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Three Steps in One Pot: Synthesis of Linear Bilateral Extended 2,2′:6′,2″-Terpyridineruthenium(II) Complexes

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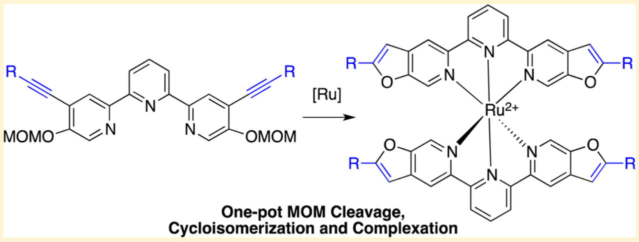
Supporting Information

ABSTRACT: Metal complexes of linear bilateral extended 2,2′:6′,2″-terpyridine [2,6-bis(2-substituted furo[2,3-*c*]pyridin-5-yl)pyridine] are topological tridentate analogues of 5,5′-functionalized 2,2′-bipyridine. The present methodology provides access to linear bilateral extended 2,2′:6′,2″-terpyridineruthenium(II) complexes starting from 5,5″-bis(methoxymethoxy)-4,4″-bis(substituted ethynyl)-2,2′:6′,2″-terpyridines via one-pot cleavage of the methoxymethyl (MOM) protecting group, cycloisomerization, and metal complexation in the presence of Ru(DMSO)$_4$Cl$_2$. In this reaction, ruthenium(II) likely plays a triple role, acting as a Lewis acid to cleave the MOM ether, a catalyst facilitating 5-endo-dig cyclization, and a coordination metal center, being an integral part of the final product.



■ INTRODUCTION

The characteristic thermodynamically strong and kinetically inert metal−ligand coordinative bonds of classical tridentate 2,2′:6′,2″-terpyridine (terpy) ligands with ruthenium(II), have been exploited within various design elements in supramolecular chemistry.[1−4] Their photophysical and electrochemical properties make polypyridineruthenium complexes particularly well suited to the development of dye-sensitized solar cells.[5,6] Recently, bilateral extended terpy ligands [2,6-bis(2-substituted furo[2,3-*c*]pyridin-5-yl)pyridine] have appeared as a new class of building blocks in supramolecular chemistry.[7] These octahedral metal complexes of tridentate terpy fused with five-membered furan rings mimic the crossing topology normally associated with tetrahedral metal complexes of bidentate 5,5′-functionalized 2,2′-bipyridine (bipy; Figure 1). Such directional metal complexes are potential building blocks for the assembly of heterometallic coordination polymers and metal−organic frameworks (MOFs).

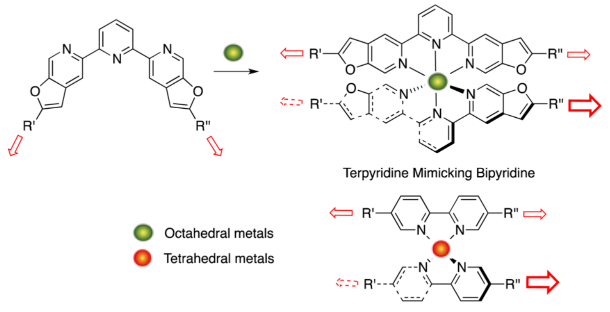


Figure 1. Linear bilateral extended terpy mimicking the topology of bidentate 5,5′-functionalized bipy.

Previous methods to access alkyl-, aryl-, and heteroaryl-substituted linear bilateral extended terpy derivatives did not tolerate functional groups sensitive to acidic and basic conditions.[7] Therefore, a synthetic methodology to obtain these ligands or metal complexes directly under neutral conditions would be of great utility. Synthetic methods to the furo[2,3-*c*]pyridine fragment, the key structural element for these linear bilateral terpy ligands, deserve particular attention.

In 1987, Fràter and co-workers showed that furo[2,3-*c*]pyridine forms as a side product of Claisen rearrangement of 2-propynyl(3-pyridiyl) ethers at high temperature.[8] Since then, many other methodologies have been developed.[9−14] So far, the most efficient protocol involves a palladium-catalyzed cross-coupling reaction between 3-hydroxy-4-halopyridine and acetylene with in situ cyclization to form a fused furan ring, which was first discovered and further extended by Marinelli and co-workers.[15−17] Analogous to reports that ruthenium [CpRuCl(PPh$_3$)$_2$] catalyzes cycloisomerizations of 2-ethynylphenols to give benzofurans via the formation of ruthenium vinylidenes,[18] the ruthenium-catalyzed synthesis of furo[2,3-*c*]pyridines appears promising and consistent with ruthenium's ability to effect cycloisomerization reactions.[19,20] A 2,6-bis(2-substituted furo[2,3-*c*]pyridin-5-yl)pyridine scaffold formed spontaneously during the complexation reaction of 5,5″-bis(methoxymethoxy)-4-(2-substituted ethynyl)-2,2′:6′,2″-terpyridine with Ru(DMSO)$_4$Cl$_2$ (DMSO = dimethyl sulfoxide).[7] These observations allowed the development of a methodology that provides access to linear bilateral extended 2,2′:6′,2″-terpyridineruthenium(II) complexes via one-pot cleavage of the methoxymethyl (MOM) protecting group, cycloisomerization,

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and metal complexation of 5,5″-bis(methoxymethoxy)-4,4″-bis(substituted ethynyl)-2,2′:6′,2″-terpyridines (Figure 2).

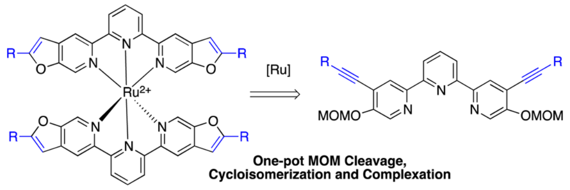


Figure 2. One-pot strategy for the synthesis of linear bilateral extended 2,2′:6′,2″-terpyridineruthenium(II) complexes from 5,5″-bis(methoxymethoxy)-4,4″-bis(substituted ethynyl)-2,2′:6′,2″-terpyridines.

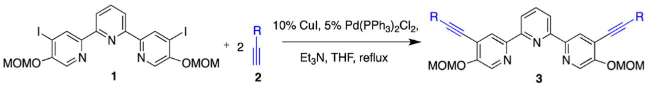
■ EXPERIMENTAL SECTION

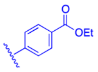
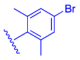
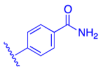
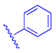
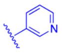
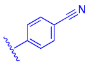
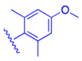
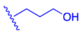
All reagents and solvents used for the reactions were reagent-grade and were used without further purification unless otherwise noted. Commercial chemicals where used as received without special purification. 4,4″-Diiodo-5,5″-bis(methoxymethoxy)-2,2′:6′,2″-terpyridine (**1**),[7] ethyl 4-ethynylbenzoate (**2a**),[21] 5-bromo-2-ethynyl-1,3-dimethylbenzene (**2b**),[22] 4-ethynylbenzamide (**2c**),[23] 4-ethynylbenzonitrile (**2f**),[24] and 2-ethynyl-5-methoxy-1,3-dimethylbenzene (**2g**)[7] were prepared according to literature procedures. Anhydrous tetrahydrofuran (THF) and toluene were supplied from an Mbraun solvent purification system. Analytical thin-layer chromatography (TLC) was performed with Macherey−Nagel POLYGRAM SIL N-HR/UV254 or ALOX N/UV254. Flash silica gel column chromatography was performed with Merck silica gel 60 (particle size 0.040−0.063 mm). Flash alumina column chromatography was performed with deactivated (5% water) Fluka alumina (particle size 0.05−0.15 mm; pH 7.0 ± 0.5).

General Procedure for the Synthesis of 5,5″-Bis(methoxymethoxy)-4,4″-bis(substituted ethynyl)-2,2′:6′,2″-terpyridines (3). To a mixture of 4,4′′-diiodo-5,5′′-bis(methoxymethoxy)-2,2′:6′,2′′-terpyridine **1** (1.0 mmol), CuI (0.1 mmol), and $PdCl_2(PPh_3)_2$ (0.05 mmol) in degassed THF/Et_3N (10 mL/10 mL) was added acetylene **2** (see Table 1 and the Supporting Information, SI) under a N_2 atmosphere at 80 °C. The reaction mixture was heated to reflux, followed by TLC to completion, allowed to cool to room temperature, and evaporated to dryness under reduced pressure. The residue was dissolved in CH_2Cl_2 (30 mL) and then washed with 10% aqueous NH_4OH, water, and brine. The organic phase was dried over $MgSO_4$, filtered, and evaporated under reduced pressure. Purification of the crude product afforded **3** (see the SI).

General Procedure for the Synthesis of Bis[2,6-bis(2-substituted furo[2,3-*c*]pyridin-5-yl)pyridine]ruthenium(II)·2PF$_6$ (4) Complexes. A mixture of **3** (0.02 mmol) and $Ru(DMSO)_4Cl_2$ (0.01 mmol) in ethylene glycol (8 mL) was heated to 120 °C under a N_2 atmosphere for the indicated time (see the SI). The mixture was allowed to cool to room temperature, and aqueous KPF_6 was added. The resulting deep-red precipitate was collected by filtration on a bed of Celite, which was then washed with water, Et_2O, and hexane. After washing, the complex was released from the bed by elution with acetonitrile into a clean flask. The solvent was evaporated to give a deep-red residue, which was purified by silica gel column chromatography. The combined fractions containing product **4** were evaporated under reduced pressure, then dissolved in a minimum amount of acetonitrile, and induced to precipitate **4** with an aqueous KPF_6 solution. The precipitate was collected by filtration on a bed of Celite, which was then washed with water, Et_2O, and hexane, and then eluted into a clean flask with acetonitrile. Evaporation of the solvent afforded **4**. (For purification details and characterization of the products, see the SI.)

Table 1. Synthesis of Terpyridines 3

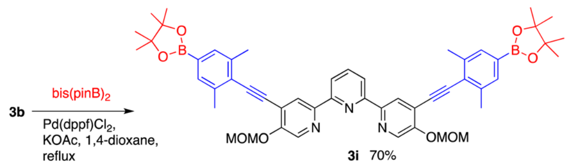


entry	R=	eq 2	time (h)	product	yield (%)
1		2.5	18	**3a**	83
2		2.2	18	**3b**	64
3		2.4	18	**3c**	85
4		2.5	20	**3d**	95
5		7.8	20	**3e**	85
6		2.4	18	**3f**	85
7		2.3	8	**3g**	91
8		2.4	18	**3h**	71

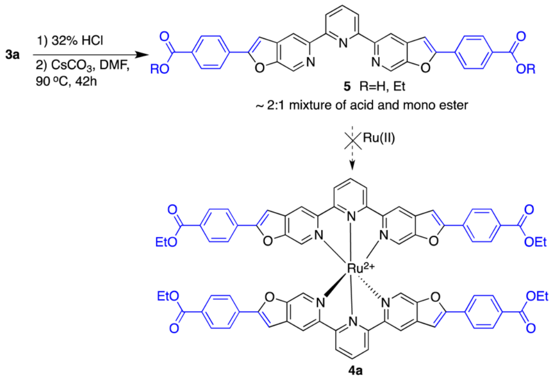
■ RESULTS AND DISCUSSION

Sonogashira coupling[25] of **1** and various acetylenes **2** gave bis(ethynylterpyridines) **3a**−**3h** bearing aryl, haloaryl, amide, ester, heteroaryl, nitrile, and alkyl groups with good-to-high yields (Table 1).

Scheme 1. Synthesis of 4,4′′-Bis((2,6-dimethyl-4-(3,3,4,4-tetramethylborolan-1-yl)phenyl)ethynyl)-5,5′′-bis(methoxymethoxy)-2,2′:6′,2′′-terpyridine 3i

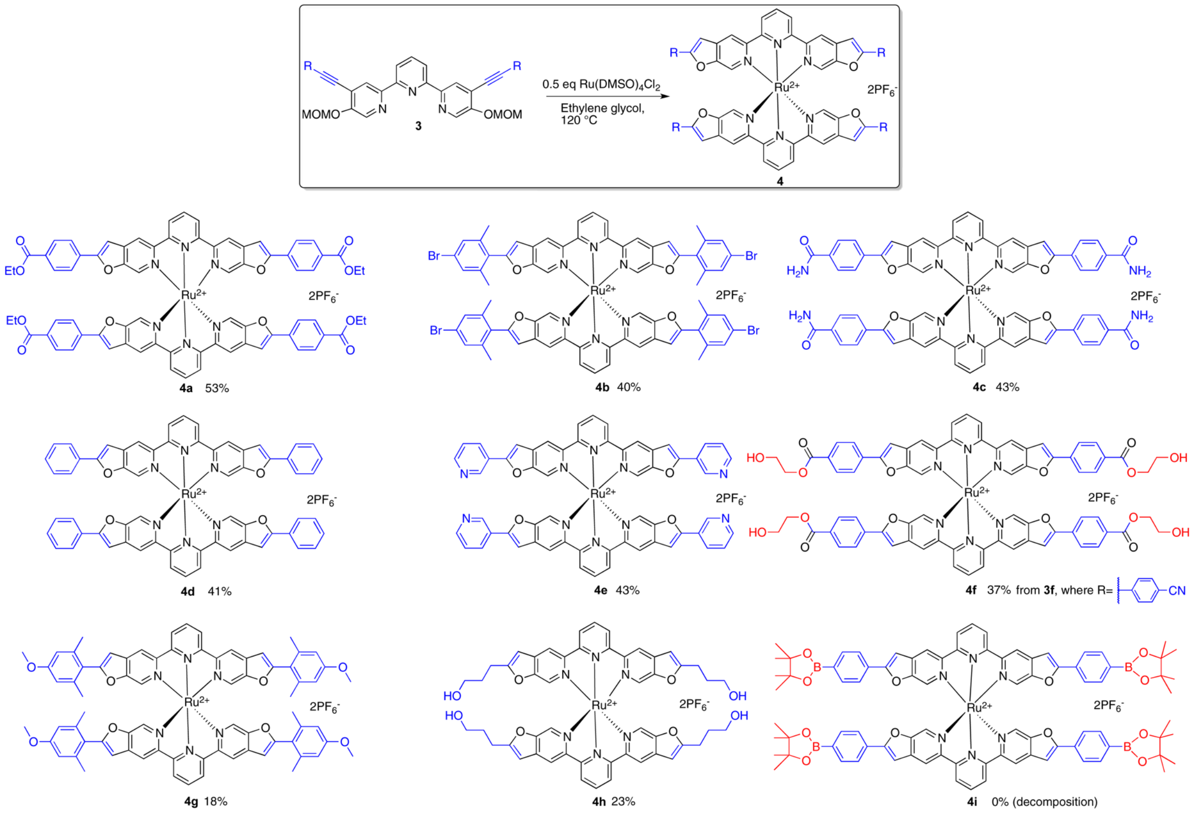


Scheme 2. Synthetic Attempts toward Ru(II)[diethyl 4,4′-(5,5′-(pyridine-2,6-diyl)bis(furo[2,3-*c*]pyridine-5,2-diyl))dibenzoate]2·2PF$_6$ Complex 4a



Miyaura borylation[26] of dibromo derivative **3b** afforded 4,4′′-bis((2,6-dimethyl-4-(3,3,4,4-tetramethylborolan-1-yl)phenyl)-

Scheme 3. Synthesis of Complexes 4



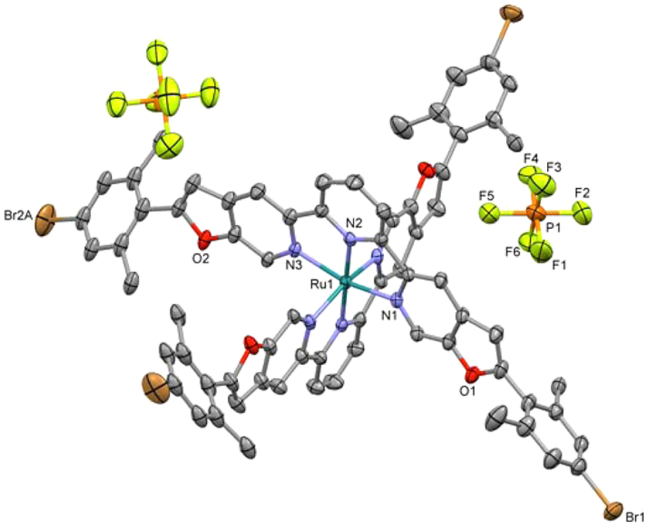
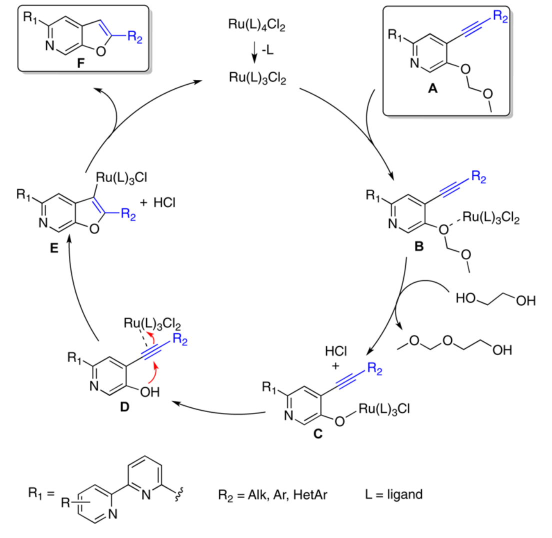


Figure 3. Molecular structure of ruthenium(II) complex **4b**. Hydrogen atoms were removed for clarity, and displacement ellipsoids were drawn at the 50% probability level.

ethynyl)-5,5′′-bis(methoxymethoxy)-2,2′:6′,2′′-terpyridine **3i** (Scheme 1).

Attempts to obtain ruthenium(II) complex **4a** functionalized with ester groups via free ligand **5** following complexation were not successful (Scheme 2). The hydrolysis of ester groups during the one-pot acidic MOM deporotection and base-assisted cycloisomerization[7] of **3a** did not give the desired diester **5**; instead, the ∼2:1 mixture of acid and monoester was formed. This motivated us to test diester **3a** as the first substrate for the neutral one-pot preparation of complex **4a**.

Scheme 4. Proposed Mechanism for Ruthenium(II)-Catalyzed MOM Deprotection and Cycloisomerization of 3



Scheme 5. Synthesis of Zwitterionic Ruthenium(II) Complex 4j

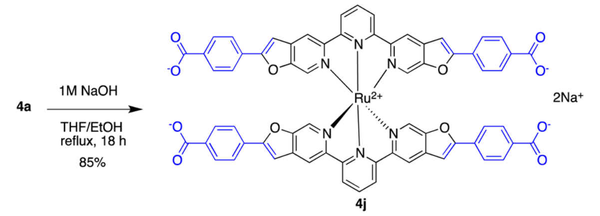


Table 2. Absorption and Emission Maxima, Molar Absorptivity Values (log *ε*), Quantum Yields (ϕ_f), and Lifetimes (τ_f) for 4

	UV−vis[a]		fluorescence[a]		
	λ_{abs} (nm)	log *ε* (log(cm^{-1} mol^{-1} L))	λ_{em} (nm)	ϕ_f[b] (%)	τ_f (ns)
4a	256, 311, 324, 330, **341**, 399, 466, 503	4.86, 5.10, 5.06, 5.01, **5.21**, 4.59, 4.35, 4.27	383	0.04	4.60
4b	256, 318sh, **330**, 376, 461, 494	5.11, 5.01, 4.89, **5.09**, 4.37, 4.22, 4.00	*c*	*c*	*c*
4c	256, 312, 325, **340**, 396, 465, 509	4.61, 4.71, 4.90, 4.89, **5.02**, 4.51, 4.36, 4.30	379, **399**	0.01	4.20
4d	258, 291, 307, 324, **338**, 389, 464, 506	4.90, 5.01, 4.99, 4.98, **5.16**, 4.57, 4.30, 3.73	349	0.06	3.22
4e	256, 291, 306, 323, **337**, 391, 464, 509	4.89, 4.99, 4.97, 4.90, **5.11**, 4.49, 4.27, 4.12	359	0.17	4.58
4f	256, 311, 324, **341**, 400, 465, 506	4.75, 5.00, 4.97, **5.09**, 4.50, 4.27, 4.20	380	<0.01[d]	*e*
4g	242, 274, 288, **330**, 372, 462, 508	5.02, 4.86, 4.83, **5.08**, 4.45, 4.22, 3.98	364	<0.01[d]	*e*
4h	**247**, 326, 366, 461, 499	**4.99**, 4.97, 4.23, 4.16, 3.85	*c*	*c*	*c*
4j[f]	258, 297, 313, 326, **341**, 390, 466, 508	4.52, 4.66, 4.69, 4.70, **4.79**, 4.26, 4.00, 3.90	*c*	*c*	*c*

[a] All values were measured in MeCN unless otherwise stated. The absorption and emission maxima are highlighted in bold. [b] Measured with an integrating sphere. [c] Nonluminescence at room temperature. [d] Below the detection limit. [e] Because of the low emission, this cannot be measured reliably. [f] Measured in the 1:1 mixture of MeCN/H_2O.

The diethyl ester **3a** and 0.5 equiv of $Ru(DMSO)_4Cl_2$ were heated in ethylene glycol to 120 °C for 24 h (Scheme 3). Electrospray ionization mass spectrometry analysis supported the formation of the 2:1 ligand-to-ruthenium(II) complex; the molecular ion showed that MOM protecting groups were cleaved in the course of the reaction. Chromatographic separation of the crude reaction mixture led to isolation of a red band, consistent with a bis(2,2′:6′,2″-terpyridine)-ruthenium(II) species.

The ^{1}H and ^{13}C NMR spectra reveal the product to contain the furo[2,3-*c*]pyridine moieties formed by cyclization of the intermediate diacetylene.

In comparison to the ^{1}H NMR spectrum of bis(ethynyl-2,2′:6′,2″-terpyridine) **3a**, a singlet appears at 7.47 ppm in the spectrum of complex **4a**, which is characteristic for hydrogen at the C3 position of a furo[2,3-*c*]pyridine fragment. The characteristic signals for the disubstituted ethynyl group are absent in the ^{13}C NMR of **4a**, but a CH signal appears at 104.3 ppm (multiplicity determined from DEPT90 and DEPT135 experiments), which corresponds to the C3 position of the furan ring. Overall, spectral data are compatible with the previously reported ruthenium(II) complexes of linear bilateral extended terpyridines[7] and support the formation of product **4a**.

To test the scope of the reaction, various bis(ethynyl-2,2′:6′,2″-terpyridines) **3** were used to obtain one-pot MOM deprotection, furan cyclization, and ruthenium(II) complexation products **4** (Scheme 3).

The diacetylene-2,2′:6′,2″-terpyridine derivatives **3a**−**3e** give the desired products **4a**−**4e** in 40−53% yield.

Unexpectedly, nitrile groups of **3f** underwent solvolysis to give ethylene glycol ester **4f**; thus, this reaction comprises four transformations in one pot. Substrates with electron-donating groups give low yields of the desired complexes, as shown with the examples of **4g** and **4h**. Pinacol boronate **3i** decomposed under the reaction conditions, and no desired product **4i** was obtained.

The slow Et_2O vapor diffusion into the acetonitrile solution of ruthenium(II) complex **4b** afforded dark-red crystals suitable for single-crystal X-ray analysis. The molecular structure was successfully solved in the *Fdd*2 space group. As shown in Figure 3, the X-ray data support the fact that the ligands in complex **4b** indeed contain cyclized furan rings.

A plausible mechanism for the ruthenium(II)-catalyzed MOM deprotection and cycloisomerization of motif **A** involves the ruthenium(II) species initially acting as a Lewis acid to activate the methoxymethoxy (OMOM) group of the intermediate **B** toward attack by ethylene glycol (Scheme 4), and the formed ruthenium pyridine-3-olate **C** converts to the 4-ethynyl-3-hydroxypyridyl intermediate **D** in the presence of previously generated H$^+$. Ruthenium then coordinates to the acetylene group, activating it for the 5-endo-dig cyclization and affording the intermediate **E** and ultimately the desired furopyridine motif **F**. Concomitantly, ruthenium(II) species are trapped by terpy, affording the desired complexes **4**.

The diethyl Ru(II)[diethyl 4,4′-(5,5′-(pyridine-2,6-diyl)bis-(furo[2,3-*c*]pyridine-5,2-diyl))dibenzoate]2·2PF_6 complex **4a** can be further used to obtain a water-soluble zwitterionic complex **4j**, with four terminal carboxylate groups (Scheme 5). Such molecular “crossing” with carboxylate groups has the potential as a functional building block for the synthesis of ruthenium-containing MOFs.

The photophysical properties of ruthenium complexes **4** are summarized in Table 2. The UV−vis spectra of **4** display pronounced ligand-centered (LC) absorptions with maxima at ∼330−341 nm and characteristic lower-energy metal-to-ligand charge-transfer (MLCT) bands (400−509 nm; see the SI).The MLCT bands of **4** are nonluminescent at room temperature. However, excitation at the LC bands of **4a** and **4c**−**4g** show weak but detectable emission. The fluorescence quantum yields of these complexes are very low and range from 0.01% to 0.17%. The emission for **4f** and **4g** can be observed; however, quantum yields could not be reliably measured because of the low values. The fluorescence lifetimes for complexes **4a** and **4c**−**4e** are in the range of 3.22−4.60 ns.

■ CONCLUSIONS

In summary, the development of a novel one-pot MOM deprotection, cycloisomerization, and complexation reaction provides access to linear bilateral extended 2,2′:6′,2″-terpyridineruthenium(II) complexes starting from 5,5″-bis-(methoxymethoxy)-4-(2-substituted ethynyl)-2,2′:6′,2″-terpyridine. These reaction conditions broaden the scope of ruthenium(II) complexes of linear bilateral extended teryridines applicable as potential building blocks for the construction of MOFs and other designed supramolecular architectures.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

X-ray crystallographic data for complex **4b** in CIF format, detailed experimental procedures, and characterization data for the products, including ^{1}H and ^{13}C NMR, UV−vis, and emission spectra and single-crystal X-ray data. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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