JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

Iron-Catalyzed Acylation-Oxygenation of Terminal Alkenes for the Synthesis of Dihydrofurans Bearing a Quaternary Carbon

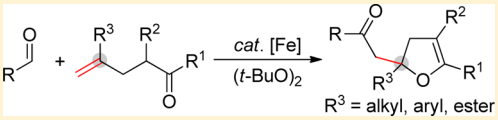
Leiyang Lv,[†] Shenglin Lu,[†] Qiaoxia Guo,[‡] Baojian Shen,[‡] and Zhiping Li*[,†,‡]

[†]Department of Chemistry, Renmin University of China, Beijing 100872, China

[‡]State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China

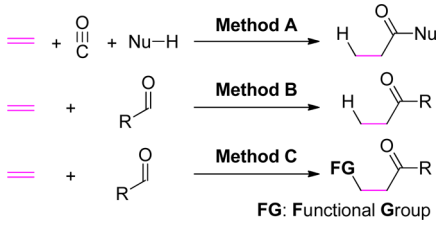
Supporting Information

ABSTRACT: Iron-catalyzed acylation-oxygenation of terminal alkenes is reported. Acyl radicals generated by the oxidation of aldehydes add to terminal alkenes and followed by intramolecular oxygenation give functionalized 2,3-dihydrofuran derivatives bearing a quaternary carbon.



Carbonylation of alkenes has gained widespread acceptance in both industry and academia for the synthesis of carbonyl compounds. Hydroformylation and the Reppe process using carbon monoxide present a reliable and powerful strategy for carbonylation of alkenes (Scheme 1, Method A).[1] Direct

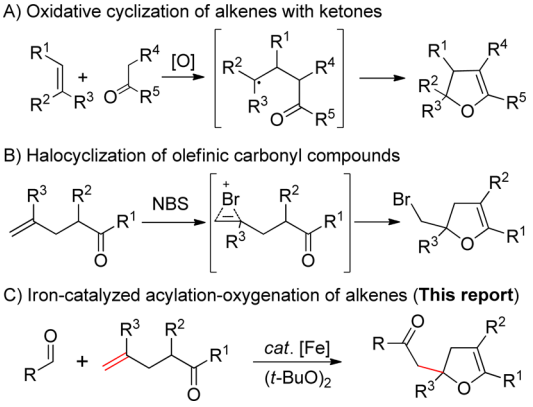
Scheme 1. Examples for the Synthesis of Carbonyl Compounds from Alkenes



transformation of formyl C–H bonds to form C–C bonds provides great synthetic benefits for carbonylation reactions from the points of view of the difficulty in handling gaseous carbon monoxide and the readily available aldehydes (Scheme 1, Method B).[2] Difunctionalization of alkenes deserves diligent attention in view of its rapid introduction of two functional groups across a C–C double bond in one step.[3] Despite this successful approach, difunctionalization of alkenes with a carbonyl and other functional groups remained challenging,[4] including the limitations of alkene carbonylation reactions and the difficulty of the introduction of the second functional group. To address this issue, we envisioned that aldehyde as a carbonyl unit might facilitate the process and extend the scope of carbonylation of alkenes (Scheme 1, Method C).[5]

The dihydrofuran skeleton is an important subunit of biologically active compounds and also a useful building block in organic synthesis.[6] A variety of synthetic methods have been successfully developed for synthesis of dihydrofuran derivatives.[7−9] Oxidative cyclization of alkenes with ketones presents one of the typical routes for 2,3-dihydrofuran formation (Scheme 2A).[8] Halocyclization of olefinic carbonyl compounds provided an excellent access to introduce a functional group into the dihydrofuran skeleton, which could

Scheme 2. Synthesis of Dihydrofurans from Alkenes

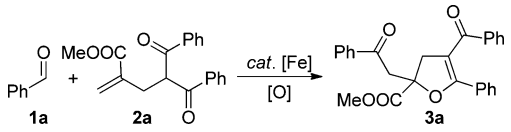


be used for the further transformation (Scheme 2B).[9] Following our efforts on acylation of alkenes with aldehydes,[10] we here wish to report an iron-catalyzed[11] acylation-oxygenation of terminal alkenes to synthesize 2,3-dihydrofurans (Scheme 2C). The salient feature of the method includes the introduction of a carbonyl substituent and a quaternary carbon bearing a variety of functional groups (alkyl, aryl, and ester) onto the dihydrofuran skeleton.

Initially, the reaction of benzaldehyde **1a** with alkene **2a** was chosen as a model reaction to establish the reaction conditions (Table 1). A 65% yield of the desired dihydrofuran product **3a** was obtained by applying $FeCl_2$ as catalyst and di-*tert*-butylperoxide as oxidant (entry 1). Interestingly, the yields of **3a** were less affected by the choice of iron catalysts (entries 2–5), while other catalysts such as Cu, Co, and Mn completely inhibited the desired transformation and over 95% of **2a** was recovered (entries 6–9). Importantly, **3a** was formed in a 20% yield along with the recovery of **2a** in 19% without a catalyst (entry 10). These results indicate that the iron catalyst is unique and important for the efficiency of this transformation. Other oxidants such as *tert*-butyl hydroperoxide, *tert*-butyl

Received: November 6, 2014
Published: November 26, 2014

Table 1. Optimization of Reaction Conditions[a]



entry	[Fe]	[O]	yield of **3a** (%)[b]
1	$FeCl_2$	$(t\text{-BuO})_2$	65(56)
2	$FeBr_2$	$(t\text{-BuO})_2$	65
3	$Fe(OAc)_2$	$(t\text{-BuO})_2$	65
4	$Fe_2(CO)_9$	$(t\text{-BuO})_2$	62
5	$FeCl_3$	$(t\text{-BuO})_2$	64
6	$CuCl_2$	$(t\text{-BuO})_2$	trace
7	$CoCl_2$	$(t\text{-BuO})_2$	trace
8	$MnBr_2$	$(t\text{-BuO})_2$	trace
9	$Mn(OAc)_2$	$(t\text{-BuO})_2$	trace
10		$(t\text{-BuO})_2$	20
11	$FeCl_2$	*t*-BuOOH	18[c]
12	$FeCl_2$	PhCOOOBu-*t*	40
13	$FeCl_2$	$(PhCOO)_2$	trace
14	$FeCl_2$	$(t\text{-BuO})_2$	N.D.[d]

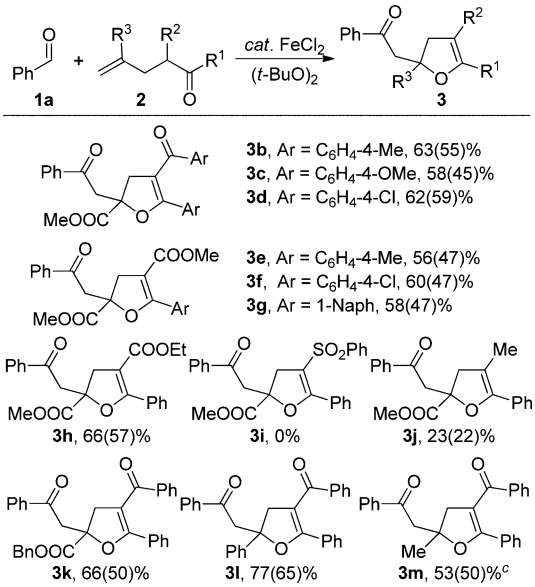
[a]Reaction conditions: **1a** (1.5 mmol), **2a** (0.3 mmol), [Fe] (2.5 mol %), [O] (0.75 mmol), PhCl (1.0 mL), 120 °C, 1 h, under N_2. [b]NMR yields were determined by ^{1}H NMR using an internal standard (the yield in parentheses). [c]An acylation-peroxidation product was obtained in 70% yield; see ref 10d. [d]100 °C; Not Detected.

peroxybenzoate, and benzoyl peroxide were also examined and found less effective than di-*tert*-butyl peroxide (entries 11−13). It should be noted that the reaction failed to facilitate the desired transformation and **2a** was recovered quantitatively at 100 °C (entry 14). This result supported that (1) the acylation step of this reaction is most likely reversible; (2) the formation of **3a** plays a driving force in the present transformation. On the basis of the above optimization, we chose $FeCl_2$ as catalyst and di-*tert*-butylperoxide as oxidant under 120 °C (entry 1) for the following studies.

Subsequently, the generality of the transformation was investigated under the optimized reaction conditions (Tables 2 and 3). First, the scope and limitation of alkenes were investigated under the optimized reaction conditions (Table 2). Olefinic β-diketones smoothly reacted with benzaldehyde **1a** to give the corresponding dihydrofurans **3b−d**. Olefinic β-ketone esters (R^2 is ester group) were also successfully applied to this transformation and led to **3e−g** in moderate yields. However, the reaction of benzaldehyde **1a** and the substrate with a SO_2Ph group was messy and the desired product **3i** was not observed by ^{1}H NMR analysis. The low yield of **3j** was obtained when R^2 is a methyl group. We hypothesized that the efficiency of the reaction might be associated with the step of the deprotonation of the intermediate **H** (Scheme 3) in the latter case. To our delight, the substrates bearing a benzyl ester, phenyl group, and methyl at the C=C moiety (R^3) smoothly underwent the acylation-oxygenation transformation to give **3k−m** in good to moderate yields under the standard reaction conditions.

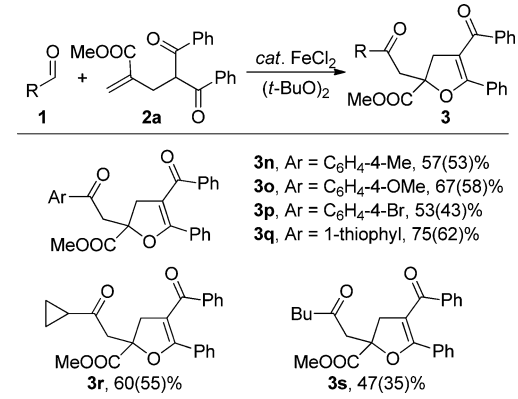
Next, the scope of aldehydes **1** was investigated. Both aromatic and aliphatic aldehydes reacted smoothly with **2a** and afforded the desired products **3n−s** in good to moderate yields under the standard conditions (Table 3). However, the decarbonylation products **4** and **5** were obtained when cyclohexane carboxaldehyde **1h** and pivaldehyde **1i** were applied (eqs 1 and 2). These results are consistent with the stabilities of the generated acyl radicals.[12]

Table 2. Scope of Alkene 2[a,b,c]



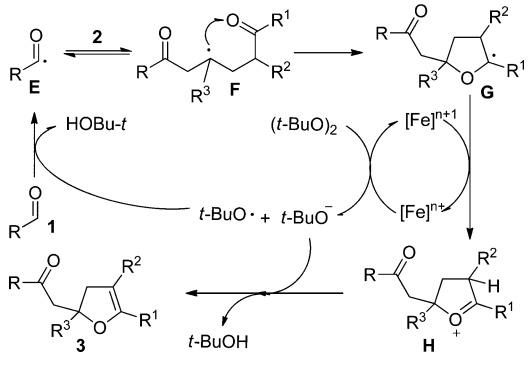
[a]Reaction conditions: **1a** (1.5 mmol), **2** (0.3 mmol), $FeCl_2$ (2.5 mol %), $(t\text{-BuO})_2$ (0.75 mmol), PhCl (1.0 mL), 120 °C, 1 h, under N_2. [b]Reported yields were based on **2** and determined by ^{1}H NMR using an internal standard; the yields are given in parentheses. [c]2 h.

Table 3. Scope of Aldehyde 1[a,b]



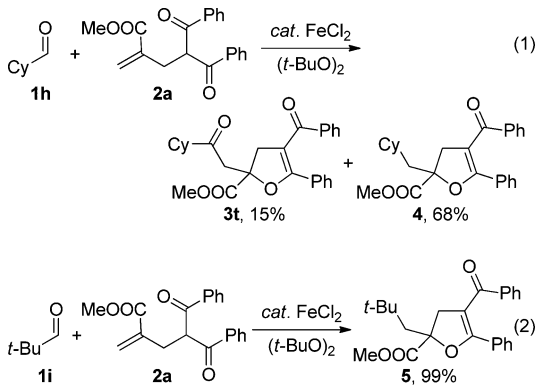
[a]Reaction conditions: **1** (1.5 mmol), **2a** (0.3 mmol), $FeCl_2$ (2.5 mol %), $(t\text{-BuO})_2$ (0.75 mmol), PhCl (1.0 mL), 120 °C, 1 h, under N_2. [b]Reported yields were based on **2a** and determined by ^{1}H NMR using an internal standard; the yields are given in parentheses.

Scheme 3. A Tentative Reaction Mechanism

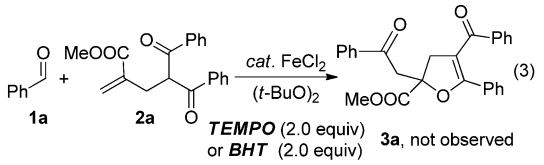


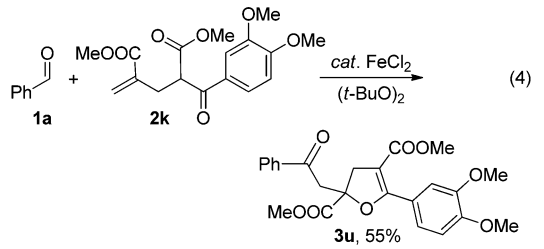
To further understand the mechanism of this reaction, the control experiments were carried out under the standard

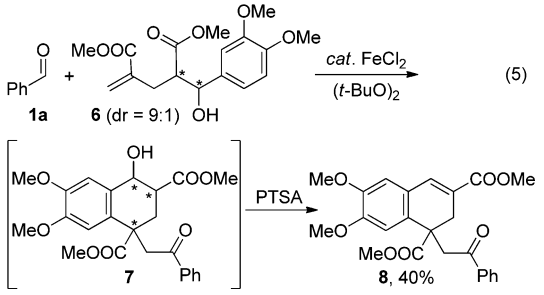
dx.doi.org/10.1021/jo502535k | J. Org. Chem. 2015, 80, 698−704



conditions (eqs 3−5). The radical scavengers 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) and butylated hydroxytoluene (BHT) completely inhibited the dihydrofuran formation, and **2a** was recovered quantitatively (eq 3). These results supported that the present transformation is initiated by the addition of the generated acyl radical to the C=C bond. The reaction of **1a** with olefinic ketone **2k** gave the desired dihydrofuran **3u** in 55% yield (eq 4). In contrast, a tetrahydronaphthalene product **7** was obtained as a major product when the alkene **6** bearing a hydroxyl group instead of a carbonyl group was applied, followed by dehydration to give the dihydronaphthalene derivative **8** (eq 5). The expected tetrahydrofuran product **9** via the possible intermediate **A** or **B** was not observed (Figure 1, above). On the basis of these results, we hypothesized that the formation of dihydrofuran **3u** was not likely through the possible intermediate **C** or **D** (Figure 1, below).







Based on our results and the previous results,[5,10] a tentative reaction mechanism for the iron-catalyzed oxidative acylation-oxygenation process is illustrated in Scheme 3. Hydrogen abstraction of aldehyde **1** by *tert*-butoxyl radical gives acyl

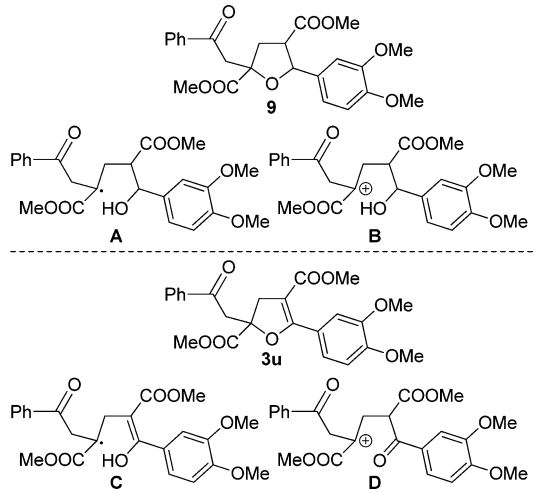


Figure 1. Types of the possible intermediates.

radical **E**. Subsequently, the radical addition of **E** to the C=C bond of **2** affords the corresponding carbon radical intermediate **F**, which undergoes 5-endo-trig radical addition to generate the intermediate **G**.[13] Following iron-catalyzed oxidation, the oxonium cation **H** is formed. The reduced iron catalyst reacts with di-*tert*-butylperoxide to give a *tert*-butoxyl radical along with a *tert*-butoxide anion. Finally, deprotonation of **H** releases the dihydrofuran **3**.

In summary, we have demonstrated a new and practical strategy for the acylation-oxygenation of terminal alkenes in the presence of an iron catalyst. A variety of multifunctional dihydrofuran derivatives bearing a quaternary carbon were synthesized selectively. The reaction may proceed via a tandem C−C/C−O radical oxidative coupling pathway.

EXPERIMENTAL SECTION

General Information. ^{1}H NMR spectra were recorded on a 400 MHz spectrometer, and the chemical shifts were reported in parts per million (δ) relative to the internal standard TMS (0 ppm) for $CDCl_3$. The peak patterns are indicated as follows: s, singlet; d, doublet; dd, doublet of doublet; t, triplet; q, quartet; m, multiplet. The coupling constants, *J*, are reported in hertz (Hz). ^{13}C NMR spectra were obtained at 100 MHz and referenced to the internal solvent signals (central peak is 77.0 ppm in $CDCl_3$, 29.8 ppm in $(CD_3)_2CO$). $CDCl_3$ was used as the NMR solvent. Flash column chromatography was performed over silica gel 200−300. All reagents were weighed and handled in air at room temperature. All reagents were purchased from a commercial source and used without further purification. $FeCl_2$ was purchased from Alfa, and the purity was 99.5% (metals basis). Chlorobenzene was dried and purified according to the procedure from the *Purification of Laboratory Chemicals* book.[14] The HRMS measurements were recorded on an FTMS analyzer using an ESI source in the positive mode.

General Procedure for Substrates 2. The substrates **2** were prepared according to the reported literatures.[9,15]

General Procedure for Products 3. To a mixture of alkene **1** (0.3 mmol), aldehyde **2** (1.5 mmol), and $FeCl_2$ (1.0 mg, 2.5 mol %), chlorobenzene (1.0 mL) was added under nitrogen at room temperature. Then, pure *di-tert*-butyl peroxide (137 μL, 0.75 mmol) was dropped into the mixture. The resulting mixture was stirred at 120 °C for 1 h. After the mixture was cooled to room temperature, the resulting solution was directly filtered through a pad of silica by EtOAc. The solvent was evaporated in vacuo to give the crude products. NMR yields were determined by ^{1}H NMR using dibromomethane as an internal standard. The residue was purified

dx.doi.org/10.1021/jo502535k | J. Org. Chem. 2015, 80, 698−704

by flash column chromatography on silica gel (ethyl acetate/petroleum ether) to give the pure product **3**.

*Methyl 4-Benzoyl-2-(2-oxo-2-phenylethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3a**).* (72 mg, 55%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.5); IR (neat): ν_{max} 1745, 1689, 1605, 1570, 1364, 1225, 1050, 1025, 899 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, J = 8.0 Hz, 2H), 7.58 (t, J = 7.4 Hz, 1H), 7.48−7.45 (m, 4H), 7.26−7.21 (m, 3H), 7.16 (t, J = 7.4 Hz, 1H), 7.08 (t, J = 7.8 Hz, 2H), 7.04 (t, J = 7.4 Hz, 2H), 3.95 (d, J = 17.5 Hz, 1H), 3.87 (d, J = 17.5 Hz, 1H), 3.87 (s, 3H), 3.68 (d, J = 15.8 Hz, 1H), 3.50 (d, J = 15.8 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.3, 193.0, 171.6, 164.4, 138.4, 136.1, 133.6, 131.4, 130.2, 129.4, 129.2, 128.9, 128.7, 128.1, 127.7, 127.5, 111.0, 85.1, 52.9, 46.2, 42.9; HRMS (ESI) calcd for $C_{27}H_{23}O_5$ [M + H^+], 427.1540; found: 427.1547.

*Methyl 4-(4-Methylbenzoyl)-2-(2-oxo-2-phenylethyl)-5-(p-tolyl)-2,3-dihydrofuran-2-carboxylate (**3b**).* (75 mg, 55%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.3); IR (neat): ν_{max} 1743, 1688, 1604, 1365, 1227, 1182, 1037, 895, 823 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, J = 7.3 Hz, 2H), 7.57 (t, J = 7.3 Hz, 1H), 7.46 (t, J = 7.6 Hz, 2H), 7.42 (d, J = 8.3 Hz, 2H), 7.17 (d, J = 8.1 Hz, 2H), 6.92 (d, J = 8.0 Hz, 2H), 6.86 (d, J = 8.0 Hz, 2H), 3.93 (d, J = 17.4 Hz, 1H), 3.86 (s, 3H), 3.84 (d, J = 17.4 Hz, 1H), 3.67 (d, J = 15.7 Hz, 1H), 3.46 (d, J = 15.7 Hz, 1H), 2.42 (s, 3H), 2.21 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.4, 192.8, 171.7, 163.5, 142.0, 140.4, 136.1, 135.8, 133.5, 129.3, 129.1, 128.6, 128.4, 128.2, 128.1, 126.4, 110.1, 84.8, 52.9, 46.2, 43.1, 21.4, 21.3; HRMS (ESI) calcd for $C_{29}H_{27}O_5$ [M + H^+], 455.1853; found: 455.1851.

*Methyl 4-(4-Methoxybenzoyl)-5-(4-methoxyphenyl)-2-(2-oxo-2-phenylethyl)-2,3-dihydrofuran-2-carboxylate (**3c**).* (66 mg, 45%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:2, R_f = 0.3); IR (neat): ν_{max} 1743, 1688, 1600, 1510, 1364, 1255, 1175, 1029, 895, 840 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, J = 7.8 Hz, 2H), 7.57 (t, J = 7.4 Hz, 1H), 7.53 (d, J = 8.8 Hz, 2H), 7.46 (t, J = 7.8 Hz, 2H), 7.25 (d, J = 8.8 Hz, 2H), 6.63 (d, J = 8.8 Hz, 2H), 6.59 (d, J = 8.8 Hz, 2H), 3.92 (d, J = 17.4 Hz, 1H), 3.85 (s, 3H), 3.84 (d, J = 17.4 Hz, 1H), 3.73 (s, 3H), 3.69 (s, 3H), 3.62 (d, J = 15.6 Hz, 1H), 3.46 (d, J = 15.6 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.5, 191.8, 171.8, 162.7, 162.4, 160.9, 136.1, 133.6, 131.3, 131.1, 128.6, 128.1, 121.7, 113.1, 109.2, 84.5, 55.2, 55.1, 52.9, 46.3, 43.4; HRMS (ESI) calcd for $C_{29}H_{27}O_7$ [M + H^+], 487.1751; found: 487.1750.

*Methyl 4-(4-Chlorobenzoyl)-5-(4-chlorophenyl)-2-(2-oxo-2-phenylethyl)-2,3-dihydrofuran-2-carboxylate (**3d**).* (88 mg, 59%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.3); IR (neat): ν_{max} 1745, 1689, 1613, 1592, 1488, 1448, 1401, 1361, 1250, 1225, 1140, 1092, 893, 839 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, J = 7.2 Hz, 2H), 7.59 (t, J = 7.2 Hz, 1H), 7.48 (t, J = 7.5 Hz, 2H), 7.43 (d, J = 8.6 Hz, 2H), 7.21 (d, J = 8.6 Hz, 2H), 7.12 (d, J = 8.6 Hz, 2H), 7.08 (d, J = 8.6 Hz, 2H), 3.92 (d, J = 17.5 Hz, 1H), 3.87 (d, J = 17.5 Hz, 1H), 3.86 (s, 3H), 3.63 (d, J = 15.9 Hz, 1H), 3.48 (d, J = 15.9 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.1, 191.3, 171.4, 163.1, 138.0, 136.7, 136.6, 136.0, 133.7, 130.7, 130.3, 128.7, 128.2, 128.1, 128.0, 127.5, 111.1, 85.2, 53.0, 46.1, 42.9; HRMS (ESI) calcd for $C_{27}H_{21}Cl_2O_5$ [M + H^+], 495.0761; found: 495.0774.

*Dimethyl 2-(2-Oxo-2-phenylethyl)-5-(p-tolyl)-2,3-dihydrofuran-2,4-dicarboxylate (**3e**).* (56 mg, 47%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.3); IR (neat): ν_{max} 1755, 1710, 1688, 1450, 1353, 1257, 1223, 1096, 831 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, J = 8.4 Hz, 2H), 7.72 (d, J = 8.0 Hz, 2H), 7.57 (t, J = 7.4 Hz, 1H), 7.46 (t, J = 8.0 Hz, 2H), 7.17 (d, J = 8.0 Hz, 2H), 3.91 (d, J = 17.4 Hz, 1H), 3.83 (s, 3H), 3.75 (d, J = 17.4 Hz, 1H), 3.68 (s, 3H), 3.65 (d, J = 15.9 Hz, 1H), 3.22 (d, J = 15.9 Hz, 1H), 2.36 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.5, 171.4, 165.0, 164.0, 141.0, 136.2, 133.5, 129.4, 128.6, 128.3, 128.1, 126.1, 100.9, 84.7, 52.9, 51.0, 46.3, 41.2, 21.5; HRMS (ESI) calcd for $C_{23}H_{23}O_6$ [M + H^+], 395.1489; found: 395.1490.

*Dimethyl 5-(4-Chlorophenyl)-2-(2-oxo-2-phenylethyl)-2,3-dihydrofuran-2,4-dicarboxylate (**3f**).* (58 mg, 47%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.6); IR (neat): ν_{max} 2957, 2926, 2855, 1749, 1699, 1678, 1622, 1595, 1489, 1450, 1433, 1364, 1344, 1282, 1265, 1254, 1224, 1217, 1014, 1001, 840, 762 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.94 (d, J = 7.9 Hz, 2H), 7.79 (d, J = 8.6 Hz, 2H), 7.58 (t, J = 7.3 Hz, 1H), 7.46 (t, J = 7.3 Hz, 2H), 7.33 (d, J = 8.6 Hz, 2H), 3.89 (d, J = 17.5 Hz, 1H), 3.83 (s, 3H), 3.76 (d, J = 17.5 Hz, 1H), 3.68 (s, 3H), 3.63 (d, J = 16.1 Hz, 1H), 3.23 (d, J = 16.1 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.4, 171.3, 164.7, 162.5, 136.6, 136.1, 133.6, 130.8, 128.7, 128.1, 127.9, 127.4, 102.1, 84.9, 53.0, 51.2, 46.2, 41.2; HRMS (ESI) calcd for $C_{22}H_{20}ClO_6$ [M + H^+], 415.0943; found: 415.0944.

*Dimethyl 5-(Naphthalen-1-yl)-2-(2-oxo-2-phenylethyl)-2,3-dihydrofuran-2,4-dicarboxylate (**3g**).* (61 mg, 47%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.5); IR (neat): ν_{max} 1745, 1691, 1438, 1365, 1264, 1116, 1078 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.09−8.04 (m, 1H), 7.97 (d, J = 8.0 Hz, 2H), 7.90 (d, J = 8.3 Hz, 1H), 7.86−7.83 (m, 1H), 7.61−7.56 (m, 2H), 7.49−7.44 (m, 5H), 4.01 (d, J = 17.6 Hz, 1H), 3.90 (s, 3H), 3.86 (d, J = 17.6 Hz, 1H), 3.78 (d, J = 15.8 Hz, 1H), 3.48 (s, 3H), 3.38 (d, J = 15.8 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.4, 171.2, 164.6, 164.2, 136.1, 133.6, 133.2, 131.0, 130.4, 128.6, 128.2, 128.1, 127.3, 126.5, 125.9, 125.2, 124.6, 105.1, 86.2, 53.0, 51.0, 46.3, 40.3; HRMS (ESI) calcd for $C_{26}H_{23}O_6$ [M + H^+], 431.1489; found: 431.1495.

*4-Ethyl 2-Methyl 2-(2-oxo-2-phenylethyl)-5-phenyl-2,3-dihydrofuran-2,4-dicarboxylate (**3h**).* (67 mg, 57%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:5, R_f = 0.3); IR (neat): ν_{max} 2917, 2849, 1738, 1687, 1449, 1251, 1224, 1094, 1072 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, J = 8.0 Hz, 2H), 7.81 (d, J = 8.0 Hz, 2H), 7.57 (t, J = 7.4 Hz, 1H), 7.46 (t, J = 7.6 Hz, 2H), 7.40−7.33 (m, 3H), 4.14 (qd, J = 7.2, 1.7 Hz, 2H), 3.92 (d, J = 17.4 Hz, 1H), 3.83 (s, 3H), 3.76 (d, J = 17.4 Hz, 1H), 3.67 (d, J = 15.9 Hz, 1H), 3.24 (d, J = 15.9 Hz, 1H), 1.22 (t, J = 7.2 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.5, 171.4, 164.4, 163.5, 136.2, 133.6, 130.5, 129.4, 129.1, 128.6, 128.1, 127.5, 101.9, 84.8, 59.9, 52.9, 46.3, 41.2, 14.1; HRMS (ESI) calcd for $C_{23}H_{23}O_6$ [M + H^+], 395.1489; found: 395.1502.

*Methyl 4-Methyl-2-(2-oxo-2-phenylethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3j**).* (22 mg, 22%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:10, R_f = 0.4); IR (neat): ν_{max} 2951, 2918, 2856, 1748, 1732, 1687, 1597, 1580, 1495, 1449, 1314, 1256, 1223, 1207, 1134, 1065, 765, 694 cm^{-1}; ^1H NMR (400 MHz, $(CD_3)_2CO$) δ 8.04 (m, 2H), 7.64 (t, J = 7.4 Hz, 1H), 7.54−7.49 (m, 4H), 7.36 (t, J = 7.4 Hz, 2H), 7.31−7.28 (m, 1H), 3.95 (d, J = 17.4 Hz, 1H), 3.76 (d, J = 17.4 Hz, 1H), 3.72 (s, 3H), 3.38 (dd, J = 16.4, 1.4 Hz, 1H), 2.95 (dd, J = 16.4, 1.4 Hz, 1H), 1.90 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $(CD_3)_2CO$) δ 197.3. 172.7, 147.4, 137.7, 134.1, 132.4, 129.5, 128.9, 128.6, 127.8, 105.8, 83.6, 52.6, 47.3, 47.2, 12.5; HRMS (ESI) calcd for $C_{21}H_{20}NaO_4$ [M + Na^+], 359.1254; found: 359.1264.

*Benzyl 4-Benzoyl-2-(2-oxo-2-phenylethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3k**).* (76 mg, 50%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.3); IR (neat): ν_{max} 2925, 1736, 1689, 1619, 1597, 1493, 1448, 1365, 1224, 1180, 1118, 1072, 891 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, J = 8.0 Hz, 2H), 7.58 (t, J = 7.4 Hz, 1H), 7.47 (t, J = 7.8 Hz, 2H), 7.41−7.39 (m, 4H), 7.35−7.32 (m, 3H), 7.23−7.20 (m, 3H), 7.15 (t, J = 7.6 Hz, 1H), 7.03 (t, J = 7.6 Hz, 2H), 7.01(t, J = 7.6 Hz, 2H), 5.33 (d, 2H), 3.97 (d, J = 17.6 Hz, 1H), 3.91 (d, J = 17.6 Hz, 1H), 3.67 (d, J = 15.8 Hz, 1H), 3.54 (d, J = 15.8 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.3, 193.2, 171.0, 164.6, 138.3, 136.1, 135.2, 133.6, 131.4, 130.1, 129.4, 129.2, 128.9, 128.6, 128.5, 128.4, 128.3, 128.1, 127.6, 127.5, 111.1, 85.2, 67.6, 46.2, 43.0; HRMS (ESI) calcd for $C_{33}H_{27}O_5$ [M + H^+], 503.1853; found: 503.1856.

*2-(4-Benzoyl-2,5-diphenyl-2,3-dihydrofuran-2-yl)-1-phenyl Ethanone (**3l**).* (87 mg, 65%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:10, R_f = 0.3); IR (neat): ν_{max} 2929, 2856, 1737, 1690, 1612, 1595, 1447, 1371, 1242, 1075 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, J = 8.3 Hz, 2H), 7.57 (d, J = 7.8 Hz, 2H), 7.52 (t, J = 7.4 Hz, 1H), 7.42−7.37 (m, 6H), 7.30 (t, J = 7.4 Hz,

dx.doi.org/10.1021/jo502535k | J. Org. Chem. 2015, 80, 698−704

1H), 7.23−7.15 (m, 4H), 7.08−7.02 (m, 4H), 3.92 (d, J = 15.3 Hz, 1H), 3.84 (d, J = 15.3 Hz, 1H), 3.74 (d, J = 14.8 Hz, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 196.2, 193.1, 163.8, 144.6, 138.8, 137.3, 133.1, 131.1, 129.9, 129.7, 129.2, 128.8, 128.5, 128.4, 128.3, 127.6, 127.5, 127.4, 124.8, 112.0, 88.5, 49.3, 44.6; HRMS (ESI) calcd for $C_{31}H_{25}O_3$ [M + H^+], 445.1798; found: 445.1810.

*2-(4-Benzoyl-2-methyl-5-phenyl-2,3-dihydrofuran-2-yl)-1-phenylethanone (**3m**).* (58 mg, 50%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.5); IR (neat): ν_{max} 1688, 1594, 1491, 1447, 1369, 1217, 1069, 1003, 865 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.00 (d, J = 8.0 Hz, 2H), 7.58 (d, J = 7.4 Hz, 1H), 7.47 (d, J = 7.6 Hz, 2H), 7.44 (d, J = 7.6 Hz, 2H), 7.21 (d, J = 7.4 Hz, 1H), 7.17−7.12 (m, 3H), 7.07 (t, J = 7.9 Hz, 2H), 7.03 (t, J = 7.9 Hz, 2H), 3.57 (s, 2H), 3.41 (d, J = 15.4 Hz, 1H), 3.27 (d, J = 15.4 Hz, 1H), 1.73 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 196.7, 193.4, 164.0, 139.0, 137.3, 133.3, 131.0, 130.1, 129.8, 129.2, 128.8, 128.6, 128.2, 127.6, 127.5, 112.0, 86.4, 48.0, 44.3, 26.8; HRMS (ESI) calcd for $C_{26}H_{23}O_3$ [M + H^+], 383.1642; found: 383.1641.

*Methyl 4-Benzoyl-2-(2-oxo-2-(p-tolyl)ethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3n**).* (70 mg, 53%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:5, R_f = 0.3); IR (neat): ν_{max} 1742, 1686, 1608, 1575, 1365, 1230, 1205, 1138, 1049, 1027, 893 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, J = 8.2 Hz, 2H), 7.47−7.45 (m, 2H), 7.27−7.21 (m, 5H), 7.16 (t, J = 7.5 Hz, 1H), 7.08 (t, J = 7.8 Hz, 2H), 7.03 (t, J = 7.8 Hz, 2H), 3.93 (d, J = 17.5 Hz, 1H), 3.87 (s, 3H), 3.85 (d, J = 17.5 Hz, 1H), 3.67 (d, J = 15.7 Hz, 1H), 3.49 (d, J = 15.7 Hz, 1H), 2.40 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 194.9, 193.1, 171.7, 164.5, 144.5, 138.4, 133.6, 131.4, 130.2, 129.5, 129.3, 129.2, 128.9, 128.2, 127.7, 127.5, 111.0, 85.1, 53.0, 46.2, 42.9, 21.6; HRMS (ESI) calcd for $C_{28}H_{25}O_5$ [M + H^+], 441.1697; found: 441.1700.

*Methyl 4-Benzoyl-2-(2-(4-methoxyphenyl)-2-oxoethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3o**).* (80 mg, 58%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:5, R_f = 0.3); IR (neat): ν_{max} 1740, 1679, 1599, 1574, 1447, 1364, 1260, 1235, 1172, 1028, 893 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.94 (d, J = 8.9 Hz, 2H), 7.46 (d, J = 7.8 Hz, 2H), 7.26−7.21(m, 3H), 7.16 (t, J = 7.6 Hz, 1H), 7.07 (t, J = 7.6 Hz, 2H), 7.03 (t, J = 7.6 Hz, 2H), 6.93 (d, J = 8.9 Hz, 2H), 3.90 (d, J = 17.3 Hz, 1H), 3.87 (s, 3H), 3.85 (s, 3H), 3.82 (d, J = 17.3 Hz, 1H), 3.67 (d, J = 15.8 Hz, 1H), 3.48 (d, J = 15.8 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 193.8, 193.0, 172.0, 164.4, 163.9, 138.4, 131.4, 130.4, 130.1, 129.5, 129.3, 128.9, 127.7, 127.5, 113.8, 111.0, 85.3, 55.4, 52.9, 45.9, 42.9; HRMS (ESI) calcd for $C_{28}H_{25}O_6$ [M + H^+], 457.1646; found: 457.1647.

*Methyl 4-Benzoyl-2-(2-(4-bromophenyl)-2-oxoethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3p**).* (65 mg, 43%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.3); IR (neat): ν_{max} 1742, 1689, 1613, 1586, 1446, 1365, 1223, 1137, 1072, 998, 893 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, J = 8.7 Hz, 2H), 7.61 (d, J = 8.7 Hz, 2H), 7.46 (d, J = 7.5 Hz, 2H), 7.25−7.22 (m, 3H), 7.17 (t, J = 7.7 Hz, 1H), 7.08 (t, J = 7.8 Hz, 2H), 7.04 (t, J = 7.5 Hz, 2H), 3.89 (d, J = 17.6 Hz, 1H), 3.88 (s, 3H), 3.83 (d, J = 17.6 Hz, 1H), 3.65 (d, J = 15.8 Hz, 1H), 3.49 (d, J = 15.8 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 194.4, 193.0, 171.6, 164.4, 138.3, 134.8, 132.0, 131.5, 130.2, 129.6, 129.4, 129.1, 128.9, 127.7, 127.6, 110.9, 84.9, 53.1, 46.1, 42.9; HRMS (ESI) calcd for $C_{27}H_{22}BrO_5$ [M + H^+], 505.0645; found: 505.0651.

*Methyl 4-Benzoyl-2-(2-oxo-2-(thiophen-2-yl)ethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3q**).* (81 mg, 62%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.2); IR (neat): ν_{max} 2954, 2924, 2852, 1742, 1659, 1613, 1596, 1461, 1416, 1376, 1237, 1137, 1050, 892 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.76 (dd, J = 3.8, 1.1 Hz, 1H), 7.67 (dd, J = 4.9, 1.1 Hz, 1H), 7.46 (d, J = 8.4 Hz, 2H), 7.25−7.21 (m, 3H), 7.17 (d, J = 7.4 Hz, 1H), 7.15−7.13 (m, 1H), 7.08 (t, J = 7.9 Hz, 2H), 7.04 (d, J = 7.9 Hz, 2H), 3.88 (s, 3H), 3.85 (d, J = 17.0 Hz, 1H), 3.80 (d, J = 17.0 Hz, 1H), 3.64 (d, J = 15.7 Hz, 1H), 3.52 (d, J = 15.7 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 192.9, 188.0, 171.5, 164.3, 143.4, 138.4, 134.4, 132.6, 131.4, 130.2, 129.4, 129.1, 128.9, 128.2, 127.7, 127.5, 110.9, 85.0, 53.0, 46.4, 42.8; HRMS (ESI) calcd for $C_{25}H_{21}O_5S$ [M + H^+], 433.1104; found: 433.1111.

*Methyl 4-Benzoyl-2-(2-cyclopropyl-2-oxoethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3r**).* (65 mg, 55%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.2); IR (neat): ν_{max} 2953, 2923, 2854, 1744, 1702, 1614, 1596, 1492, 1446, 1390, 1366, 1248, 1210, 1074, 1046, 893 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.43 (d, J = 8.1 Hz, 2H), 7.25−7.19 (m, 3H), 7.16 (d, J = 7.4 Hz, 1H), 7.08−7.02 (m, 4H), 3.83 (s, 3H), 3.54 (d, J = 15.8 Hz, 1H), 3.50 (d, J = 17.3 Hz, 1H), 3.43 (d, J = 17.3 Hz, 1H), 3.38 (d, J = 15.8 Hz, 1H), 1.98−1.92 (m, 1H), 1.09−1.06 (m, 2H), 0.93−0.88 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 205.8, 193.0, 171.6, 164.5, 138.4, 131.4, 130.2, 129.4, 129.2, 128.9, 127.6, 127.5, 110.9, 84.8, 52.9, 50.3, 42.8, 20.9, 11.3; HRMS (ESI) calcd for $C_{24}H_{23}O_5$ [M + H^+], 391.1540; found: 391.1537.

*Methyl 4-Benzoyl-2-(2-oxohexyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3s**).* (43 mg, 35%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.5); IR (neat): ν_{max} 2957, 1743, 1719, 1615, 1596, 1492, 1447, 1365, 1248, 890 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.43 (d, J = 8.2 Hz, 2H), 7.25−7.20 (m, 3H), 7.16 (t, J = 7.6 Hz, 1H), 7.08−7.02 (m, 4H), 3.87 (s, 3H), 3.52 (d, J = 15.7 Hz, 1H), 3.37 (d, J = 15.7 Hz, 1H), 3.33 (d, J = 17.4 Hz, 1H), 3.28 (d, J = 17.4 Hz, 1H), 2.45 (t, J = 7.5 Hz, 2H), 1.56 (m, 2H), 1.29 (m, 2H), 0.87 (t, J = 7.3 Hz, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 206.2, 193.0, 171.7, 164.4, 138.4, 131.4, 130.2, 129.4, 129.2, 128.9, 127.7, 127.6, 110.9, 84.9, 52.9, 49.6, 42.9, 25.5, 22.1, 13.7; HRMS (ESI) calcd for $C_{25}H_{27}O_5$ [M + H^+], 407.1853; found: 407.1861.

*Methyl 4-Benzoyl-2-(2-cyclohexyl-2-oxoethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**3t**).* (13 mg, 10%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:5, R_f = 0.5); IR (neat): ν_{max} 2920, 2850, 1739, 1712, 1615, 1596, 1448, 1368, 1250, 1119, 1072, 889 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.44 (d, J = 8.4 Hz, 2H), 7.25−7.21 (m, 3H), 7.18 (t, J = 7.4 Hz, 1H), 7.09−7.03 (m, 4H), 3.86 (s, 3H), 3.55 (d, J = 15.8 Hz, 1H), 3.36 (s, 2H), 3.36 (d, J = 15.8 Hz, 1H), 2.40−2.33 (m, 1H), 1.89−1.86 (m, 2H), 1.80−1.76 (m, 2H), 1.67−1.65 (m, 2H), 1.41−1.25 (m, 4H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 209.2, 193.0, 171.7, 164.5, 138.4, 131.4, 130.1, 129.4, 129.2, 128.9, 127.6, 127.5, 110.9, 85.0, 52.9, 50.7, 47.8, 42.9, 29.6, 28.1, 28.0, 25.6, 25.4, 25.3; HRMS (ESI) calcd for $C_{27}H_{29}O_5$ [M + H^+], 433.2010; found: 433.2021.

*Dimethyl 5-(3,4-Dimethoxyphenyl)-2-(2-oxo-2-phenylethyl)-2,3-dihydrofuran-2,4-dicarboxylate (**3u**).* (60 mg, 45%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.3); IR (neat): ν_{max} 2945, 2922, 1746, 1701, 1684, 1632, 1601, 1587, 1518, 1450, 1441, 1364, 1317, 1265, 1248, 1229, 1179, 1144, 1099, 1020, 819, 760, 691 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, J = 8.1 Hz, 2H), 7.60−7.56 (m, 2H), 7.51 (dd, J = 2.0, 8.5 Hz, 1H), 7.46 (t, J = 7.6 Hz, 2H), 6.84 (d, J = 8.5 Hz, 1H), 3.91 (d, J = 17.2 Hz, 1H), 3.89 (s, 3H), 3.87 (s, 3H), 3.83 (s, 3H), 3.73 (d, J = 17.2 Hz, 1H), 3.70 (s, 3H), 3.64 (d, J = 15.9 Hz, 1H), 3.23 (d, J = 15.9 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 195.6, 171.4, 165.0, 163.3, 151.0, 147.9, 136.2, 133.5, 128.6, 128.0, 123.2, 121.4, 112.6, 110.0, 100.3, 84.5, 55.9, 55.8, 52.9, 51.1, 46.2, 41.4; HRMS (ESI) calcd for $C_{27}H_{23}O_5$ [M + H^+], 427.1540; found: 427.1547.

*Methyl 4-Benzoyl-2-(cyclohexylmethyl)-5-phenyl-2,3-dihydrofuran-2-carboxylate (**4**).* (62 mg, 51%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:5, R_f = 0.3); IR (neat): ν_{max} 2924, 2852, 1742, 1616, 1596, 1492, 1447, 1365, 1245, 1139, 1073, 1023, 888 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, J = 8.2 Hz, 2H), 7.26 (d, J = 8.2 Hz, 2H), 7.21 (t, J = 7.4 Hz, 1H), 7.18 (t, J = 7.4 Hz, 1H), 7.06 (t, J = 7.6 Hz, 4H), 3.84 (s, 3H), 3.51 (d, J = 15.5 Hz, 1H), 3.33 (d, J = 15.5 Hz, 1H), 2.10 (dd, J = 14.6, 6.2 Hz, 1H), 1.97 (dd, J = 14.6, 6.2 Hz, 1H), 1.89−1.86 (m, 1H), 1.75−1.51 (m, 5H), 1.30−1.14 (m, 3H), 1.07−0.94 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 193.1, 173.3, 165.1, 138.6, 131.2, 130.1, 129.6, 129.5, 128.8, 127.6, 127.5, 111.0, 88.7, 52.6, 45.0, 43.7, 34.2, 34.0, 33.6, 26.1, 26.0; HRMS (ESI) calcd for $C_{26}H_{29}O_4$ [M + H^+], 405.2060; found: 405.2058.

dx.doi.org/10.1021/jo502535k | J. Org. Chem. 2015, 80, 698−704

*Methyl 4-Benzoyl-2-neopentyl-5-phenyl-2,3-dihydrofuran-2-carboxylate (**5**).* (108 mg, 95%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:5, R_f = 0.5); IR (neat): ν_{max} 2954, 1746, 1616, 1596, 1492, 1366, 1244, 1201, 1179, 1136, 1059, 1019, 888 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.42 (d, J = 8.2 Hz, 2H), 7.29 (d, J = 8.4 Hz, 2H), 7.22 (t, J = 7.2 Hz, 1H), 7.18 (d, J = 7.2 Hz, 1H), 7.08−7.04 (m, 4H), 3.82 (s, 3H), 3.48 (d, J = 15.6 Hz, 1H), 3.34 (d, J = 15.6 Hz, 1H), 2.30 (d, J = 14.8 Hz, 1H), 2.06 (d, J = 14.8 Hz, 1H), 1.03 (s, 9H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 193.1, 173.8, 165.2, 138.6, 131.2, 130.1, 129.6, 129.5, 128.8, 127.6, 127.5, 110.5, 88.2, 52.4, 50.7, 46.4, 31.2, 30.3; HRMS (ESI) calcd for $C_{24}H_{27}O_4$ [M + H^+], 379.1904; found: 379.1906.

*Dimethyl 6,7-Dimethoxy-1-(2-oxo-2-phenylethyl)-1,2-dihydronaphthalene-1,3-dicarboxylate (**8**).* (41 mg, 32%). Isolated by flash column chromatography (ethyl acetate/petroleum ether = 1:3, R_f = 0.7); IR (neat): ν_{max} 3001, 2951, 2914, 2837, 1701, 1686, 1630, 1600, 1560, 1516, 1240, 1078, 1001 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, J = 8.1 Hz, 2H), 7.53 (t, J = 7.6 Hz, 1H), 7.51 (s, 1H), 7.41 (t, J = 7.6 Hz, 2H), 7.03 (s, 1H), 6.79 (s, 1H), 3.90 (s, 3H), 3.89 (s, 3H), 3.83 (s, 3H), 3.77 (s, 3H), 3.56 (d, J = 18.0 Hz, 1H), 3.48 (d, J = 18.0 Hz, 1H), 3.26−3.15 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 196.8, 174.7, 167.3, 150.3, 148.2, 136.6, 135.5, 133.2, 129.9, 128.5, 127.9, 124.9, 124.7, 112.0, 109.9, 56.0, 52.6, 51.8, 47.9, 44.6, 30.2; HRMS (ESI) calcd for $C_{24}H_{24}NaO_7$ [M + Na^+], 447.1414; found: 447.1416.

■ ASSOCIATED CONTENT

Supporting Information

Copies of ^1H and ^{13}C NMR spectra of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: zhipingli@ruc.edu.cn (Z.L.).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Dedicated to Professor Tamotsu Takahashi on the occasion of his 60th birthday. Financial support by State Key Laboratory of Heavy Oil Processing, the National Science Foundation of China (21272267), the Fundamental Research Funds for the Central Universities, the Research Funds of Renmin University of China (10XNL017), and Beijing National Laboratory for Molecular Sciences (BNLMS).

■ REFERENCES

(1) For selected reviews, see: (a) Sumino, S.; Fusano, A.; Fukuyama, T.; Ryu, I. *Acc. Chem. Res.* **2014**, *47*, 1563. (b) Wu, X.-F.; Neumann, H.; Beller, M. *Chem. Rev.* **2013**, *113*, 1. (c) Franke, R.; Selent, D.; Borner, A. *Chem. Rev.* **2012**, *112*, 5675. (d) Liu, Q.; Zhang, H.; Lei, A. *Angew. Chem., Int. Ed.* **2011**, *50*, 10788. (e) Brennfuhrer, A.; Neumann, H.; Beller, M. *Angew. Chem., Int. Ed.* **2009**, *48*, 4114. (f) Gabriele, B.; Salerno, G.; Costa, M. *Top. Organomet. Chem.* **2006**, *18*, 239. (g) Beller, M.; Seayad, J.; Tillack, A.; Jiao, H. *Angew. Chem., Int. Ed.* **2004**, *43*, 3368. (h) Kiss, G. *Chem. Rev.* **2001**, *101*, 3435.

(2) For selected reviews, see: (a) Wu, L.; Liu, Q.; Jackstell, R.; Beller, M. *Angew. Chem., Int. Ed.* **2014**, *53*, 6310. (b) Fujihara, T.; Iwai, T.; Terao, J.; Tsuji, Y. *Synlett* **2010**, 2537. (c) Leung, J. C.; Krische, M. J. *Chem. Sci.* **2012**, *3*, 2202. (d) Willis, M. C. *Chem. Rev.* **2010**, *110*, 725. (e) Jun, C.-H.; Jo, E.-A.; Park, J.-W. *Eur. J. Org. Chem.* **2007**, 1869. (f) Morimoto, T.; Kakiuchi, K. *Angew. Chem., Int. Ed.* **2004**, *43*, 5580. For selected examples and reviews on acyl radicals mediated hydroacylations, see: (g) Chudasama, V.; Fitzmaurice, R. J.; Caddick, S. *Nat. Chem.* **2010**, *2*, 529. (h) Recupero, F.; Punta, C. *Chem. Rev.* **2007**, *107*, 3800. (i) Schiesser, C. H.; Wille, U.; Matsubara, H.; Ryu, I. *Acc. Chem. Res.* **2007**, *40*, 303. (j) Walton, J. C.; Studer, A. *Acc. Chem. Res.* **2005**, *38*, 794. (k) Kim, S. *Adv. Synth. Catal.* **2004**, *346*, 19.

(3) For selected reviews, see: (a) Beccalli, E. M.; Broggini, G.; Gazzola, S.; Mazza, A. *Org. Biomol. Chem.* **2014**, *12*, 6767. (b) Kanai, M.; Shimizu, Y. *Tetrahedron Lett.* **2014**, *55*, 3727. (c) Zeng, X. *Chem. Rev.* **2013**, *113*, 6864. (d) Zhang, C.; Tang, C.; Jiao, N. *Chem. Soc. Rev.* **2012**, *41*, 3464. (e) McDonald, R. I.; Liu, G.; Stahl, S. S. *Chem. Rev.* **2011**, *111*, 2981. (f) Muñiz, K. *Angew. Chem., Int. Ed.* **2009**, *48*, 9412. (g) Chemler, S. R. *Org. Biomol. Chem.* **2009**, *7*, 3009. (h) Jensen, K. H.; Sigman, M. S. *Org. Biomol. Chem.* **2008**, *6*, 4083. (i) Beccalli, E. M.; Broggini, G.; Martinelli, M.; Sottocornola, S. *Chem. Rev.* **2007**, *107*, 5318. (j) Minatti, A.; Muñiz, K. *Chem. Soc. Rev.* **2007**, *36*, 1142.

(4) (a) Yang, X.-H.; Wei, W.-T.; Li, H.-B.; Song, R.-J.; Li, J.-H. *Chem. Commun.* **2014**, *50*, 12867. (b) Mai, W.-P.; Sun, G.-C.; Wang, J.-T.; Song, G.; Mao, P.; Yang, L.-R.; Yuan, J.-W.; Xiao, Y.-M.; Qu, L.-B. *J. Org. Chem.* **2014**, *79*, 8094. (c) Fusano, A.; Sumino, S.; Fukuyama, T.; Ryu, I. *Org. Lett.* **2011**, *13*, 2114. (d) Taniguchi, T.; Sugiura, Y.; Zaimoku, H.; Ishibashi, H. *Angew. Chem., Int. Ed.* **2010**, *49*, 10154. (e) Cernak, T. A.; Lambert, T. H. *J. Am. Chem. Soc.* **2009**, *131*, 3124. (f) Uenoyama, Y.; Tsukida, M.; Doi, T.; Ryu, I.; Studer, A. *Org. Lett.* **2005**, *7*, 2985. (g) Miura, K.; Tojino, M.; Fujisawa, N.; Hosomi, A.; Ryu, I. *Angew. Chem., Int. Ed.* **2004**, *43*, 2423. (h) Ryu, I.; Kreimerman, S.; Araki, F.; Nishitani, S.; Oderaotoshi, Y.; Minakata, S.; Komatsu, M. *J. Am. Chem. Soc.* **2002**, *124*, 3812.

(5) (a) Niu, B.; Xu, L.; Xie, P.; Wang, M.; Zhao, W.; Pittman, C. U.; Zhou, A. *ACS Comb. Sci.* **2014**, *16*, 454. (b) Luo, J.-Y.; Hua, H.-L.; Chen, Z.-S.; Zhou, Z.-Z.; Yang, Y.-F.; Zhou, P.-X.; He, Y.-T.; Liu, X.-Y.; Liang, Y.-M. *Chem. Commun.* **2014**, *50*, 1564. (c) Wang, J.; Liu, C.; Yuan, J.; Lei, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 2256. (d) Zhou, M.-B.; Song, R.-J.; Ouyang, X.-H.; Liu, Y.; Wei, W.-T.; Deng, G.-B.; Li, J.-H. *Chem. Sci.* **2013**, *4*, 2690. (e) Shi, Z.; Schrcder, N.; Glorious, F. *Angew. Chem., Int. Ed.* **2012**, *51*, 8092.

(6) For selected reviews, see: (a) Kilroy, T. G.; O'Sullivan, T. P.; Guiry, P. J. *Eur. J. Org. Chem.* **2005**, 4929. (b) Hou, X.-L.; Yang, Z.; Yeung, K.-S.; Wong, H. N. C. *Prog. Heterocycl. Chem.* **2005**, *17*, 142. (c) Faul, M. M.; Huff, B. E. *Chem. Rev.* **2000**, *100*, 2407. (d) Fraga, B. M. *Nat. Prod. Rep.* **1992**, *9*, 217. (e) Merrit, A. T.; Ley, S. V. *Nat. Prod. Rep.* **1992**, *9*, 243.

(7) (a) Zhu, F.-L.; Wang, Y.-H.; Zhang, D.-Y.; Xu, J.; Hu, X.-P. *Angew. Chem., Int. Ed.* **2014**, *53*, 10223. (b) Nakano, T.; Miyazaki, K.; Kamimura, A. *J. Org. Chem.* **2014**, *79*, 8103. (c) Chagarovsky, A. O.; Budynina, E. M.; Ivanova, O. A.; Villemson, E. V.; Rybakov, V. B.; Trushkov, I. V.; Melnikov, M. Y. *Org. Lett.* **2014**, *16*, 2830. (d) Li, M.; Lin, S.; Dong, Z.; Zhang, X.; Liang, F.; Zhang, J. *Org. Lett.* **2013**, *15*, 3978. (e) Zhou, J.-L.; Wang, L.-J.; Xu, H.; Sun, X.-L.; Tang, Y. *ACS Catal.* **2013**, *3*, 685. (f) Dou, X.; Zhong, F.; Lu, Y. *Chem.—Eur. J.* **2012**, *18*, 13945. (g) Calter, M. A.; Korotkov, A. *Org. Lett.* **2011**, *13*, 6328. (h) Zhong, C.; Liao, T.; Tuguldur, O.; Shi, X. *Org. Lett.* **2010**, *12*, 2064. (i) Rueping, M.; Parra, A.; Uria, U.; Besselievre, F.; Merino, E. *Org. Lett.* **2010**, *12*, 5680. (j) Zheng, J.-C.; Zhu, C.-Y.; Sun, X.-L.; Tang, Y.; Dai, L.-X. *J. Org. Chem.* **2008**, *73*, 6909. (k) Zhang, R.; Liang, Y.; Zhou, G.; Wang, K.; Dong, D. *J. Org. Chem.* **2008**, *73*, 8089. (l) Son, S.; Fu, G. C. *J. Am. Chem. Soc.* **2007**, *129*, 1046. (m) Alcaide, A.; Almendrous, P.; Campo, T. M. *Angew. Chem., Int. Ed.* **2006**, *45*, 4501. (n) Xia, W.; Yang, C.; Patrick, B. O.; Scheffer, J. R.; Scott, C. *J. Am. Chem. Soc.* **2005**, *127*, 2725. (o) Calter, M. A.; Phillips, R. M.; Flaschenriem, C. *J. Am. Chem. Soc.* **2005**, *127*, 14566. (p) Ma, S.; Lu, L.; Zhang, J. L. *J. Am. Chem. Soc.* **2004**, *126*, 9645. (q) Evans, D. A.; Sweeney, Z. K.; Rovis, T.; Tedrow, J. S. *J. Am. Chem. Soc.* **2001**, *123*, 12095. (r) Davies, H. M.; Ahmed, G.; Calvo, R. L.; Churchill, M. R.; Churchill, D. G. *J. Org. Chem.* **1998**, *63*, 2641.

(8) (a) Naveen, T.; Kancherla, R.; Maiti, D. *Org. Lett.* **2014**, *16*, 5446. (b) Ye, Y.; Wang, L.; Fan, R. *J. Org. Chem.* **2010**, *75*, 1760. (c) Snider, B. B. *Tetrahedron* **2009**, *65*, 10738. (d) Wang, G.-W.; Dong, Y.-W; Wu, P.; Yuan, T.-T.; Shen, Y.-B. *J. Org. Chem.* **2008**, *73*, 7088.

(9) Zhao, Y.; Jiang, X.; Yeung, Y.-Y. *Angew. Chem., Int. Ed.* **2013**, *52*, 8597.

(10) (a) Lv, L.; Shen, B.; Li, Z. *Angew. Chem., Int. Ed.* **2014**, *53*, 4164. (b) Jia, F.; Liu, K.; Xi, H.; Lu, S.; Li, Z. *Tetrahedron Lett.* **2013**, *54*,

6337. (c) Liu, K.; Li, Y.; Liu, W.; Zheng, X.; Zong, Z.; Li, Z. *Chem.—Asian. J.* **2013**, *8*, 359. (d) Liu, K.; Li, Y.; Zheng, X.; Liu, W.; Li, Z. *Tetrahedron* **2012**, *68*, 10333. (e) Liu, W.; Li, Y.; Liu, K.; Li, Z. *J. Am. Chem. Soc.* **2011**, *133*, 10756.

(11) For selected reviews, see: (a) Jia, F.; Li, Z. *Org. Chem. Front.* **2014**, *1*, 194. (b) Gopalaiah, K. *Chem. Rev.* **2013**, *113*, 3248. (c) Sun, C.-L.; Li, B.-J.; Shi, Z.-J. *Chem. Rev.* **2011**, *111*, 1293. (d) Correa, A.; García Mancheño, O.; Bolm, C. *Chem. Soc. Rev.* **2008**, *37*, 1108. (e) Bolm, C.; Legros, J.; Le Paih, J.; Zani, L. *Chem. Rev.* **2004**, *104*, 6217. For a book on iron-catalyzed organic reactions, see: (f) Plietker, B., Ed. *Iron Catalysis in Organic Chemistry: Reactions and Applications*; Wiley-VCH: Weinheim, Germany, 2008.

(12) (a) Moteki, S. A.; Usui, A.; Selvakumar, S.; Zhang, T.; Maruoka, K. *Angew. Chem., Int. Ed.* **2014**, *53*, 11060. (b) Watanabe, E.; Kaiho, A.; Kusama, H.; Iwasawa, N. *J. Am. Chem. Soc.* **2013**, *135*, 11744. (c) Jensen, C. M.; Lindsay, K. B.; Taaning, R. H.; Karaffa, J.; Hansen, A. M.; Skrydstrup, T. *J. Am. Chem. Soc.* **2005**, *127*, 6544. (d) Chatgilialoglu, C.; Crich, D.; Komatsu, M.; Ryu, I. *Chem. Rev.* **1999**, *99*, 1991.

(13) (a) Liu, D.; Tang, S.; Yi, H.; Liu, C.; Qi, X.; Lan, Y.; Lei, A. *Chem.—Eur. J.* **2014**, *20*, 15605. (b) Jiang, H.; Cheng, Y.; Zhang, Y.; Yu, S. *Org. Lett.* **2013**, *15*, 4884. (c) Cui, X.; Xu, X.; Wojtas, L.; Kim, M. M.; Zhang, X. P. *J. Am. Chem. Soc.* **2012**, *134*, 19981.

(14) Armarego, W. L. F., Perrin, D. D. Purification of Laboratory Chemicals, 4th edition; Butterworth-Heinemann, Linacre House, Jordan Hill: Oxford, 1997; pp 140.

(15) Hok, S.; Schore, N. E. *J. Org. Chem.* **2006**, *71*, 1736.