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A general and efficient synthesis of substituted furans and dihydrofurans via gold-catalyzed cyclization of (*Z*)-2-en-4-yn-1-ols

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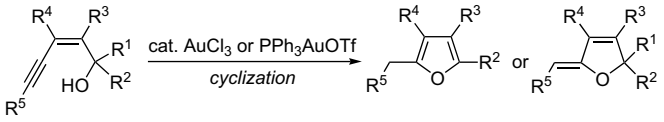
ABSTRACT

A highly efficient Au-catalyzed cyclization of (*Z*)-enynols that proceeds under mild reaction conditions has been developed. This methodology provides rapid access to substituted furans and stereodefined (*Z*)-5-ylidene-2,5-dihydrofurans in a regioselective manner from suitably substituted (*Z*)-2-en-4-yn-1-ols.

1. Introduction

The furan rings and its analogues widely occur as key structural subunits in numerous natural products, they also can find a variety of applications such as pharmaceuticals, flavor and fragrance compounds.[1] Substituted furans are of significant interest since they are useful and versatile synthetic intermediates for access to heterocyclic and acyclic compounds.[2] As a consequence, much attention has been paid to the synthesis of furan derivatives either by traditional methods[3] or by transition-metal-catalyzed reactions including cyclization of allenyl ketones[4] and 3-alkyn-1-ones,[5] cycloisomerizations of (*Z*)-2-en-4-yn-1-ols,[4l,6] Pd-catalyzed cyclization of (*Z*)-2-iodoalk-2-enyl ketones,[7] and so on. A particularly attractive methodology is based on cycloisomerization of (*Z*)-2-en-4-yn-1-ols.[6] Although a number of methods have been reported for the synthesis of furans from this kind of substrate, they have certain drawbacks. For example, base-promoted cyclization of (*Z*)-enynols was achieved under strongly basic conditions, which was not suitable for the synthesis of base-sensitive furan.[6c–e] A Ru-catalyzed cyclization was only suitable for terminal alkynes.[6f–h] A K_2PdI_4-based catalytic system was reported to accomplish the cycloisomerization of a wide variety of (*Z*)-enynols under neutral conditions. However, the reaction was usually carried out in a dipolar aprotic solvent such as DMA at temperatures of 25–100 °C, especially, when (*Z*)-enynols bearing a phenyl substituent at C-3, a high temperature of 80–100 °C and long reaction time were required.[6a] Thus, the catalytic version of enynol-cyclization that proceeds under mild conditions in combination with the efficient (*Z*)-enynol construction would greatly enhance the utility of this reaction. Recently, Hashmi et al. reported a gold-catalyzed[8] cyclization of 2-methylpent-2-en-4-yn-1-ol to furan.[4g] We have also reported that gold could be used as catalyst for the cyclization of (*Z*)-enynols[9] prepared via zirconium-mediated three-components coupling of alkyne, aldehyde (or ketone), and alkynyl bromide in a one-pot procedure, which offers an efficient and straightforward route to fully substituted furans or dihydrofurans under mild reaction conditions. However, only fully substituted (*Z*)-enynols (substituted at all the C-1 to C-5 positions) were used as the substrates. In this paper, we wish to report the full details of this study with a wide range of different substituted (*Z*)-2-en-4-yn-1-ols, in which a variety of mono- to tetra-substituted furans and its derivatives could be efficiently synthesized (Scheme 1).



Scheme 1.

2. Results and discussion

2.1. Gold-catalyzed formation of furans from fully substituted (*Z*)-2-en-4-yn-1-ols

As shown in Table 1, a wide range of fully substituted (*Z*)-enynols with a secondary alcohol group at C-1 participated in the gold-catalyzed cycloisomerization reactions.[9] The reactions can be run using $AuCl_3$ or cationic gold(I) complex $(PPh_3)AuCl/AgOTf$ as catalyst at low catalyst loadings (1 mol %), and the reactions were usually complete within several hours. Alkyl, alkenyl, and aryl

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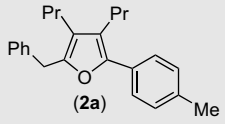
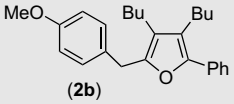
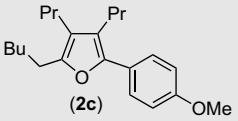
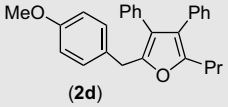
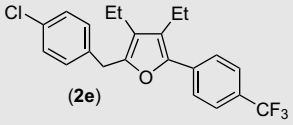
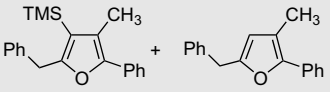
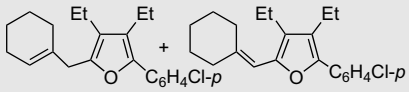
Table 1
Gold-catalyzed cyclization of enynols: formation of fully substituted furans

Entry	Enynol	R^2	R^3	R^4	R^5	Condition[a]	Product	Yield[b] (%)
1	**1a**	*p*-MeC_6H_4	Pr	Pr	Ph	A, 4 h	 (**2a**)	92
2	**1b**	Ph	Bu	Bu	*p*-$MeOC_6H_4$	B, 3 h	 (**2b**)	85
3	**1c**	*p*-$MeOC_6H_4$	Pr	Pr	Bu	A, 2 h	 (**2c**)	85
4	**1d**	Pr	Ph	Ph	*p*-$MeOC_6H_4$	A, 3 h	 (**2d**)	79
5	**1e**	*p*-$CF_3C_6H_4$	Et	Et	*p*-ClC_6H_4	B, 2 h	 (**2e**)	64
6	**1f**	Ph	CH_3	TMS	Ph	A, 1 h	 (**2f**) (2:1)	92
7	**1g**	*p*-ClC_6H_4	Et	Et	Cy[c]	B, 3 h	 (**2g**) (2:1)	82

[a] All the reactions were carried out at rt using 1 mol % catalyst. Condition A: 1% $AuCl_3$, in CH_2Cl_2. Condition B: 1% $(PPh_3)AuCl$, 1% AgOTf, in THF. In all cases, R^1=H.
[b] Isolated yields.
[c] Cy is 1-cyclohexenyl group.

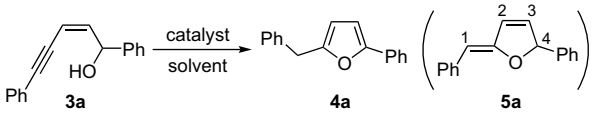
substitution at C1–C5 were all compatible with cyclization conditions, good yields of the corresponding furans were obtained in each case (64–92%). Substitution at C-1 with an electron-withdrawing group *p*-$CF_3C_6H_4$, as in **1e**, led to the corresponding product **2e** in 64% yield (Table 1, entry 5). Enynol substituted at C-3 with a TMS group (*E*-**1f**) resulted in partial desilylation during the separation, the two products were obtained in a ratio of 2:1 with a combined yield of 92% (Table 1, entry 6). When the alkyne moiety in **1g** terminated with 1-cyclohexenyl group, a double bond isomerization to an exocyclic double bond was observed, owing to better conjugation with furan ring in product **2g** (Table 1, entry 7).

2.2. Gold-catalyzed formation of furans from various substituted (*Z*)-2-en-4-yn-1-ols

The requisite (*Z*)-enynols were easily synthesized through multistep transformations by the modified procedures of the published reports.[10] We chose (*Z*)-enynol 1,5-diphenyl-pent-2-en-4-yn-1-ol **3a** for the optimization studies (Table 2). Treatment of **3a** with 1 mol % $AuCl_3$ in CH_2Cl_2 resulted, however, in this case, in a complicated reaction mixture as observed by ^1H NMR. In the presence of 1 mol % cationic gold(I) complex $(PPh)_3AuCl/AgOTf$, the desired furan **4a** was isolated in 74% yield. Monitoring the reaction mixture by TLC indicated that the expected furan **4a** was accompanied by some amounts of a byproduct. The ^1H NMR (in C_6D_6/THF) of the reaction mixture revealed that the ratio of **4a** with the byproduct is ca. 1:1. It was suggested that the byproduct might be dihydrofuran **5a**, since it shows a characteristic singlet at δ 5.42 ppm corresponding to side-chain vinylic proton of **5a**, while the signals of H-2 to H-4 appeared in the range of 5.85–6.01 ppm. Compound **5a** was highly unstable and could isomerize completely to the corresponding furan **4a** upon evaporation of the solvent or chromatographic purification on Al_2O_3.[11] When the reaction was carried out at 50 °C, the side product of **5a** was mostly converted into furan **4a** during the reaction, and the desired furan **4a** was obtained in 70% yield.

The method has been applied successfully to a variety of (*Z*)-enynols, and the results are summarized in Table 3. The cyclization

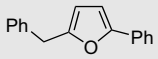
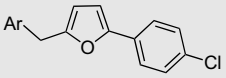
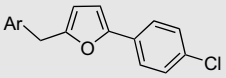
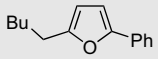
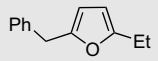
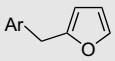
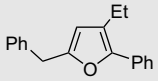
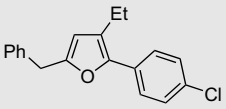
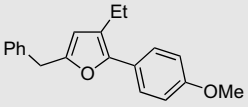
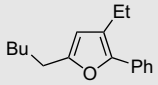
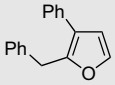
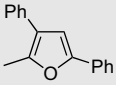
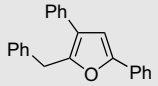
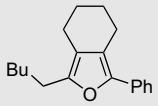
Table 2
Optimization study of gold-catalyzed cyclization of (*Z*)-enynols



Entry	Conditions	Isolated yield of **4a** (%)
1	$AuCl_3$ (1 mol %), in CH_2Cl_2, rt, 1 h	—[a]
2	$(Ph_3P)AuCl/AgOTf$ (1 mol %), in THF, rt, 1 h	74
3	$(Ph_3P)AuCl/AgOTf$ (2 mol %), in THF, rt, 3 h	73
4	$(Ph_3P)AuCl/AgOTf$ (1 mol %), in THF, 50 °C, 1 h	70

[a] Complicated reaction mixture was observed by ^1H NMR.

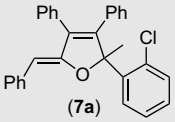
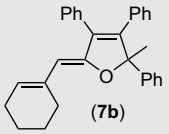
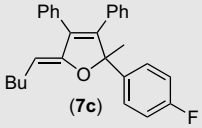
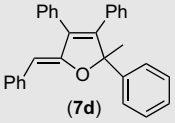
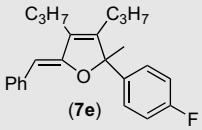
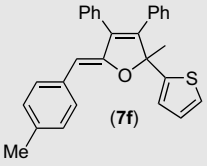
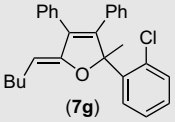
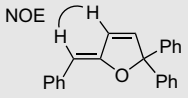
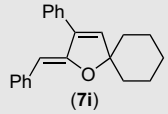
Table 3
Formation of various substituted furans catalyzed by gold

Entry	Enynol	R^2	R^3	R^4	R^5	Product	Yield[a] (%)
1	**3a**	Ph	H	H	Ph	 **4a**	70
2	**3b**	*p*-ClC_6H_4	H	H	*p*-$MeOC_6H_4$	 **4b** Ar=*p*-$MeOC_6H_4$	71[b]
3	**3c**	*p*-ClC_6H_4	H	H	*p*-ClC_6H_4	 **4c** Ar=*p*-ClC_6H_4	85[b]
4	**3d**	Ph	H	H	Bu	 **4d**	76
5	**3e**	Et	H	H	Ph	 **4e**	67
6	**3f**	H	H	H	*p*-$MeOC_6H_4$	 **4f** Ar=*p*-$MeOC_6H_4$	69
7	**3g**	Ph	Et	H	Ph	 **4g**	99
8	**3h**	*p*-ClC_6H_4	Et	H	Ph	 **4h**	92
9	**3i**	*p*-$MeOC_6H_4$	Et	H	Ph	 **4i**	86
10	**3j**	Ph	Et	H	Bu	 **4j**	91[b]
11	**3k**	H	H	Ph	Ph	 **4k**	93
12	**3l**	Ph	H	Ph	H	 **4l**	57
13	**3m**	H	H	Ph	H	 **4m**	67[b]
14	**3n**	Ph	H	Ph	Ph	 **4n**	11[b,c]
15	**3o**	Ph	$-(CH_2)_4-$		Bu	 **4o**	56[d]

[a] Isolated yields. Unless noted, all the reactions were carried out using 1 mol % $(Ph_3P)AuCl/AgOTf$ as catalyst at 50 °C for 1 h. In all cases, R^1=H.
[b] Catalyst (5 mol %) was used.
[c] In this case, some unidentified side products were formed.
[d] The reaction was carried out at rt in dichloromethane for 30 min using 2 mol % $(Ph_3P)AuCl/AgOTf$ as catalyst.

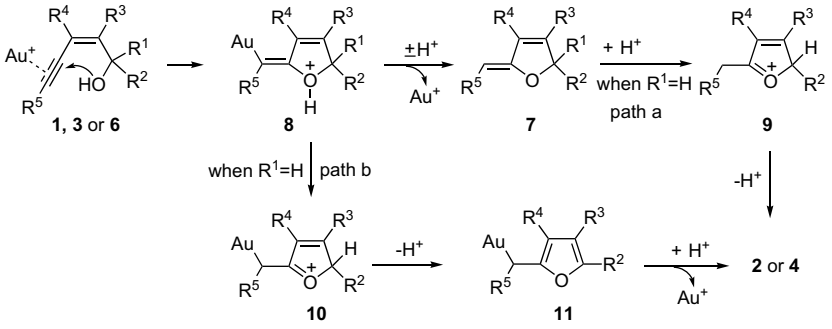
of enynols **3a**–**3f** unsubstituted both at C-2 and C-3 was investigated firstly. The aromatic rings of R^2 and/or R^5 bearing an electron-withdrawing group (–Cl) or an electron-donating group (–OMe) had no significant influence on the product yields, and the desired furans **4b** and **4c** were isolated in 71% and 85% yields, respectively (Table 3, entries 2 and 3). C-5 or C-1-Alkyl substituted **3d** and **3e** afforded the corresponding furans **4d** and **4e** in good yields of 76% and 67%, respectively (Table 3, entries 4 and 5). C-1-Unsubstituted **3f** also afforded **4f** in a satisfactory yield of 69% at 50 °C (Table 3, entry 6). When the reaction was carried out at room

Table 4
Gold-catalyzed cyclization of (*Z*)-enynols: formation of (*Z*)-5-ylidene-2,5-dihydrofurans

Entry	Enynol	R^1	R^2	R^3	R^4	R^5	Condition[a]	Product	Yield[b] (%)
1	**6a**	Me	*o*-ClC_6H_4	Ph	Ph	Ph	A, 3 h	 (**7a**)	97
2	**6b**	Me	Ph	Ph	Ph	Cy[c]	A, 1 h	 (**7b**)	92
3	**6c**	Me	*p*-FC_6H_4	Ph	Ph	Bu	A, 1 h	 (**7c**)	89
4	**6d**	Me	Ph	Ph	Ph	Ph	A, 3 h	 (**7d**)	91
5	**6e**	Me	*p*-FC_6H_4	C_3H_7	C_3H_7	Ph	B, 3 h	 (**7e**)	84
6	**6f**	Me	2-Thienyl	Ph	Ph	*p*-MeC_6H_4	B, 3 h	 (**7f**)	87
7	**6g**	Me	*o*-ClC_6H_4	Ph	Ph	Bu	A, 1 h	 (**7g**)	83
8	**6h**	Ph	Ph	H	H	Ph	B, 30 min	 (**7h**)	85
9	**6i**	–$(CH_2)_5$–		H	Ph	Ph	B, 50 min	 (**7i**)	87

[a] All the reactions were carried out at rt using 1 mol % catalyst. Condition A: 1% $AuCl_3$, in CH_2Cl_2. Condition B: 1% $(PPh_3)AuCl$, 1% AgOTf, in THF.
[b] Isolated yields.
[c] Cy is 1-cyclohexenyl group.

temperature, enynol **3f** could not be completely consumed even prolonged the reaction time to 48 h. Introducing one more substituent at C-2, that means for enynols **3g**–**3j**, resulted in an increase in reactivity as shown in entries 7–10, the corresponding products **4g**–**4j** were formed in high yields of 86–99%. This may due to the steric effect between a C-1 and C-2 group, which makes the hydroxyl group much closer to the triple bond. The results of enynols bearing a phenyl group at C-3 are highly dependent on the substituents at C-1 and C-5. C-1-Unsubstituted **3k** afforded furan **4k** smoothly in a high yield of 93% (Table 3, entry 11). Terminal enynols with a phenyl substituent at C-1 (**3l**) or without any substituent at C-1 (**3m**) led to moderate to good yields of **4l**–**4m** (Table 3, entries 12 and 13). However, for 1,3,5-triphenyl-pent-2-en-4-yn-1-ol **3n** substituted at C-1 with a phenyl group and with an internal triple bond, only low yield (11%) of **4n** was observed (Table 3, entry 14). In this case, the main products were isolated as a mixture of two compounds, the structure of which has not been identified yet (they could not be separated from each other through column chromatography). A furan derivative fused with a six-membered ring **4o** could also be synthesized in 56% yield by this method



Scheme 2.

(Table 3, entry 15). It is interesting to note that this strategy offers the additional flexibility to the existing methodology in the creation of regiochemical patterns around the furan nucleus.

2.3. Gold-catalyzed formation of dihydrofurans from (*Z*)-2-en-4-yn-1-ols bearing a tertiary alcoholic group

We have also investigated the cyclization of (*Z*)-enynols **6** bearing a tertiary alcoholic group for the synthesis of dihydrofurans. To our delight, it has been proved that the cyclization proceeded quite smoothly using these substrates to afford the high yields of fully or non-fully substituted dihydrofurans **7** (Table 4). The alkyne moiety in enynols **6** bearing an aromatic ring as well as alkyl substrate, all reacted very well to provide the 5-*exo*-*dig* cyclization products in high yields (83–97%). The appearance of a vinylic group at C-5 in **6b** did not influence the efficiency of this reaction, in which the corresponding product **7b** was formed in 92% yield (Table 4, entry 2). C-1-Substituted with two phenyl groups **6h** afforded the desired 5-benzylidene-2,2-diphenyl-2,5-dihydrofuran **7h** in 85% yield, while a spirocyclic dihydrofuran **7i** was formed in 87% yield for 50 min (Table 4, entries 8 and 9). A high reactivity of enynols **6** may also due to the steric effect between two groups on tertiary alcoholic carbon, which makes the hydroxyl group closer to the triple bond. It is interesting to note that only stereoisomerically pure compounds (*Z*)-**7** derived from 5-*exo*-*dig* cyclization were obtained. The stereochemistry of the products was unambiguously established by 2D NMR spectroscopy of several products and the single-crystal analysis of **7a**.[9] The results suggested that the activation of the alkyne and the subsequent addition of the oxygen nucleophile were highly stereoselective.

2.4. Mechanistic aspects

We propose the following mechanism for this reaction, which is analogous to what has been previously reported on Pd-catalyzed cycloisomerization of (*Z*)-enynols[6a] (Scheme 2). In the first step, the coordination of the triple bond of enynol **1**, **3** or **6** to PPh_3AuOTf enhances the electrophilicity of alkyne, and the subsequent *anti*-5-*exo*-*dig* nucleophilic attack of the hydroxyl group on a Au(I)–alkyne complex would form complex **8**. Protonolysis of **8** affords dihydrofuran **7** and regenerate Au^+. Furans **2** or **4** were formed either by isomerization of **7** (path a) or through isomerization/protonolysis pathway (path b). The above results also indicated that the oxyauration from (*Z*)-enynols is highly stereoselective.

In summary, we have developed a highly efficient Au(I)-catalyzed cyclization of (*Z*)-enynols that proceeds under neutral conditions at room temperature or 50 °C. This methodology provides rapid access to substituted furans and stereodefined (*Z*)-5-ylidene-2,5-dihydrofurans in a regioselective manner from suitably substituted (*Z*)-2-en-4-yn-1-ols.

3. Experimental section

3.1. General

All reactions were carried out under nitrogen or argon. THF was distilled from sodium and benzophenone. All commercially available materials were used without further purification. $AuCl(PPh_3)$ was prepared according to the published method.[12] $AuCl_3$ was used as a 0.05 M solution in MeCN $AuCl(PPh_3)$ was used as a 0.05 M solution in THF and AgOTf was used as a 0.05 M or 0.1 M solution in THF. ^1H and ^{13}C NMR spectra were recorded at 300 and 75.4 MHz, respectively, on Varian XL-300 MHz spectrometer at room temperature, and in $CDCl_3$ (containing 0.03% TMS) solutions.

The spectroscopic data of **2a**–**2g**, **7a**–**7g** have been reported.[9]

The spectroscopic data of **4a**,[13] **4d**,[14] **4f**,[15] **4l**,[16] **4m**,[17] and **4n**[18] are in agreement with those previously reported.

3.2. A typical procedure for the gold-catalyzed synthesis of furans and dihydrofurans from (*Z*)-enynols

To a solution of (*Z*)-enynols (0.35 mmol) in 3.5 mL THF was added 1 mol% $(PPh_3)AuCl$ followed by AgOTf (1 mol%). The resulting solution was stirred at 50 °C or at room temperature until the reaction was complete as monitored by thin-layer chromatography. The solvent was removed in vacuo and the residue was purified by flash chromatography on neutral Al_2O_3 or silica gel to afford the furan and dihydrofuran derivatives **2**, **4** or **7**.

*3.2.1. 2-(4-Chlorophenyl)-5-(4-methoxybenzyl)furan (**4b**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=40:1) afforded the title product in 71% isolated yield as a white solid. Mp 77–79 °C. ^1H NMR ($CDCl_3$, Me_4Si) δ 3.77 (s, 3H), 3.94 (s, 2H), 6.02 (s, 1H), 6.51 (d, J=3.0 Hz, 1H), 6.85 (d, J=8.4 Hz, 2H), 7.18 (d, J=8.1 Hz, 2H), 7.28 (d, J=8.1 Hz, 2H), 7.51 (d, J=8.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 33.71, 55.17, 106.22, 108.31, 113.86, 124.56, 128.70, 129.5, 129.47, 129.78, 132.32, 151.66, 155.17, 158.23; IR (neat) 3007, 2937, 1515, 1253, 1031, 824, 683 cm^{-1}. Anal. Calcd for $C_{18}H_{15}O_2Cl$: C, 72.36; H, 5.06; Cl, 11.87. Found C, 71.96; H, 5.12; Cl, 12.24.

*3.2.2. 2-(4-Chlorobenzyl)-5-(4-chlorophenyl)furan (**4c**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=40:1) afforded the title product in 85% isolated yield as a white solid. Mp 91–93 °C. ^1H NMR ($CDCl_3$, Me_4Si) δ 3.95 (s, 2H), 6.03 (d, J=2.7 Hz, 1H), 6.50 (d, J=3.0 Hz, 1H), 7.16 (d, J=8.4 Hz, 2H), 7.24–7.29 (m, 4H), 7.47–7.51 (m, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 33.89, 106.21, 108.73, 124.58, 128.61, 128.73, 129.29, 130.02, 132.34, 132.50, 136.22, 151.94, 153.93; IR (neat) 1540, 1481, 1093, 829, 796 cm^{-1}. Anal. Calcd for $C_{17}H_{12}OCl_2$: C, 67.35; H, 3.99; Cl, 23.39. Found C, 67.11; H, 4.14; Cl, 23.24.

*3.2.3. 2-Benzyl-5-ethylfuran (**4e**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=60:1) afforded the title product in 67% isolated yield as a colorless oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.19 (t, J=7.2 Hz, 3H), 2.59 (q, J=7.5 Hz, 2H), 3.91 (s, 2H), 5.85 (s, 2H), 7.18–7.31 (m, 5H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.12, 21.33, 34.51, 104.31, 106.62, 126.30, 128.38, 128.67, 138.45, 152.55, 156.74; IR (neat) 3029, 2973, 1564, 1496, 1454, 1012, 706 cm^{-1}; HRMS (EI) calcd for $C_{13}H_{14}O$: 186.1045, found 186.1049.

*3.2.4. 5-Benzyl-3-ethyl-2-phenylfuran (**4g**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=60:1) afforded the title product in 99% isolated yield as a yellow oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.18 (d, J=7.5 Hz, 3H), 2.61 (q, J=7.5 Hz, 2H), 3.95 (s, 2H), 5.95 (s, 1H), 7.15–7.34 (m, 8H), 7.56 (d, J=7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.37, 19.17, 34.59, 109.80, 123.85, 125.21, 126.34, 126.40, 128.39, 128.44, 128.76, 131.91, 138.06, 146.85, 153.11; IR (neat) 3085, 2967, 1599, 1493, 982, 695 cm^{-1}; HRMS (EI) calcd for $C_{19}H_{18}O$: 262.1358, found 262.1353.

*3.2.5. 5-Benzyl-2-(4-chlorophenyl)-3-ethylfuran (**4h**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=60:1) afforded the title product in 92% isolated yield as a pale yellow oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.17 (t, J=7.5 Hz, 3H), 2.57 (q, J=7.5 Hz, 2H), 3.95 (s, 2H), 5.96 (s, 1H), 7.19–7.32 (m, 7H), 7.44–7.48 (m, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.24, 19.20, 34.57, 109.95, 124.40, 126.28, 126.48, 128.48, 128.57, 128.75, 130.35, 131.89, 137.88, 145.80, 153.43; IR (neat) 3085, 2968, 1487, 1094, 982, 830 cm^{-1}; HRMS (EI) calcd for $C_{19}H_{17}OCl$: 296.0968, found 296.0979.

*3.2.6. 5-Benzyl-3-ethyl-2-(4-methoxyphenyl)furan (**4i**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=60:1) afforded the title product in 86% isolated yield as a yellow oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.18 (t, J=7.5 Hz, 3H), 2.58 (q, J=7.5 Hz, 2H), 3.75 (s, 3H), 3.95 (s, 2H), 5.94 (s, 1H), 6.89 (d, J=9.0 Hz, 2H), 7.20–7.32 (s, 5H), 7.48 (d, J=9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.46, 19.05, 34.57, 55.13, 109.54, 113.84, 122.22, 124.86, 126.35, 126.70, 128.41, 128.75, 138.19, 146.90, 152.45, 158.20; IR (neat) 3029, 2965, 1604, 1505, 1251, 1177, 832 cm^{-1}; HRMS (EI) calcd for $C_{20}H_{20}O_2$: 292.1463, found 292.1468.

*3.2.7. 3-Ethyl-5-pentyl-2-phenylfuran (**4j**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=100:1) afforded the title product in 91% isolated yield as a pale yellow oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.91 (t, J=6.9 Hz, 3H), 1.23 (t, J=7.5 Hz, 3H), 1.34–1.39 (m, 4H), 1.63–1.72 (m, 2H), 2.60–2.69 (m, 4H), 5.99 (s, 1H), 7.18–7.22 (m, 1H), 7.37 (t, J=7.8 Hz, 2H), 7.58 (d, J=7.2 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.02, 14.44, 19.23, 22.44, 27.75, 28.09, 31.46, 108.25, 123.73, 125.10, 126.14, 128.41, 132.13, 146.04, 155.17; IR (neat) 3085, 2931, 1600, 1492, 1070, 763, 694 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{22}O$: 242.1671, found 242.1665.

*3.2.8. 2-Benzyl-3-phenylfuran (**4k**)*

Column chromatography on neutral Al_2O_3 (eluent: petroleum ether/ethyl acetate=60:1) afforded title product in 93% isolated yield as a pale yellow oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 4.12 (s, 2H), 6.53 (d, J=1.5 Hz, 1H), 7.18–7.40 (m, 11H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 32.78, 111.31, 122.33, 126.38, 126.65, 127.70, 128.28, 128.51, 128.55, 128.61, 133.83, 138.45, 141.26, 149.23; IR (neat) 3029, 1603, 1494, 1140, 1057, 697 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{14}O$: 234.1045, found 234.1041.

*3.2.9. 1-Pentyl-3-phenyl-4,5,6,7-tetrahydro-isobenzofuran (**4o**)*

Column chromatography on silica gel (eluent: petroleum ether/ethyl acetate=60:1) afforded title product in 56% isolated yield as a pale yellow oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.90 (t, J=6.6 Hz, 3H), 1.31–1.38 (m, 4H), 1.61–1.77 (m, 6H), 2.45 (t, J=5.7 Hz, 2H), 2.57 (t, J=7.5 Hz, 2H), 2.75 (t, J=6.0 Hz, 2H), 7.12–7.20 (m, 1H), 7.32–7.37 (m, 2H), 7.58 (d, J=7.2 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.05, 20.65, 22.46, 22.99, 23.04, 23.49, 26.36, 28.04, 31.48, 117.95, 119.09, 123.79, 125.46, 128.39, 132.40, 144.35, 149.17; IR (neat) 3056, 2932, 1768, 1671, 1492, 762 cm^{-1}; HRMS (EI) calcd for $C_{19}H_{24}O$: 268.1827, found 268.1839.

*3.2.10. (Z)-5-Benzylidene-2,2-diphenyl-2,5-dihydrofuran (**7h**)*

Column chromatography on silica gel (eluent: petroleum ether) afforded title product in 85% isolated yield as a pale yellow oil. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 5.44 (s, 1H), 6.28 (d, J=5.4 Hz, 1H), 6.69 (d, J=5.4 Hz, 1H), 7.09–7.13 (m, 1H), 7.22–7.37 (m, 12H), 7.73 (d, J=7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 98.54, 99.65, 125.29, 126.04, 126.50, 127.72, 127.88, 128.35, 128.37, 136.58, 137.50, 142.60, 158.60; IR (neat) 3084, 1953, 1765, 1649, 1490, 937, 694 cm^{-1}; HRMS (EI) calcd for $C_{23}H_{18}O$: 310.1358, found 310.1349.

*3.2.11. (Z)-2-Benzylidene-3-phenyl-1-oxa-spiro[4.5]dec-3-ene (**7i**)*

Column chromatography on silica gel (eluent: petroleum ether) afforded the title product as a brown solid in 87% isolated yield. Mp 112–114 °C. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.37–1.48 (m, 1H), 1.56–1.73 (m, 5H), 1.79–1.93 (m, 4H), 5.42 (s, 1H), 6.31 (s, 1H), 7.09 (tt, J=7.5, 1.2 Hz, 1H), 7.26–7.32 (m, 2H), 7.34–7.46 (m, 5H), 7.67 (d, J=7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 22.94, 25.11, 36.02, 91.95, 97.60, 124.81, 127.56, 128.14, 128.21, 128.43, 128.48, 133.32, 136.99, 137.44, 138.73, 158.46. Anal. Calcd for $C_{22}H_{22}O$: C, 87.38; H, 7.33. Found C, 87.16; H, 7.14.

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2008.11.109.

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