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Ruthenium-Catalyzed Dimerization of 7-Oxabicyclo[2,2,1]hepta-2,5-diene-2,3-dicarboxylates

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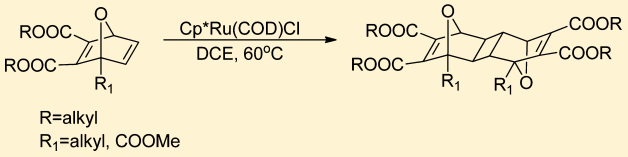
Supporting Information

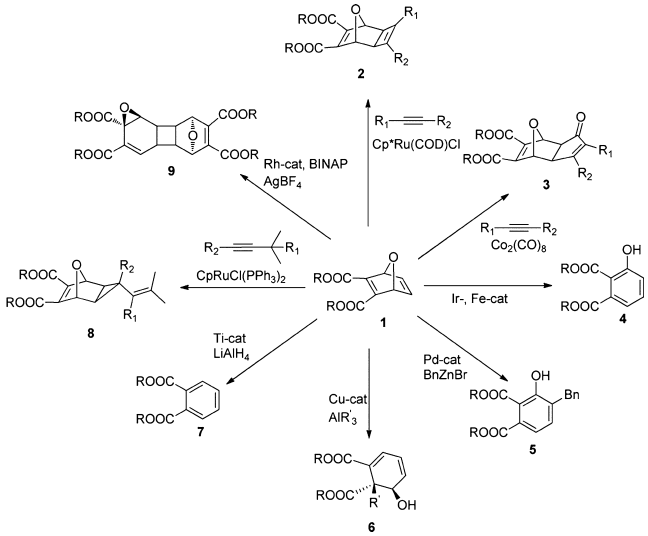
ABSTRACT: The ruthenium catalyzed dimerization of oxanorbornadiene dicarboxylates was studied. The effects of the ester moiety and the addition of a C1 substituent to the bicyclic alkene on the reaction were explored, and moderate yields and excellent regioselectivities were obtained.



Bicyclic alkenes are synthetically useful molecules due to their rigid structure and high ring strain which allows for participation in reactions not available to other alkenes.[1] The bridged structure of [2.2.1] bicyclic alkenes provides two faces on which reactions can occur. The *exo* face is encompassed by the oxygen bridgehead which provides additional electron density. Homoconjugation of the π-orbitals of the two alkenes acts to increase the reactivity of these olefins and the electron density of the *endo* face. Norbornadienes, specifically, have been used as intermediates toward to the natural product synthesis of compounds such as prostaglandin endoperoxides PGH_2 and PGG_2, *cis*-trikentrin B, and β-santalol.[2−5] Oxabicyclic alkenes are often used in the creation of highly substituted ring systems as well as in the formation of the core structure of many natural products.[6−9] The oxygen functionality presents synthetic opportunities for oxabicyclic alkenes that are not present in hydrocarbon bicyclic alkenes. Our group has thoroughly explored reactions of oxabenzonorbornadienes with much success.[9] Less work, however, has been done with 7-oxabicyclo[2.2.1]hepta-2,5-diene-2,3-dicarboxylates **1**. Insight into the reactivity of this compound allowed our group and others to demonstrate its versatility in a wide variety of metal catalyzed reactions (Scheme 1).

For example, when **1** reacted with an alkyne in the presence of Cp*Ru(COD)Cl, a [2 + 2] cycloaddition resulted in cyclobutene **2**.[10,11] A Pauson−Khand [2 + 2 + 1] cycloaddition will occur in the presence of an alkyne with $Co_2(CO)_8$ to provide **3**.[12] The oxanorbornadiene can be opened and aromatized using either an iron or iridium catalyst to give **4**.[13] The ring opening can also be accomplished using a palladacycle with a benzylzinc halide to produce **5**[14] or with a copper catalyst and a trialkyl aluminum reagent to give **6**.[15] Deoxygenenation of the 7-oxa moiety to give **7** can be achieved using a titanium catalyst with $LiAlH_4$.[16,17] Ru catalysts can promote the cyclopropanation of 7-oxanorbornadienes using propargylic alcohols or acetates to yield **8**.[18,19] The asymmetric dimerization to provide **9** is accomplished using a rhodium catalyst.[20,21]

Scheme 1. Metal Catalyzed Reactions of 7-Oxanorbornadienes



Dimerization reactions are of great interest due to their high atom efficiency.[22] Whipple and co-workers first explored the dimerization of norbornadiene in 1965. Although there are six norbornadiene dimers possible (Figure 1) due to the two faces of the bicyclic alkene (three *cis* and three *trans*), only the three possible *trans* dimers **10a−c** were obtained using a $Co_2(CO)_6(Ph_3P)_2$ or $Ni(CO)_4$ catalyst.[23] Further studies of this reaction have been carried out involving other Ni and Co catalysts as well as Fe, Cr, and Rh catalysts. Regardless of the catalyst system employed, only *trans* norbornadiene dimers were obtained as products, confirmed by ^1H coupling constants.[24] The dimers resulting from the Rh catalyzed reactions were minor products in the formation of trimers and other more complex cycloadducts.[25,26] Despite the many

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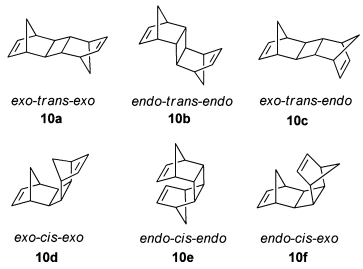
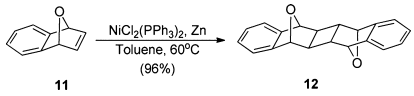


Figure 1. Possible structures of norbornadiene dimers.

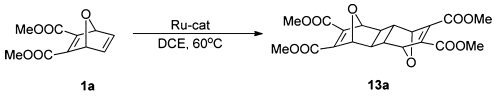
literature examples of the dimerization of norbornadiene, Cheng and co-workers provided the only example of the dimerization of an oxabicyclic alkene. It was shown that oxabenzonorbornadiene **11** will undergo a [2 + 2] dimerization in the presence of $NiCl_2(PPh_3)_2$ and Zn to give dimer **12** in high yield (96%) (Scheme 2). The *exo-trans-exo* conformation was predicted based on the ^1H and ^{13}C NMR spectra and confirmed using X-ray diffraction.[24]

Scheme 2. Dimerization of Oxabenzonorbornadiene



Our interest in oxabicyclic alkenes and the lack of investigation into the dimerization of these compounds lead to our study of the Ru catalyzed dimerization of 7-oxabicyclo-[2,2,1]hepta-2,5-diene-2,3-dicarboxylates. Our investigations began by screening various Ru catalysts to determine their efficacy in this dimerization (Table 1). Initially, Cp*Ru(COD)-

Table 1. Dimerization Catalyst Optimization



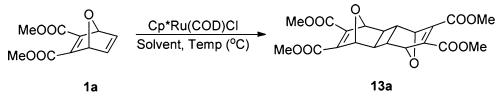
entry	catalyst	yield (%)[a]
1	Cp*Ru(COD)Cl	66
2	CpRu(COD)Cl	24
3	CpRu(COD)Br	32
4	CpRu(COD)I	16
5	Cp*Ru(COD)Br	70
6	$[Cp^*Ru(CH_3CN)_3]^+PF_6^-$	55
7	$[CpRu(CH_3CN)_3]^+PF_6^-$	58
8	$Ru(COD)Cl_2$	0
9	$(Ph_3P)_2CpRuCl$	0

[a]Isolated yields after column chromatography.

Cl, a useful catalyst in many other reactions of bicyclic alkenes, was tested for its ability to dimerize **1a**, yielding 66% of the product **13a**. The CpRu(COD)X series (where X = Cl, Br, and I, entries 2−4) were also examined resulting in lower yields in all three cases. Interestingly, the use of CpRu(COD)Br produced more product than its counterparts leading us to attempt the dimerization reaction catalyzed by Cp*Ru(COD)-Br (entry 5). The use of the bromide ligand in this case also lead to an increase in yield compared to the chloride ligand, obtaining 70% conversion to the desired product. Two cationic Ru catalysts were additionally investigated (entries 6 and 7). Both gave good yields but were not as effective as either of the Cp*Ru(COD)X variants. $Ru(COD)Cl_2$ and $(Ph_3P)_2CpRuCl$ provided no discernible products from reaction under these conditions. Since there is very little difference in the product yields when Cp*Ru(COD)Cl or Cp*Ru(COD)Br was used, Cp*Ru(COD)Cl was chosen for all further investigations due to its commercial availability.

With our catalyst of choice, Cp*Ru(COD)Cl, in hand, we went on to explore solvent and temperature effects on this dimerization (Table 2). All solvents tested provided moderate

Table 2. Solvent and Temperature Optimization



entry	solvent	temp (°C)	yield (%)[a]
1	DMSO	60	39
2	toluene	60	44
3	DMF	60	45
4	THF	60	50
5	hexane	60	51
6	DCE	60	66
7	DCE	45	54
8	DCE	25	61

[a]Isolated yields after column chromatography.

yields of the dimer; however, some proved more effective than others. DMSO provided the lowest yield of 39% (entry 1). Toluene and DMF (entries 2 and 3) resulted in slightly higher yields at 44% and 45%, respectively. When the reaction was ran in THF or hexanes (entries 4 and 5) an increased yield was again observed providing 50% and 51% of the desired product, respectively. Utilizing DCE (entry 6) as a solvent resulted in a much higher yield of 66% and was thus selected as our solvent of choice. Less variability was observed when the effect of temperature on the dimerization was explored (entries 6−8). Running the reaction at 60 °C provided a slightly higher yield than at 45 or 25 °C.

Having determined the optimal conditions for our desired reaction, we moved on to explore the scope of the reaction (Table 3). We first examined the effect of changing the alkyl component of the ester. Increasing the size of the ester moiety did not affect the reaction (entries 1−3). Regardless of whether a Me, Et, or ^{t}Bu ester was present on C2 and C3 of the starting oxabicyclic alkene **1a−c**, the yield of the dimer **13a−c** remained constant at 66%. These results negate any steric effect of the ester component of the bicyclic in the reaction mechanism. The [2 + 2] cycloaddition that takes place to produce the dimerized product occurs between C5 and C6 of both oxabicyclic alkenes, so it follows that added steric bulk at C2 and C3 would not have an effect on the outcome of the reaction. The stereochemistry of the dimerized product **13c** was confirmed by X-ray crystallography and was found to have an *exo-trans-exo* geometry.[27a]

We have examined the effect of a substitutent at the C1 position of the bicyclic alkene on the Ru-catalyzed dimerization reaction (Table 3, entries 4−11). Two possible *exo-trans-exo* dimerization products could be formed: one with the two C1 substituents *syn* to each other, and another with the two C1 substituents *anti* to each other (Figure 2). To our delight, the reactions were highly regioselective, and only the *syn exo-trans-exo* dimers were formed in all cases. Although the *syn*-dimers

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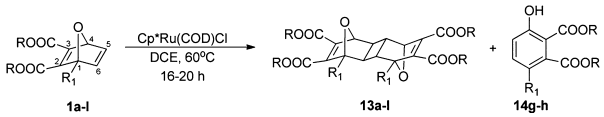
Table 3. Dimerization Reactions of Oxanorbornadienes



entry	alkene	R	R_1	yield (%)[a]
1	**1a**	Me	H	66
2	**1b**	Et	H	66
3	**1c**	^{t}Bu	H	66
4	**1d**	Me	Me	57
5	**1e**	Me	Et	24
6	**1f**	Me	$(CH_2)_4CH_3$	23
7	**1g**	Me	^{t}Bu	0 (68)[b]
8	**1h**	Me	TMS	0 (47)[b]
9	**1i**	Me	COOMe	53
10	**1j**	Me	Ph	0[c]
11	**1k**	Me	CH_2OH	0[c]

[a]Isolated yields. [b]Yields of ring opened aromatized products **14** in parentheses when the reactions were run at 80 °C for 48 h. [c]Complicated mixture of products was obtained.

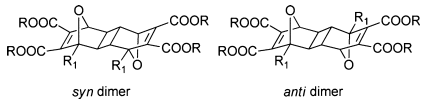
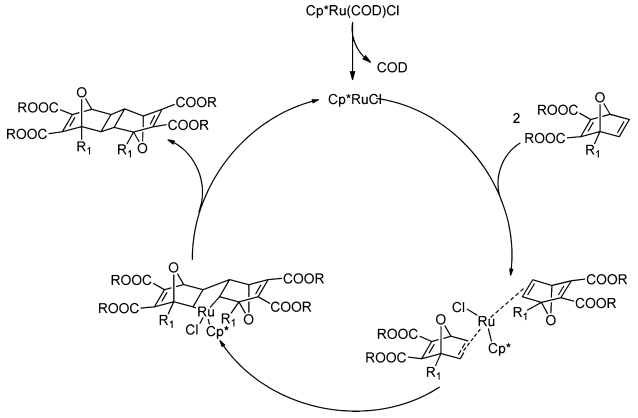


Figure 2. Two possible *exo-trans-exo* dimerization products.

might be expected to be less stable due to R1−R1 interactions that are not present in the *anti*-dimers,[28] they are the only isolated products and the structures of dimers **13d** and **13i** were confirmed by X-ray crystallography.[27b,c] We do not have a good explanation at this point why the *syn*-dimers were formed preferentially, and further mechanistic studies including computation calculations will be required. When a methyl group was introduced at the C1 position of the bicyclic alkene (entry 4), a slight decrease in yield to 57% was observed. Substitution at this position does have a steric effect on the reaction as indicated by the sharp decrease in yield when the size of the substituent was increased from a methyl group to an ethyl or pentyl group which produced the corresponding dimer in a 24% and 23% yield, respectively (Table 3, entries 5 and 6). With successful examples of primary alkyl groups, the dimerization of a C1 ^{t}Bu oxabicyclic alkene **1g** was undertaken (entry 7). To our surprise, starting material was recovered with no observable reaction under the initial conditions. In an attempt to try and promote the reaction to occur, the temperature was increased to 80 °C and the reaction was allowed to stir for 48 h instead of the usual 18 h. The change in conditions did not produce the desired dimer but instead resulted in ring opened aromatized product **14g** in a 68% yield. Similarly when the C1 TMS substituted oxabicyclic alkene **13h** (entry 8) was subjected to our standard conditions, no [2 + 2] dimerization product was obtained and the ring opened aromatized product **14h** was formed in 47% yield. An increase in in the size of the C1 substituent (from 1° alkyl groups Me, Et, and pentyl to 3° alkyl group ^{t}Bu or a TMS group) may lead to the disfavored sterically crowded Ru-pentacycle (Scheme 3) with two bulky R1 groups close to the Cp* ligand on the Ru, and therefore with bulky R1 groups, only ring opened aromatized products were obtained. Changing the electronic nature of the C1 substituent to the electron-withdrawing methyl ester **1i** resulted in the dimerized oxanorbornadiene in

Scheme 3. Proposed Dimerization Mechanism



53% yield (Table 3, entry 9). The presence of other C1 substituents such as Ph and CH_2OH (**1j**−**1k**, entries 10−11) led to decomposition of the oxanorbornadiene and produced a complicated mixture of products.

Having been able to confirm the *exo-trans-exo* configuration of our dimerized products, we can propose a mechanism for the formation of these products (Scheme 3). Following dissociation of the COD ligand from Cp*Ru(COD)Cl, there is coordination of the new Ru complex to the C2−C3 olefin of the bicyclics. Oxidative cyclization provides a metallacyclopentane intermediate which undergoes reductive elimination to provide the dimerized oxanorbornadiene and regenerate the Ru-catalyst. Coordination of the catalyst preferentially takes place on the *exo* face, as it is more sterically favorable.

In conclusion, we have demonstrated the ruthenium catalyzed dimerization reaction of oxanorbornadiene dicarboxylates. Dimerization of the parent compound proceeded smoothly, with yields decreasing when substituents are added at the C1 position. The ruthenium catalyzed dimerization reactions of C1 substituted oxanorbornadiene dicarboxylates were found to be highly regioselective, giving only the *syn*-dimers in moderate yields.

EXPERIMENTAL SECTION

General Information. All reactions were carried out in an atmosphere of dry nitrogen or argon. ^{1}H and ^{13}C spectra were recorded on a 400 MHz spectrometer. Starting alkenes were prepared according to the following known literature procedures: **1a**,[29] **1b**,[30] **1c**,[31] **1d**,[17] **1e**,[32] **1f**,[33] **1h**,[34] **1i**,[35] **1j**,[36] and **1k**.[31]

Oxanorbornadiene 1g. Dimethylacetylene dicarboxylate (0.39 mL, 3.2 mmol) was measured and added via syringe into an N_2 purged oven-dried screw cap vial. 2-*tert*-Butylfuran (0.50 mL, 3.5 mmol) was added dropwise via syringe. The vial was purged with N_2, and the septum was replaced with a cap. The reaction was heated to 90 °C and allowed to stir for 12 h. The crude product was purified by column chromatography (EtOAc/hexanes 3:7) to give oxanorbornadiene **1g** (638 mg, 2.4 mmol, 75%) as a yellow oil. R_f 0.43 (EtOAc/hexanes 3:7); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.14 (dd, 1H, J = 1.8, 5.3 Hz), 7.08 (d, 1H, J = 5.3 Hz), 5.59 (d, 1H, J = 1.8 Hz), 3.79 (s, 3H), 3.68 (s, 3H), 1.06 (s, 9H); ^{13}C (APT, $CDCl_3$, 100 MHz) δ 167.7, 162.1, 159.2, 149.4, 145.0, 142.7, 105.5, 82.1, 52.3, 52.0, 32.6, 26.1; IR (neat) 3434, 3095, 2957, 2911, 2846, 1732, 1634, 1560, 1436, 1399, 1248, 1222, 1146, 1075, 1035, 996, 953, 936, 885, 821, 756, 737, 709, 684 cm^{-1}; HRMS (EI-TOF) calcd for $C_{14}H_{18}O_5$ (M^+): 266.1154; found: 266.1159.

General Procedure for the Ru-Catalyzed Dimerization of Oxanorbornadienes (Table 3, Entry 1). Oxanorbornadiene **1a** (44 mg, 0.21 mmol) was weighed into an oven-dried screw-cap vial. The vial was purged with nitrogen, taken into the drybox where

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Cp*RuCl(COD) (8 mg, 0.02 mmol) and DCE (0.3 mL) were added, and sealed. The reaction mixture was stirred outside the glovebox at 60 °C for 16−20 h. The crude product was purified by flash chromatography to yield the corresponding cycloadduct (ethyl acetate/hexanes mixture).

Dimer 13a (Table 3, Entry 1). The crude product was purified by column chromatography (EtOAc/hexanes 2:3) to give the dimer **13a** (29.0 mg, 0.069 mmol, 66%) as a white solid (mp 180−182 °C). R_f 0.2 (EtOAc/hexanes 2:3); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.16 (s, 4H), 3.79 (s, 12H), 2.17 (s, 4H); ^{13}C (APT, $CDCl_3$, 100 MHz) δ 162.6, 142.7, 82.6, 52.2, 39.6; IR (CH_2Cl_2) 3007, 2955, 2847, 1717, 1631, 1437, 1306, 1229, 1121, 917, 746 cm^{-1}; HRMS (EI-TOF) calcd for $C_{20}H_{20}O_{10}$ (M^+): 420.1056; found: 420.1073.

Dimer 13b (Table 3, Entry 2). The crude product was purified by column chromatography (EtOAc/hexanes 3:7) to give the dimer **13b** (106.2 mg, 0.22 mmol, 66%) as a white solid (mp 173−175 °C); R_f 0.31 (EtOAc/hexanes 3:7); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.14 (s, 4H), 4.20−4.26 (q, 8H, J = 7.1 Hz), 2.16 (s, 4H), 1.27−1.30 (t, 12H, J = 6.7 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 162.3, 142.5, 82.6, 61.3, 39.7, 14.0; IR (CH_2Cl_2) 2941, 1707, 1630, 1333, 1227, 1122, 1022, 918 cm^{-1}; HRMS (EI-TOF) calcd for $C_{24}H_{28}O_{10}$ (M^+): 476.1683; found: 476.1665.

Dimer 13c (Table 3, Entry 3). The crude product was purified by column chromatography (EtOAc/hexanes 1:9) to give dimer **13c** (28.8 mg, 0.050 mmol, 66%) as a white solid (mp 120 °C dec.); R_f 0.22 (EtOAc/hexanes 1:9); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.07 (s, 4H), 2.14 (s, 4H), 1.49 (s, 36H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 161.7, 142.7, 82.7, 82.4, 40.0, 28.0; IR (CH_2Cl_2) 1725, 1655, 1422, 1370, 1164, 1123, 896 cm^{-1}; HRMS (ESI-Quadrupole TOF) calcd for $C_{32}H_{44}O_{10}$ (M^+Na^+): 611.2832; found 611.2829.

Dimer 13d (Table 3, Entry 4). The crude product was purified by column chromatography (EtOAc/hexanes 2:3) to give dimer **13d** (23.7 mg, 0.053 mmol, 57%) as a white solid (mp 129−131 °C); R_f 0.29 (EtOAc/hexanes 2:3); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.07 (s, 2H), 3.82 (s, 6H), 3.76 (s, 6H), 2.16 (s, 4H), 1.63 (s, 6H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 164.4, 162.2, 146.8, 140.8, 89.4, 81.32, 52.3, 52.2, 41.3, 41.2, 12.4; IR (CH_2Cl_2) 2955, 2846, 1721, 1634, 1437, 1389, 1200, 1063, 1001, 832 cm^{-1}; HRMS (EI-TOF) calcd for $C_{22}H_{24}O_{10}$ (M^+): 448.1370; found: 448.1355.

Dimer 13e (Table 3, Entry 5). The crude product was purified by column chromatography (EtOAc/hexanes 2:3) to give dimer **13e** (48.4 mg, 0.086 mmol, 24%) as a white solid (mp 110−115 °C); R_f 0.44 (EtOAc/hexanes 2:3); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.10 (s, 2H), 3.83 (s, 6H), 3.76 (s, 6H), 2.14−2.20 (m, 4H), 1.96−2.10 (m, 4H), 0.99−1.03 (t, 6H, J = 7.5 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 164.9, 162.1, 146.5, 141.1, 94.1, 81.1, 52.3, 52.2, 41.6, 40.7, 19.7, 9.3; IR (CH_2Cl_2) 2955, 2884, 1720, 1631, 1437, 1330, 1226, 1074, 1014, 938, 896 cm^{-1}; HRMS (EI-TOF) calcd for $C_{24}H_{28}O_{10}$ (M^+): 476.1683; found: 476.1702.

Dimer 13f (Table 3, Entry 6). The crude product was purified by column chromatography (EtOAc/hexanes 1:4) to give dimer **13f** (24.5 mg, 0.044 mmol, 23%) as a white solid (mp 71−72 °C); R_f 0.29 (EtOAc/hexanes 1:4); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.10 (s, 2H), 3.83 (s, 6H), 3.76 (s, 6H), 2.18−2.19 (d, 2H, J = 5.80 Hz), 2.13−2.14 (d, 2H, J = 5.80 Hz), 1.95−1.96 (m, 4H), 1.48−1.49 (m, 2H), 1.29−1.35 (m, 6H), 0.87−0.90 (t, 6H, J = 6.68 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 165.0, 162.2, 146.6, 141.0, 93.7, 81.2, 52.3, 52.2, 41.5, 41.0, 32.1, 26.6, 24.9, 22.3, 13.9; IR (CH_2Cl_2) 2955, 2872, 1720, 1630, 1437, 896 cm^{-1}; HRMS (EI-TOF) calcd for $C_{30}H_{40}O_{10}$ (M^+): 560.2622; found: 560.2636.

Dimer 13i (Table 3, Entry 9). The crude product was purified by column chromatography (EtOAc/hexanes 1:1) to give dimer **13i** (165.5 mg, 0.617 mmol, 53%) as a white solid (mp 196−198 °C); R_f 0.40 (EtOAc/hexanes 1:1); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.25 (s, 2H), 3.87 (s, 6H), 3.81 (s, 6H), 3.79 (s, 6H), 2.60−2.61 (d, 2H, J = 5.4 Hz), 2.35−2.37 (d, 2H, J = 5.4 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 165.9, 162.5, 161.6, 143.8, 140.4, 90.5, 82.0, 53.0, 52.7, 52.6, 41.8, 41.0; IR (CH_2Cl_2) 2956, 2850, 1743, 1438, 1331, 1204, 1158, 1082, 1036, 896 cm^{-1}; HRMS (EI-TOF) calcd for $C_{24}H_{24}O_{14}$ (M^+): 536.1166; found: 536.1166.

Phenol 14g (Table 3, entry 7). The crude product was purified by column chromatography (EtOAc/hexanes 2:3) to give phenol **14g** (45.3 mg, 0.169 mmol, 68%) as a brown oil; R_f 0.18 (EtOAc/hexanes 2:3); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 10.81 (s, 1H), 7.60−7.63 (d, 1H, J = 9.12), 6.98−7.01 (d, 1H, J = 9.08), 3.92 (s, 3H), 3.84 (s, 3H), 1.35 (s, 9H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 170.6, 169.7, 159.4, 138.3, 134.5, 133.0, 118.8, 110.2, 53.0, 52.1, 35.8, 31.5; IR (CH_2Cl_2) 3423, 2956, 1738, 1675, 1591, 1441, 1326, 1193, 1161, 1012 cm^{-1}; HRMS (EI-TOF) calcd for $C_{14}H_{18}O_5$ (M^+): 266.1154; found: 266.1162.

Phenol 14h (Table 3, Entry 8). The crude product was purified by column chromatography (EtOAc/hexanes 1:9) to give phenol **14h** (10.9 mg, 0.042 mmol, 47%) as a yellow oil; R_f 0.32 (EtOAc/hexanes 1:9); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 10.84 (s, 1H), 7.61−7.63 (d, 1H, J = 8.44 Hz), 7.03−7.05 (d, 1H, J = 8.48 Hz), 3.92 (s, 3H), 3.86 (s, 3H), 0.254 (s, 9H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ170.1, 169.6, 161.7, 140.9, 140.9, 128.1, 118.4, 110.0, 52.9, 52.1, −0.5; IR (CH_2Cl_2) 3423, 2955, 1736, 1677, 1577, 1458, 1343, 1255, 1212, 1130, 1014, 895, 877, 802 cm^{-1}; HRMS (EI-TOF) calcd for $C_{13}H_{18}O_5Si$ (M^+): 282.0924; found: 282.0935.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H and ^{13}C NMR spectra all new compounds. 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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■ REFERENCES

(1) Khoury, P. R.; Goddard, J. D.; Tam, W. *Tetrahedron* **2004**, *60*, 8103.

(2) Corey, E. J.; Shibasaki, M.; Nicolaou, K. C.; Malmsten, C. L.; Samuelsson, B. *Tetrahedron Lett.* **1976**, 737.

(3) Lee, M.; Ikeda, I.; Kawabe, T.; Mori, S.; Kanematsu, K. *J. Org. Chem.* **1996**, *61*, 3406.

(4) Sato, K.; Miyamoto, O.; Inoue, S.; Honda, K. *Chem. Lett.* **1981**, 1183.

(5) Monti, H.; Corriol, C.; Bertrand, M. *Tetrahedron Lett.* **1982**, *23*, 5539.

(6) Rayabarapu, D. K.; Cheng, C.-H. *Acc. Chem. Res.* **2007**, *40*, 971.

(7) Lautens, M.; Fagnou, K.; Hiebert, S. *Acc. Chem. Res.* **2003**, *36*, 48.

(8) Schindler, C. S.; Carreira, E. M. *Chem. Soc. Rev.* **2009**, *38*, 3222.

(9) Tam, W.; Cockburn, N. *Synlett* **2010**, 1170.

(10) Burton, R. R.; Tam, W. *J. Org. Chem.* **2007**, *72*, 7333.

(11) Cockburn, N.; Karimi, E.; Tam, W. *J. Org. Chem.* **2009**, *74*, 5762.

(12) Ahmar, M.; Cazes, B. *Tetrahedron Lett.* **2003**, *44*, 5403.

(13) Shinohara, H.; Sonoda, M.; Atobe, S.; Masuno, H.; Ogawa, A. *Tetrahedron Lett.* **2011**, *52*, 6238.

(14) Zhang, T.-K.; Yuan, K.; Hou, X.-L. *J. Organomet. Chem.* **2007**, *692*, 1912.

(15) Ladjel, C.; Fuchs, N.; Zhao, J.; Bernardinelli, G.; Alexakis, A. *Eur. J. Org. Chem.* **2009**, 4949.

(16) Wong, C. H.; Hung, C. W.; Wong, H. N. C. *J. Organomet. Chem.* **1988**, *342*, 9.

(17) Xing, Y. D.; Huang, N. Z. *J. Org. Chem.* **1982**, *47*, 140.

(18) Villeneuve, K.; Tam, W. *Organometallics* **2007**, *26*, 6082.

(19) Tenaglia, A.; Marc, S. *J. Org. Chem.* **2006**, *71*, 3569.
(20) Allen, A.; Le, M. P.; Burton, R.; Villeneuve, K.; Tam, W. *J. Org. Chem.* **2007**, *72*, 7849.
(21) Nishimura, T.; Kawamoto, T.; Sasaki, K.; Tsurumaki, E.; Hayashi, T. *J. Am. Chem. Soc.* **2007**, *129*, 1492.
(22) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 259.
(23) Arnold, D. R.; Trecker, D. J.; Whipple, E. B. *J. Am. Chem. Soc.* **1965**, *87*, 2596.
(24) Huang, D.-J.; Cheng, C.-H. *J. Organomet. Chem.* **1995**, *490*, C1.
(25) Acton, N.; Roth, R. J.; Katz, T. J.; Frank, J. K.; Maier, C. A.; Paul, I. C. *J. Am. Chem. Soc.* **1972**, *94*, 5446.
(26) Katz, T. J.; Acton, N. *Tetrahedron Lett.* **1967**, 2601.
(27) (a) Lough, A. J.; Jack, K.; Tam, W. *Acta Crystallogr.* **2012**, *E68*, o2962. (b) Lough, A. J.; Jack, K.; Tam, W. *Acta Crystallogr.* **2012**, *E68*, o2961. (c) Lough, A. J.; Jack, K.; Tam, W. *Acta Crystallogr.* **2012**, *E68*, o2963.
(28) Lautens, M.; Fillion, E. *J. Org. Chem.* **1997**, *62*, 4418.
(29) van Berkel, S. S.; Dirks, A. J.; Debets, M. F.; van Delft, F. L.; Cornelissen, J. J. L. M.; Nolte, R. J. M.; Rutjes, F. P. J. T. *ChemBioChem* **2007**, *8*, 1504.
(30) Safaei-Ghomi, J.; Tajbakhsh, M.; Kazemi-Kani, Z. *Acta Chim. Slov.* **2004**, *51*, 545.
(31) Weber, G.; Menke, K.; Hopf, H. *Chem. Ber.* **1980**, *113*, 531.
(32) Fry, A. J.; Sherman, L. R.; Beaulieu, A. R.; Sherwin, C. *J. Org. Chem.* **1990**, *55*, 389.
(33) Bighelli, A.; Tomi, F.; Casanova, J. *Magn. Reson. Chem.* **1992**, *30*, 1268.
(34) Tanaka, A.; Harigaya, Y.; Nishino, N.; Nakayama, K. *Heterocycles* **1988**, *27*, 1115.
(35) Burton, R. R.; Tam, W. *Tetrahedron Lett.* **2006**, *47*, 7185.
(36) Bansal, R. K.; McCulloch, A. W.; Rasmussen, P. W.; McInnes, A. G. *Can. J. Chem.* **1975**, *53*, 138.

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