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New carboxy-functionalized terpyridines as precursors for zwitterionic ruthenium complexes for polymer-based solar cells

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Abstract—New carboxy-terpyridines selectively functionalized at the 4-, 4′- and 4″-positions were prepared in a three-step procedure with good yields using the Kröhnke reaction followed by saponification. Their complexation with ruthenium led to symmetric and unsymmetric terpyridinyl zwitterionic complexes.

Terpyridines substituted at the 4′-position are very attractive[1] when wishing to build linear, rod-like complexes and polymers. When suitably functionalized with groups such as carboxylic acid[2] or phosphonic acid,[3] zwitterionic forms become accessible. These can be anchored onto a transparent electrode such as anatase to give a monolayer of complexes or thin films of polymers able to convert sunlight into electricity by dye-sensitized nanocrystalline TiO_2 solar cells.[4] Terpyridines are easily accessible via different synthetic routes.[5–7] However, their derivatives bearing carboxylic acid or phosphonic acid functionalities are much more difficult to synthesize and previously reported preparations are arduous[2a] or require the development of new routes such as the oxidation of a furan[8] ring into a carboxylic group.

Recently, our group has reported the successful absorption of conjugated polymers containing terpyridinyl ruthenium complexes without anchoring groups on anatase with efficiencies of ~0.1%.[9] Previously, Renouard and Grätzel[10] reported the synthesis of quaterpyridine ligands for Ru-sensitized solar cells based on the methodology of Kröhnke. Very few reports[3b] on the development of zwitterionic species applied to sensitization of nanocrystalline TiO_2 films exist. However, recent studies[11] concerned with the influence of electrolytes and mobile counterions on the power conversion efficiency have been reported and emphasize the benefit of having neutral systems.

As part of our study to develop a new class of compounds, we synthesized terpyridines bearing carboxylic functions on various positions, 4, 4′ or 4″, using known procedures with some modifications to obtain ligands where both the number (from 1 to 3 carboxylic groups) and positions of carboxylic groups can be controlled. The complexation of the carboxy-functionalized terpyridines with ruthenium salts such as $RuCl_3 \cdot 3H_2O$ gave access to zwitterionic species with different molecular dipole moments depending on the position of the carboxylic functions.

In an initial strategy, we tried to synthesize in two steps (Scheme 1) 4-(4-bromophenyl)-2,6-bis(4-carboxypyridin-2-yl)pyridine **3**, starting from 4-(4-bromophenyl)-2,6-bis(4-methylpyridin-2-yl)pyridine **1**.

Compound **1** was prepared via aldol condensation of 2-acetyl-4-methylpyridine[12] and 4-bromobenzaldehyde followed by a Michael addition.[6] The methylpyridine moieties were then first converted to pyridine carbaldehydes via an oxidation reaction using selenium dioxide[13] and then into pyridine carboxylic acids with potassium permanganate.[14] Unfortunately, the first oxidation gave compound **2** in low yield (11%) after a long reaction time (~48 h) and formation of undesired by-products that can be attributed to selenious by-products due to the excess of SeO_2 used (6.6 equiv). The reaction was also attempted with a lower amount of selenium dioxide in combination with *t*-butyl hydroperoxide[15] as an

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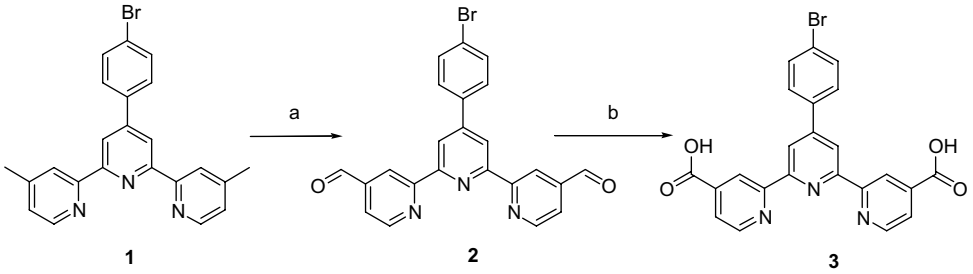


Scheme 1. Reagents and conditions: (a) 6.6 equiv SeO_2, acetic acid, reflux, 43 h; (b) 2 equiv $KMnO_4$, acetone, reflux and $Na_2S_2O_5$ followed by extraction with $CHCl_3$ and diethyl ether.

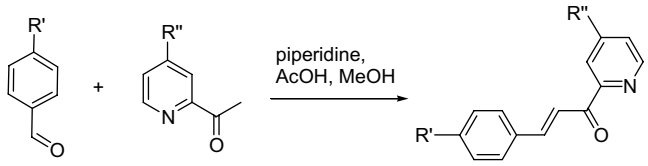
oxidizing agent. This reaction led to a mixture of three compounds, **1**, **2** and a monomethyl-terpyridine. The yield of the final step to convert compound **2** into compound **3** was very low (~6%) due to the high insolubility of **3**. The problems encountered in the isolation of the desired compound may be a consequence of the presence of **3** as zwitterionic structure.[16]

After several attempts to improve the yield of the intermediate steps, we decided to use another strategy using starting materials bearing esters groups, in three steps, including the Kröhnke reaction.[5] A series of ester-functionalized terpyridines (**8a**–**g**) were therefore synthesized using different starting aldehydes or Kröhnke's reagent which consists of the pyridinium salts **7a**,**b**. The esters were hydrolyzed to isolate the desired carboxylic acids **9a**–**g**.

The first step consists of synthesizing the enones **6a**–**d**[17] through reaction of a benzaldehyde or *p*-(carbomethoxy)benzaldehyde **4a**[18] and 2-acetylpyridine **5a** or methyl 2-acetylisonicotinate **5b**[16a] to introduce the desired functionality using 1.1 equiv of piperidinium acetate (Scheme 2 and Table 1).[10]

This reaction gave easy access to enones **6a**–**d** as orange crystals by precipitation in cold methanol with yields between 33% and 38%.

Due to the high solubility of the enones, the products were washed with only a few milliliters of cold methanol and used without further purification. The ^1H NMR spectra of the enones revealed that the crude products



4a-c
a R'=$COOCH_3$
b R'=Br
c R'=CH_3

5a-b
a R"=H
b R"=$COOCH_3$

6a-d

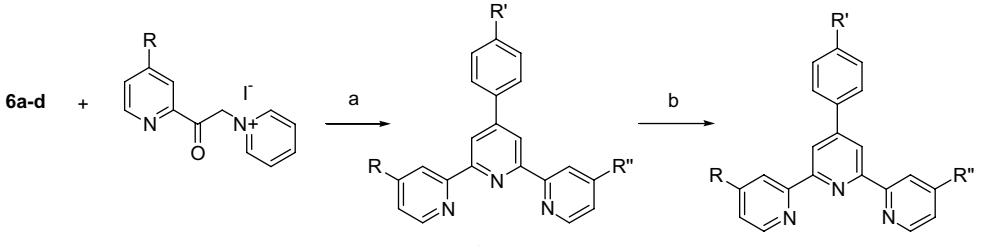
Scheme 2. Reagents and conditions: aldehyde (5.6 mmol), ketone (5.6 mmol), piperidine (6.2 mmol), acetic acid (6.2 mmol) in methanol (10 mL), reflux, 5 h.

Table 1. Synthesis of enones **6a**–**d** using piperidinium acetate

Entry	R′	R″	Product	Isolated yield (%)
1	$COOCH_3$	$COOCH_3$	**6a**	38
2	Br	$COOCH_3$	**6b**	36
3	CH_3	$COOCH_3$	**6c**	33
4	$COOCH_3$	H	**6d**	34

contained small quantities (less than 3%) of the starting aldehyde. Attempts to synthesize enones directly from the 4-carboxybenzaldehyde were not successful, confirming the need to protect the carboxylic acids as esters.[10]

Further reaction of the enones **6a**–**d** with the Kröhnke's reagents **7a**,**b** in the presence of an excess of ammonium acetate (Scheme 3) led to the desired ester-substituted



7a-b
a R=H
b R=$COOCH_3$

8a-g

9a-g

Scheme 3. Reagents and conditions: (a) enone (0.4 mmol), Kröhnke's reagent (0.5 mmol), NH_4OAc (26 mmol, excess) in methanol (3 mL), reflux, 4 h; (b) ester-substituted terpyridine (1.98 mmol), NaOH 1 N (2 equiv) in methanol (12 mL), reflux, overnight and HCl 0.5 N to pH 3.5–4.

Table 2. Preparation of terpyridines **8a–g** by reaction of enones **6a–d** with Kröhnke's reagents

Entry	Enone	R	R′	R″	Product	Isolated yield (%)
1	**6a**	H	$COOCH_3$	$COOCH_3$	**8a**	52
2	**6a**	$COOCH_3$	$COOCH_3$	$COOCH_3$	**8b**	45
3	**6b**	H	Br	$COOCH_3$	**8c**	44
4	**6b**	$COOCH_3$	Br	$COOCH_3$	**8d**	46
5	**6c**	$COOCH_3$	CH_3	$COOCH_3$	**8e**	54
6	**6d**	H	$COOCH_3$	H	**8f**	64
7	**6c**	H	CH_3	$COOCH_3$	**8g**	58

terpyridines **8a–g** (Table 2)[19] in good yields (44–64%). Depending on the number of carboxylate functions, the terpyridines showed various solubilities in chloroform. The compounds were obtained in high purity after extraction with chloroform and used without further purification or only recrystallized once from absolute ethanol.

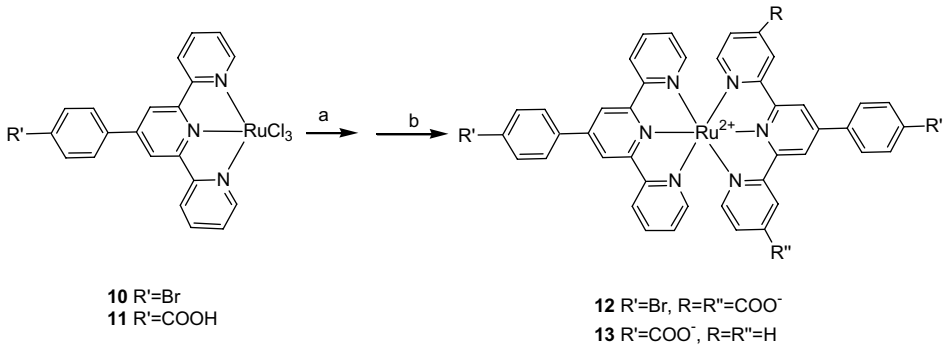
Using the same procedure, the terpyridine **8f**[20] derived from **7a** and 4-((*E*)-3-oxo-3-pyridin-2-yl-propenyl)-benzoic acid methyl ester **6d**[21] was also accessible (64%) in a slightly higher yield than that published (52%). The terpyridine **8g** derived from **7a** and **6c** was already known[16a] and the synthesis was reproduced giving the product in 58% yield.

Terpyridines **8a–g** were hydrolyzed with aqueous sodium hydroxide in methanol under reflux to give the desired carboxy-functionalized terpyridines **9a–g**[22] in high yields (~80%) after neutralization, filtration and washing with water.

Preparation of the ruthenium complexes was performed in two steps according to known procedures.[23] In a typical complexation, an appropriate quantity of $RuCl_3 \cdot 3H_2O$ was reacted under reflux overnight with 1 equiv of terpyridine 4′-(4-bromophenyl)-2,2′:6′,2″-terpyridine or **9f** in ethanol (90%) leading to the monosubstituted terpyridine ruthenium complexes **10**, **11**.[23a,24] The trichloro terpyridinyl ruthenium complex (Scheme 4) was then activated using $AgBF_4$/acetone whereby the chloride ligands were exchanged with acetone and precipitated as AgCl. The ruthenium(III) was reduced to ruthenium(II) by reflux overnight in the presence of ethanol,[23a,24] as a reducing agent, to give the ruthenium terpyridinyl complexes **12**, **13**.[25] The resulting complexes were isolated as red solids after recrystallization from a mixture of acetonitrile–diethyl ether with moderate yields (~40%). The compounds were sufficiently pure according to NMR (>99%) after recrystallization and did not require purification by chromatography.

Depending on the nature of the carboxy-functionalized terpyridine used, symmetric or asymmetric zwitterionic complexes could be obtained. Complex **12** contains a bromine on one side and anchoring groups in the form of carboxylic functions on the other side. Such architectures are highly suitable for their use as sensitizers linked to PPV type oligomers.

In conclusion, we have described the efficient synthesis of new carboxy-functionalized terpyridines in three steps. To our knowledge, terpyridines with one to three carboxylic groups in various positions such as the 4-, 4′- and 4″-positions and small functionalities like bromine or methyl have not been previously reported. This work represents a useful addition to the synthesis of terpyridine ligands bearing carboxylic acid functions. Their complexation with ruthenium led to the preparation of two new zwitterionic ruthenium complexes where it is possible to modify the molecular dipole moment of the zwitterionic complex by different combinations of the terpyridine ligands. Photophysical studies and photovoltaic applications of this new class of molecular sensitizers is currently in progress and will be the subject of a forthcoming publication.



Scheme 4. Reagents and conditions: (a) **10** or **11** (0.22 mmol) $AgBF_4$ (3.2 equiv) in acetone (80 mL), reflux, 2.5 h; (b) **9d** (R=R″=COOH, R′=Br) or **9f** (R=R″=H, R′=COOH) (0.22 mmol) in ethanol 99% (50 mL), reflux, 19 h.

Acknowledgements

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References and notes

1. (a) Cargill Thompson, A. M. W. *Coord. Chem. Rev.* **1997**, *160*, 1–52; (b) Hofmeier, H.; Schubert, U. S. *Chem. Soc. Rev.* **2004**, *33*, 373–399.
2. (a) Nazeeruddin, M. K.; Pechy, P.; Renouard, T.; Zakeeruddin, S. M.; Humphry-Baker, R.; Comte, P.; Liska, P.; Le Cevey, E. C.; Shklover, V.; Spiccia, L.; Deacon, G. B.; Bignozzi, C. A.; Grätzel, M. *J. Am. Chem. Soc.* **2001**, *123*, 1613–1624; (b) Nazeeruddin, M. K.; Péchy, P.; Grätzel, M. *Chem. Commun.* **1997**, 1705–1706; (c) Nazeeruddin, M. K.; Pechy, P.; Grätzel, M. Transition metal complex photosensitizer and use of this complex in a photovoltaic cell, PCT/IB 98/00680, CAN 130:14919.
3. (a) Zakeeruddin, S. M.; Nazeeruddin, M. K.; Pechy, P.; Rotzinger, F. P.; Humphry-Baker, R.; Kalyanasundaram, K.; Grätzel, M.; Shklover, V.; Haibach, T. *Inorg. Chem.* **1997**, *36*, 5937–5946; (b) Krebs, F. C.; Biancardo, M. *Sol. Energy Mat. Sol. Cells* **2006**, *90*, 142–165.
4. (a) Sarto Polo, A.; Kayoto Itokazu, M.; Murakami Iha, N. Y. *Coord. Chem. Rev.* **2004**, *248*, 1343–1361; (b) Grätzel, M. *J. Photochem. Photobiol. A: Chem.* **2004**, *164*, 3–14.
5. Kröhnke, F. *Synthesis* **1976**, 1–24.
6. Cave, G. W. V.; Raston, C. L. *J. Chem. Soc., Perkin Trans. 1* **2001**, 3258–3264.
7. (a) Labadie, J. W.; Stille, J. K. *J. Am. Chem. Soc.* **1983**, *105*, 6129–6137; (b) Heller, M.; Schubert, U. S. *Synlett* **2002**, 751–754.
8. Husson, J.; Beley, M.; Kirsch, G. *Tetrahedron Lett.* **2003**, *44*, 1767–1770.
9. Duprez, V.; Biancardo, M.; Spanggaard, H.; Krebs, F. C. *Macromolecules* **2005**, *38*, 10436–10448.
10. Renouard, T.; Grätzel, M. *Tetrahedron* **2001**, *57*, 8145–8150.
11. (a) Hara, K.; Nishikawa, T.; Kurashige, M.; Kawauchi, H.; Kashima, T.; Sayama, K.; Aika, K.; Arakawa, H. *Sol. Energy Mat. Sol. Cells* **2005**, *85*, 21–30; (b) Nüesch, F.; Faes, A.; Zuppiroli, L.; Meng, F.; Chen, K.; Tian, H. *J. Mater. Sci.* **2005**, *40*, 1353–1357.
12. Constable, E. C.; Heirtzeler, F.; Neuburger, M.; Zehnder, M. *J. Am. Chem. Soc.* **1997**, *119*, 5606–5617.
13. (a) Thayer, H. I.; Corson, B. B. *J. Am. Chem. Soc.* **1948**, *70*, 2330–2333; (b) Henze, H. R.; Knowles, M. B. *J. Org. Chem.* **1954**, *19*, 1127–1135; (c) Achremowicz, L. *Synth. Commun.* **1996**, *26*, 1681–1684.
14. (a) Fatiadi, A. J. *Synthesis* **1987**, 85–127; (b) Black, G.; Depp, E.; Corson, B. B. *J. Org. Chem.* **1949**, *14*, 14–17; (c) Danieli, R.; Ricci, A. *Synthesis* **1972**, 46–47.
15. Tagawa, Y.; Yamashita, K.; Higuchi, Y.; Goto, Y. *Heterocycles* **2003**, *60*, 953–957.
16. (a) Mikel, C.; Potvin, P. G. *Polyhedron* **2002**, *21*, 49–54; (b) Zadykowicz, J.; Potvin, P. G. *J. Org. Chem.* **1998**, *63*, 235–240.
17. Preparation of **6a** as a representative procedure for the synthesis of enones **6a–d**: piperidine (0.6 mL, 6.19 mmol) and acetic acid (0.35 mL, 6.19 mmol) were added to a stirred solution of **4a** (0.92 g, 5.58 mmol) and **5b** (1 g, 5.58 mmol) in methanol (10 mL). The mixture was refluxed for 5 h and turned red with precipitation of orange crystals. After cooling to room temperature, the crystals were filtered and washed with methanol (4 mL) to give **6a** as orange crystals (0.693 g, 38%). Mp: 176 °C (dec.). ^{1}H NMR ($CDCl_3$, 250.1 MHz): δ 8.89 (d, 1H, $J = 4.7$ Hz), 8.69 (s, 1H), 8.35 (d, 1H, $J = 16$ Hz), 8.07 (m, 3H), 7.96 (d, 1H, $J = 16$ Hz), 7.77 (m, 2H), 4.00 (s, 3H), 3.93 (s, 3H). ^{13}C NMR ($CDCl_3$, 62.9 MHz) δ: 188.4, 166.4, 164.9, 154.9, 149.7, 143.6, 139.2, 138.8, 131.7, 130.0, 128.6, 126.0, 122.8, 122.2, 52.8, 52.2. Anal. Calcd for $C_{18}H_{15}NO_5$: C, 66.46; H, 4.65; N, 4.31; O, 24.59. Found: C, 66.25; H, 4.75; N, 4.25.
18. Landesberg, J. M.; Slam, M. A.; Mandel, M. *J. Org. Chem.* **1981**, *46*, 5025–5027.
19. Preparation of **8a** as a representative procedure for the synthesis of terpyridines **8a–g**: **6a** (0.185 g, 0.69 mmol) and **7b** (0.327 g, 0.85 mmol) were added to a solution of excess ammonium acetate (2 g, 26 mmol) in methanol (3 mL) and the resulting solution was heated to reflux for 4 h. After cooling to room temperature, a brown precipitate started to form in the yellow solution. The precipitate was collected by filtration, and triturated successively with methanol (2×2 mL) and then with chloroform (2×2 mL). The chloroform extract was freed of solvent, to give **8a** as a brown powder (0.152 g, 52%). Mp: 238 °C (dec.). ^{1}H NMR ($CDCl_3$, 250.1 MHz): δ 11 (s, 1H), 8.83 (d, 1H, $J = 5$ Hz), 8.74–8.65 (m, 4H), 8.15 ('d', apparent, 2H, $J = 8.25$ Hz), 7.92 ('d', apparent, 2H, $J = 8.25$ Hz), 7.88 (t, 1H, $J = 2.75$, 4.5 Hz), 7.85 (d, 1H, $J = 1.75$ Hz), 7.38–7.33 (m, 1H), 4.02 (s, 3H), 3.95 (s, 3H). ^{13}C NMR ($CDCl_3$, 62.9 MHz): δ 166.6, 165.8, 157.1, 156.3, 155.7, 155.3, 149.8, 149.1, 142.7, 138.4, 136.9, 130.6, 130.2, 127.3, 124.0, 122.8, 121.5, 120.6, 119.3, 119.1, 52.7, 52.2; MS (MALDI-TOF): m/z 426.1448, calcd for $C_{25}H_{19}N_3O_4$ (MH^+) 426.1429.
20. Figgemeier, E.; Aranyos, V.; Constable, E. C.; Handel, R. W.; Housecroft, C. E.; Risinger, C.; Hagfeldt, A.; Mukhtar, E. *Inorg. Chem. Commun.* **2004**, *7*, 117–121.
21. Siemeling, U.; Vor der Brüggen, J.; Vorfeld, U.; Stammler, A.; Stammler, H.-G. *Z. Naturforsch.* **2003**, *58b*, 443–446.
22. Preparation of **9d** as a representative experimental procedure for the access to carboxy-functionalized terpyridines **9a–g**: compound **8d** (1 g, 1.98 mmol) was dissolved in hot methanol (12 mL) to which was added NaOH 1 N (3.96 mmol, 2 equiv). The reaction mixture was refluxed 24 h, cooled to room temperature and acidified with HCl 0.5 N to pH 3.5–4. The precipitate was separated by filtration, washed with water and air dried, to give **9d** as a brown powder (1.3 g, 83%). ^{1}H NMR (DMSO-d_6, 250.1 MHz): δ 8.91–8.81 (m, 4H), 8.71–8.67 (m, 2H), 7.89–7.73 (m, 6H). ^{13}C NMR (DMSO-d_6, 62.9 MHz): δ 166.5, 156.3, 155.7, 151.0, 149.1, 140.1, 136.8, 132.8, 129.5, 128.1, 123.9, 122.8, 120.1, 119.0; MS (MALDI-TOF): m/z 476.0240, calcd for $C_{23}H_{14}BrN_3O_4$ (MH^+) 476.0227.
23. (a) Collin, J.-P.; Guillerez, S.; Sauvage, J.-P.; Barigelletti, F.; De Cola, L.; Flamigni, L.; Balzani, V. *Inorg. Chem.* **1991**, *30*, 4230–4238; (b) Collin, J.-P.; Harriman, A.; Heitz, V.; Odobel, F.; Sauvage, J.-P. *J. Am. Chem. Soc.* **1994**, *116*, 5679–5690.
24. Sullivan, B. P.; Calvert, J. M.; Meyer, T. J. *Inorg. Chem.* **1980**, *19*, 1404–1407.
25. Preparation of **12** as a representative experimental procedure for the synthesis of zwitterionic ruthenium complexes. **10** (130 mg, 0.22 mmol) was dissolved in acetone (80 mL) and 3.2 equiv of $AgBF_4$ (137 mg, 0.69 mmol) were added to the solution. The resulting solution was heated to reflux for 2.5 h under argon and cooled down. The precipitate of AgCl was removed by filtration using Celite. The solvent was removed under vacuum to leave a dark blue solid. The residue was dissolved in ethanol (50 mL)

and **9d** (105 mg, 0.22 mmol). was added to the reaction mixture. The reaction was refluxed for 19 h then cooled. After filtration to remove the unreacted materials, the solvent was removed under vacuum and a red solid was obtained which was washed with water. The solid was dissolved in a minimal volume of acetonitrile and precipitated by addition of diethyl ether. The precipitate was isolated by filtration as a red powder (0.075 g, 35%). ^{1}H NMR (CD_3CN, 250.1 MHz): δ 9.18 (s, 2H), 9.11 (s, 2H), 9.01 (s, 2H), 8.65 (d, 2H, $J = 8.7$ Hz), 8.20–8.12 (m, 4H), 7.99–7.92 (m, 6H), 7.62 (s, 4H), 7.38 (d, 2H, $J = 5.5$ Hz), 7.15 (t, 2H, $J = 5.5$, 13 Hz); MS (MALDI-TOF): m/z calculated for $[C_{44}H_{26}Br_2N_6O_4Ru]$ 961.94, found 962.23.