The practical



Scheme 2 A possible sensing mechanism of the sensor L with Mg^{2+}.

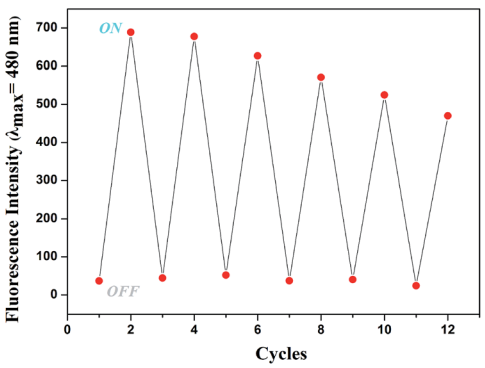


Fig. 8 Fluorescence experiment showing the reversibility and reusability of the L for sensing Mg^{2+}. Emission intensity changes at 480 nm for L upon addition of 10 equiv. Mg^{2+} before and after addition of 10 equiv. EDTA.

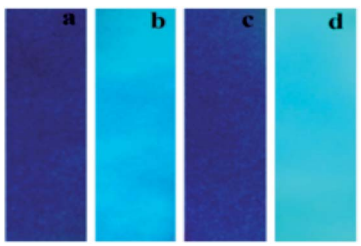


Fig. 9 Photographs of L on test strips (a) only L, (b) after immersion into solutions with Mg^{2+}, (c) after immersion into DMSO solutions with other cations, (d) after immersion into solutions with Mg^{2+} and other cations under irradiation at 365 nm.

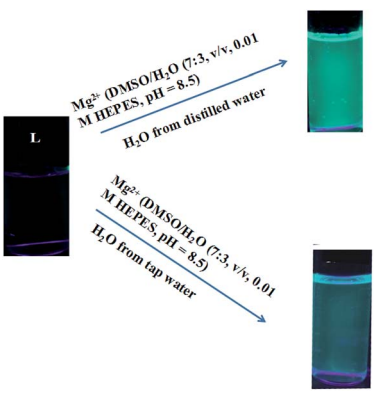


Fig. 10 Images of Mg^{2+} induced turn-on fluorescence in different sources of water.

application of sensor **L** for selective sensing of Mg^{2+} in two different sources of water, distilled and tap water, has also been demonstrated. The results showed that sensor **L** was a sensitive sensor and could be applied in environmental analysis (Fig. 10).

Conclusions

In summary, we have developed a sensor that can detect Mg^{2+} ions in a weakly alkaline medium of DMSO/H_2O (7 : 3, v/v, 0.01 M HEPES, pH = 8.5) with high selectivity and special sensitivity. Moreover, the fluorescence detection limit was low 9.2×10^{-10} M for Mg^{2+}. In addition, **L** could be used as a novel NOR logic gate triggered by Mg^{2+} and EDTA. Test strips based on **L** were also fabricated, which could serve as a practical fluorescent sensor to detect Mg^{2+} in field measurements or in test kits. Thus, the probe could have potential applications in both environmental and biological systems for the monitoring of magnesium.

Acknowledgements

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Notes and references

1 G. Men, C. Chen, S. Zhang, C. Liang, Y. Wang, M. Deng, H. Shang, B. Yang and S. Jiang, *Dolton Trans.*, 2015, **44**, 2755.
2 T. Dudev, K. Mazmanian and C. Lim, *Phys. Chem. Chem. Phys.*, 2016, **18**, 16986.
3 H. S. Yin, B. C. Li, Y. L. Zhou, H. Y. Wang, M. H. Wang and S. Y. Ai, *Biosens. Bioelectron.*, 2017, **96**, 106.
4 B. O'Rourke, P. H. Backx and E. Marban, *Science*, 1992, **257**, 245.
5 J. Smith, *J. Am. Chem. Soc.*, 1927, **69**, 1492.
6 L. Wang, W. Qin, X. Tang, W. Dou and W. Liu, *J. Phys. Chem. A*, 2011, **115**, 1609.
7 H. O. Trowbridge and J. L. Seltzer, *J. Periodontal Res.*, 1967, **2**, 147.
8 H. C. Politi and R. R. Preston, *Neuroreport*, 2003, **14**, 659.
9 Y. Ma, H. Liu, S. Liu and R. Yang, *Analyst*, 2012, **137**, 2313.
10 C. Berti, V. Zsolnay, T. R. Shannon, M. Fill and D. Gillespie, *J. Mol. Cell. Cardiol.*, 2017, **103**, 31.
11 J. Orrego-Hernández, N. Nunez-Dallos and J. Portilla, *Talanta*, 2016, **152**, 432–437.
12 L. Y. Shen, Y. H. Zhao, L. Mu, X. Zeng, R. Carl and G. Wei, *Sens. Actuators, B*, 2016, **226**, 279.
13 M. Jamshidi, O. Rezaei, A. R. Belverdi, S. Malekian and A. R. Belverdi, *J. Mol. Struct.*, 2016, **1123**, 111.
14 D. Ray and P. K. Bharadwaj, *Inorg. Chem.*, 2008, **47**, 2252.
15 C. Y. Lu, Y. W. Liu, P. J. Huang, C. F. Wan and A. T. Wu, *Analyst*, 2013, **138**, 2527.
16 S. Devaraj, Y. Tsui, C. Chiang and Y. Yen, *Spectrochim. Acta, Part A*, 2012, **96**, 594.
17 R. Alam, T. Mistri, A. Katarkar, K. Chaudhuri, S. K. Mandal, A. R. K. Bukhsh, K. K. Das and M. Ali, *Analyst*, 2014, **139**, 4022.
18 V. K. Gupta, A. K. Singh and L. K. Kumawat, *Sens. Actuators, B*, 2014, **204**, 507.
19 D. Sarkar, A. K. Pramanik and T. K. Mondal, *J. Lumin.*, 2014, **146**, 480.
20 B. B. Shi, P. Zhang, T. Wei, H. Yao, Q. Lin and Y. Zhang, *Chem. Commun.*, 2013, **49**, 7812.
21 S. Wang, X. Fei, J. Guo, Q. Yang, Y. Li and Y. Song, *Talanta*, 2016, **148**, 229.
22 Y. Sun, J. H. Hu, J. Qi and J. B. Li, *Spectrochim. Acta, Part A*, 2016, **167**, 101.
23 D. S. Kopchuk, A. M. Prokhorov, P. A. Slepukhin and D. N. Kozhevnikov, *Tetrahedron Lett.*, 2012, **53**, 6265.
24 Q. Lin, Y. P. Fu, P. Chen, T. B. Wei and Y. M. Zhang, *Dyes Pigm.*, 2013, **96**, 1.
25 (*a*) J. Liu, Q. Lin, Y. M. Zhang and T. B. Wei, *Sens. Actuators, B*, 2014, **196**, 619; (*b*) G. Chen, Z. Guo, G. Zeng and L. Tang, *Analyst*, 2015, **140**, 5400.
26 J. H. Hu, J. Qi, Y. Sun and P. X. Pei, *Phosphorus, Sulfur Silicon Relat. Elem.*, 2017, **192**, 565.
27 P. Zhang, B. B. Shi, X. M. You, Y. M. Zhang, Q. Lin, H. Yao and T. B. Wei, *Tetrahedron*, 2014, **70**, 1889.
28 H. M. Kim, P. R. Yang, M. S. Seo, J. S. Yi, J. H. Hong, S. J. Jeon, Y. G. Ko, K. J. Lee and B. R. Cho, *J. Org. Chem.*, 2007, **72**, 2088.
29 Y. Liu, M. Han, H. Zhang, L. Yang and W. Jiang, *Org. Lett.*, 2008, **10**, 2973.
30 E. J. Park, M. Brasuel, C. Behrend and M. A. Philbert, *Anal. Chem.*, 2003, **75**, 3784.
31 P. S. Hariharan and S. P. Anthony, *RSC Adv.*, 2014, **4**, 41565.
32 H. Sharma, N. Kaur, A. Singh, A. Kuwar and N. Singh, *J. Mater. Chem. C*, 2016, **4**, 5154.
33 J. H. Hu, J. B. Li, J. Qi and Y. Sun, *Sens. Actuators, B*, 2015, **208**, 581.
34 J. H. Hu, J. B. Li, J. Qi and Y. Sun, *New J. Chem.*, 2015, **36**, 4041.
35 J. B. Li, J. H. Hu, J. J. Chen and J. Qi, *Spectrochim. Acta, Part A*, 2014, **133**, 773.
36 J. H. Hu, N. P. Yan and J. J. Chen, *J. Chem. Res.*, 2012, **36**, 619.
37 J. H. Hu, N. P. Yan, J. J. Chen and J. B. Li, *Chem. Res. Chin. Univ.*, 2013, **34**, 1368.
38 J. Qi, J. H. Hu, Y. Sun and J. B. Li, *Curr. Anal. Chem.*, 2016, **12**, 119.
39 G. Wang, J. Qin, L. Fan, C. Li and Z. Yang, *J. Photochem. Photobiol., A*, 2016, **314**, 29.
40 J. Qin, Z. Yang and G. Wang, *Inorg. Chim. Acta*, 2015, **435**, 194.
41 L. Jin, Z. Guo, Z. Sun, A. Li, Q. Jin and M. Wei, *Sens. Actuators, B*, 2012, **161**, 714.