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Cu(I)-Catalyzed Synthesis of Furan-Substituted Allenes by Use of Conjugated Ene-yne Ketones as Carbene Precursors

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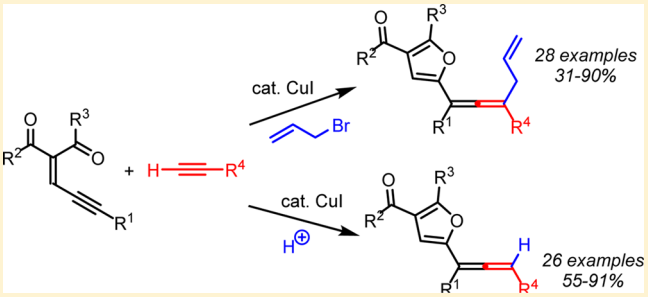
Supporting Information

ABSTRACT: The synthesis of furan-substituted allenes using conjugated ene-yne ketones as carbene source has been developed. For this reaction, bases play vital roles in controlling the reaction pathways, allowing for access to two types of allene products through trapping of different electrophiles. Mechanistically, the catalytic procedure generated a Cu(I) (2-furyl)carbene intermediate, which is subsequently followed by a migratory insertion process to afford nucleophilic organocopper species. The organocopper species thus generated can be trapped by proton or allyl halide, affording tri- or tetrasubstituted allenes, respectively. The reaction, which is characterized by its mild reaction conditions and the utilization of cheap copper(I) iodide as catalyst, allows for synthesis of a variety of furan-substituted allenes with a wide range of functional groups tolerance.

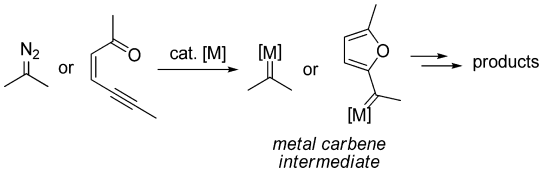


INTRODUCTION

Allenes have attracted the attention of chemists for decades due to their unique structures and chemical properties.[1,2] The diverse transformations of allenic compounds make them useful synthetic building blocks in modern organic synthesis.[2] In addition, these unsaturated three-carbon units frequently occur in natural products and pharmaceutically active compounds as well as in organic materials.[3] Due to the importance of allenes in various fields, significant efforts have been devoted to the development of highly efficient synthetic methods for allenes and related compounds.[4]

On the other hand, metal carbene species have been the active intermediates for many important transition-metal-catalyzed transformations.[5] In this context, diazo compounds, either directly used as substrates or generated in situ from *N*-tosylhydrazones, have been served as common metal carbene precursors (Scheme 1). Various transformations, such as C−H bond insertions and cyclopropanations, have been well-established based on metal carbene intermediates.[6] In addition to these classic transformations, a new type of carbene-based reaction, namely, carbene cross-coupling reaction, has recently emerged as a novel C−C bond-forming transformation.[7] In these reactions, carbene migratory insertion is the key step for C−C bond formation. Owing to our interest in metal carbene-related transformations, we have previously developed a novel strategy for the synthesis of allenes through Cu(I)-catalyzed cross-coupling of *N*-tosylhydrazones and terminal alkynes.[8] On the basis of the same protocol, we also reported the synthesis of allyl allenes through three-component reaction of *N*-tosylhydrazones, terminal alkynes, and allyl halides.[9] Notably, diazo compounds or

Scheme 1. Metal Carbenes Generated from Diazo Compounds or Conjugated Ene-yne Ketones



N-tosylhydrazones are employed as the carbene sources in these transformations.

Apart from diazo compounds, conjugated ene-yne ketones have also been recognized as new entries to metal carbene through activation of the alkyne moiety (Scheme 1).[10] In the past years, a number of elegant works have been reported that use conjugated ene-yne ketones as coupling partners.[11] For example, Vicente and co-workers[12] have recently reported cyclopropenation of alkynes using readily accessible enynones as the carbene sources. Vicente and López and co-workers[11c,d] have also explored Zn(II) (2-furyl)carbenes, which are derived from conjugated ene-yne ketones, in X−H insertion and cyclopropanation processes. Despite the impressive progress in this field, cross-coupling reactions based on carbene migratory insertion process using conjugated ene-yne ketones as carbene precursors have remained underdeveloped.

We have recently developed a palladium-catalyzed cross-coupling reaction between benzyl, aryl, or allyl bromides and

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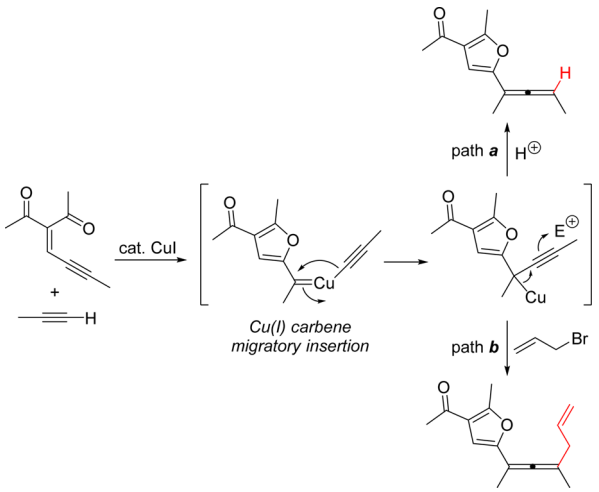
conjugated ene-yne ketones, leading to formation of 2-alkenyl-substituted furans.[13] Mechanistically, palladium (2-furyl)carbene migratory insertion has been proposed as the key step. Encouraged by this success, we have further communicated a straightforward approach for synthesis of furan-substituted allenes via a copper carbene process using conjugated ene-yne ketones as substrates (Scheme 2).[14] Furthermore, we have

Scheme 2. Synthesis of Furan-Substituted Allenes through Cu(I)-Catalyzed Reaction of Conjugated Ene-yne Ketones



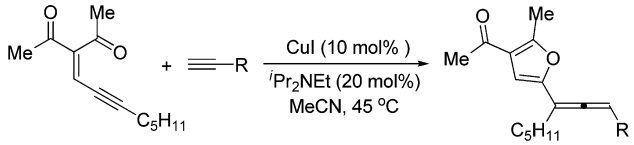
envisioned that protonation of the organocopper intermediate in the reaction mechanism (Scheme 2, path a) may be replaced by electrophilic substitution with allylic halide, thus leading to the formation of allyl- and furan-substituted allenes (Scheme 2, path b). Herein we report the details of this investigation.

RESULTS AND DISCUSSION

Initially, the conjugated ene-yne ketone **1a** and phenylacetylene **2a** were used as model substrates. Upon systematic investigation of the reaction conditions, we found that catalytic CuI in combination with ethyldiisopropylamine ($^{i}Pr_2NEt$) as the base and acetonitrile (MeCN) as the solvent at 45 °C could afford the best result, giving allene product **4a**. With these optimized reaction conditions in hand, we further proceeded to examine the substrate scope of this reaction (Table 1). A series of aryl-substituted terminal alkynes with varied electronic properties were first explored. Both electron-rich and electron-deficient moieties on the aryl group were tolerated, affording the corresponding products **4b**–**e** in satisfactory yields (entries 2–5). Notably, the heteroaryl and polycyclic aryl alkynes also worked well, which provided the products **4f** and **4g** in 64% and 62% yields, respectively (entries 6 and 7). Furthermore, we turned our attention to alkyl-substituted alkynes. As shown in entries 8–16, a series of substrates of this type reacted with good to excellent yields. Particularly significant is that the unprotected hydroxyl group was perfectly accommodated and remained intact under the reaction conditions (entries 14 and 15). Product **4p** was obtained as a 1:1 diastereomeric mixture (entry 16).

The scope of conjugated ene-yne ketones is summarized in Table 2. For a series of ene-yne ketones, the reaction proceeded well to afford the corresponding allene products. The reaction was marginally affected by the R^1 group (entries 1–6). Notably, the conjugated ene-yne ketone **1g** bearing a benzyloxy group was a suitable substrate for this reaction, although the corresponding product **5f** was obtained in only moderate yield (entry 6).

Table 1. Reaction Scope of Terminal Alkynes[a]



1a **2a-p** **4a-p**

entry	2a-p	4a-p, %[b]
1	**2a**	**4a**, 85%
2	**2b**	**4b**, 77%
3	**2c**	**4c**, 73%
4	**2d**	**4d**, 76%
5	**2e**	**4e**, 79%
6	**2f**	**4f**, 64%
7	**2g**	**4g**, 62%
8	**2h**	**4h**, 80%
9	**2i**	**4i**, 68%
10	**2j**	**4j**, 55%
11	**2k**	**4k**, 86%
12	**2l**	**4l**, 80%
13	**2m**	**4m**, 58%
14	**2n**	**4n**, 80%
15	**2o**	**4o**, 89%
16	**2p**	**4p**, 83%[c]

[a]Reaction conditions: **1a** (0.22 mmol), **2a**–**p** (0.20 mmol), CuI (10 mol %), and $^{i}Pr_2NEt$ (20 mol %) in acetonitrile (4 mL) at 45 °C for 10 h. [b]Isolated yield is given. [c]dr = 1:1.

However, only a trace amount of the desired product was obtained when R^1 was an aryl group (entry 11). Besides, the reaction was not hampered when the R^2 and R^3 were replaced with ethyl groups (entry 7). Next, the influence of nucleophilicity of the carbonyl moiety that attacks the activated triple bond was evaluated. Gratifyingly, substrates **1i** and **1j** with ester substituents afforded smoothly the corresponding allenes **5h** and **5i** in 73% and 81% yields, respectively (entries 8 and 9). Interestingly, when a mixture of *E*- and *Z*-isomeric starting material **1k** was employed, only a single product **5j** was detected (entry 10). This result indicates that ester carbonyl oxygen cannot be acting as nucleophile due to its low nucleophilicity, which is consistent with the results reported previously.[11,13]

It is noteworthy that in the last step of these transformations, the organocopper species generated from migratory insertion is protonated (Scheme 2, path a). It is thus conceivable that the organocopper species may be trapped by other electrophiles,

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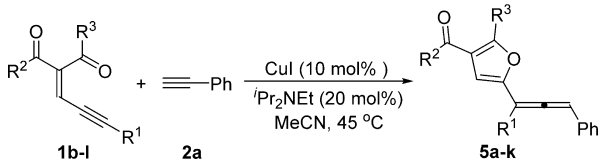
Table 2. Scope of Ene-yne Ketones[a]

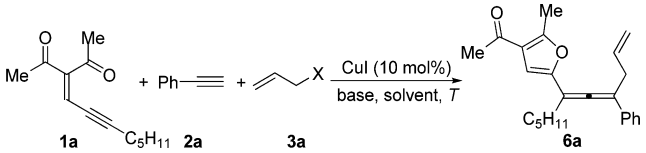


entry	ene-yne ketone 1b–k	R^1	R^2	R^3	5a–k, %[b]
1	**1b**	^{i}Pr	Me	Me	**5a**, 91
2	**1c**	^{n}Bu	Me	Me	**5b**, 82
3	**1d**	$PhCH_2CH_2$	Me	Me	**5c**, 74
4	**1e**	cyclopentyl	Me	Me	**5d**, 88
5	**1f**	cyclohexyl	Me	Me	**5e**, 88
6	**1g**	$BnOCH_2CH_2$	Me	Me	**5f**, 61
7	**1h**	$^nC_5H_{11}$	Et	Et	**5g**, 80
8	**1i**	$^nC_4H_9$	OMe	Me	**5h**, 73
9	**1j**	$^nC_4H_9$	O^{t}Bu	Me	**5i**, 81
10	**1k**	$^nC_4H_9$	OMe	Et	**5j**,[c] 60
11	**1l**	Ph	Me	Me	**5k**, trace

[a]Reaction conditions: **1b–l** (0.22 mmol), **2a** (0.20 mmol), CuI (10 mol %), and ^{i}Pr$_2$NEt (20 mol %) in acetonitrile (4 mL) at 45 °C for 10 h. [b]Isolated yield is given. [c]Ene-yne ketone **1k** (2.5 equiv) was used.

such as iodomethane, benzyl bromide, and allyl halides. Since in this way new C–C bonds can be formed, we have thus introduced these electrophiles to the reaction system. Reaction with iodomethane or benzyl bromide failed to afford any electrophilic substitution products, but reaction with allyl bromide afforded the expected tetrasubstituted allene product. Consequently, we carried out optimization experiments by using conjugated ene-yne ketone **1a**, phenylacetylene **2a**, and allyl bromide **3a** as substrates (Table 3). When Na_2CO_3 was employed as the base, the coupling product **6a** was obtained in 23% yield (entry 1). Several inorganic bases were then examined.

Table 3. Optimization of Reaction Conditions[a]



entry	base	3a	T (°C)	6a, yield[b] (%)
1	Na_2CO_3	X = Br	60	23
2	K_2CO_3	X = Br	60	67
3	Cs_2CO_3	X = Br	60	trace
4	K_3PO_4	X = Br	60	57
5	NEt_3	X = Br	60	0
6	^{i}Pr$_2$NEt	X = Br	60	8
7[c]	K_2CO_3	X = Br	40	60
8	K_2CO_3	X = Br	50	67
9[c]	K_2CO_3	X = Br	70	80
10[c]	K_2CO_3	X = Br	80	76
11[c,d]	K_2CO_3	X = Br	70	83
12	K_2CO_3	X = Cl	70	22
13	K_2CO_3	X = I	70	36

[a]Reaction conditions are as follows if not otherwise noted: **1a** (0.20 mmol), **2a** (0.20 mmol), **3a** (0.40 mmol), CuI (10 mol %), and base (1.0 equiv) in MeCN (3 mL) at the indicated temperature for 8 h. [b]All yields refer to isolated yields by column chromatography. [c]Reaction was carried out for 11 h. [d]**2a** (0.24 mmol) and K_2CO_3 (0.24 mmol) were used.

K_2CO_3 and K_3PO_4 were found to give much improved results (entries 2 and 4), while Cs_2CO_3 was proved to be ineffective (entry 3). Further optimization showed organic bases such as triethylamine (NEt_3) and ethyldiisopropylamine (^{i}Pr$_2$NEt) could not promote this reaction (entries 5 and 6).[15] We speculated that the difference in basicity and solubility of organic and inorganic bases may account for this result. Next, the reaction temperature was systematically evaluated and a slightly higher yield could be achieved at 70 °C (entries 9 and 10). Finally, allyl chloride and iodide were tested and proved less effective as electrophiles in this transformation (entries 12 and 13).

Having established the optimal reaction conditions, we then explored the scope of this reaction. With conjugated ene-yne ketone **1a** and allyl bromide **3a** as the substrates, we investigated the reaction of a variety of terminal alkynes (Scheme 3). Substrates bearing both electron-donating and -withdrawing substituents on the aryl group were well-tolerated (**6b–e**). Replacement of the aryl group with a heteroaryl or naphthyl unit had little effect on the reaction outcome (**6f–h**). Since aryl terminal alkynes were successfully coupled in this reaction, we then evaluated a serious of alkyl-substituted terminal alkynes. A diverse set of aliphatic terminal alkynes including acyclic or cyclic substituents gave the corresponding products in good to excellent yields. Remarkably, unprotected hydroxyl group was also accommodated in this reaction, albeit with slightly diminished yield (**6n**). The use of 1-ethynylcyclohexene effectively led to **6o** in 86% yield. Gratifyingly, our protocol can also be extended to ethynyltrimethylsilane, providing the corresponding product **6p** in 64% yield.

Next, we proceeded to evaluate conjugated ene-yne ketones and allyl bromides with phenylacetylene **2a** (Scheme 4). Under the standard reaction conditions, primary and secondary alkyl substituents in R^1 groups were well-tolerated, providing the corresponding allene products in good yields (**7a–f**). The aromatic group, when attached to the alkyne moiety in conjugated ene-yne ketones, seemed to make this transformation sluggish (**7g**). Similarly, the influence of the nucleophilic carbonyl oxygen was explored in the examples of **7h** and **7i**, which were isolated in 40% and 50% yields, respectively. Finally, three substituted allyl bromides were examined. Although only slightly low yields were obtained in these examples (**7j–l**), the corresponding products could not be easily prepared by other approaches.

CONCLUSION

In summary, we have developed a tunable approach for the synthesis of furan-substituted allenes, using proton and allyl halides as the trapping electrophiles. Conjugated ene-yne ketones were used as carbene precursors, and copper carbene species were employed as the key intermediate in this transformation. Owing to the frequent occurrence of allene moieties in natural products and pharmaceutical-related compounds, we expect this alternative method will be useful in furan-substituted allene synthesis.[16] Besides, it is worth mentioning that the synthesis of 3-acylfurans is challenging and the method reported in this paper represents a valuable approach toward this type of furan derivative.[17] Further studies on other related transformations using conjugated ene-yne ketones as the carbene precursors are currently ongoing in our laboratory.

EXPERIMENTAL SECTION

General Methods. All reactions were performed under a nitrogen atmosphere in a Schlenk reaction flask. All solvents were distilled under a nitrogen atmosphere prior to use. 1,4-Dioxane and toluene were

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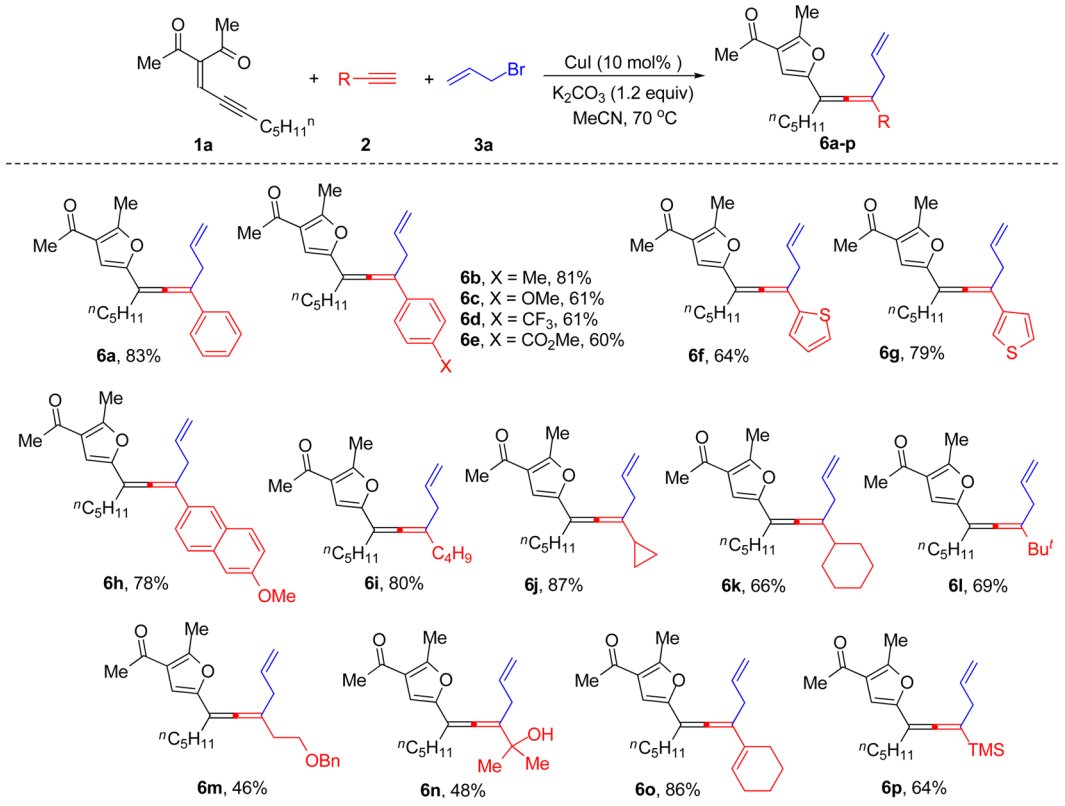
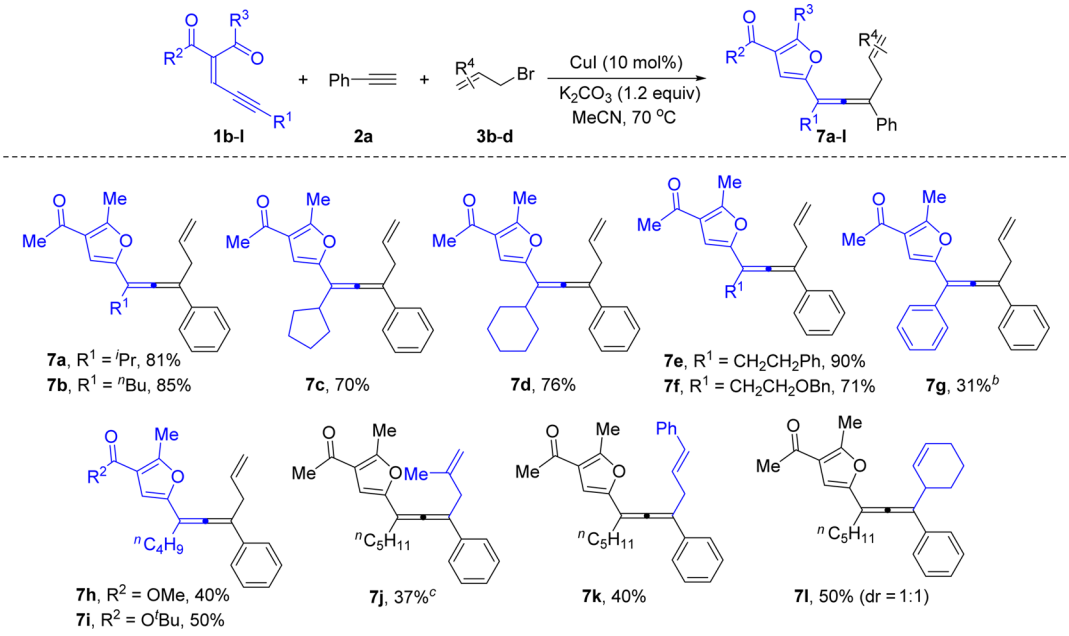
Scheme 3. Substrate Scope of Terminal Alkynes[a]



[a]Reaction conditions: **1a** (0.20 mmol), **2** (0.24 mmol), **3a** (0.40 mmol), CuI (10 mol %), and K_2CO_3 (1.2 equiv) in acetonitrile (3 mL) at 70 °C for 11 h.

Scheme 4. Substrate Scope of Conjugated Ene-yne Ketones and Allyl Halides[a]



[a]Reaction conditions: **1b–l** (0.20 mmol), **2a** (0.24 mmol), **3b–d** (0.40 mmol), CuI (10 mol %), and K_2CO_3 (1.2 equiv) in acetonitrile (3 mL) at 70 °C for 11 h. [b]Reaction was carried out at 45 °C. [c]3-Chloro-2-methylprop-1-ene **3b** was used.

dried over Na with benzophenone–ketyl intermediate as indicator. MeCN and 1,2-dichloroethane (DCE) were dried over CaH_2. The boiling point of petroleum ether was between 60 and 70 °C. For chromatography, 200–300 mesh silica gel was employed. Chemical shifts for ^{1}H NMR (400 MHz) and ^{13}C{1H}NMR spectra are reported relative to the chemical shift of tetramethylsilane (TMS): chemical shifts (δ) are reported in parts per million (ppm), and coupling constants (J) are in hertz (Hz). IR spectra are reported as wavenumbers, cm^{-1}. For high-resolution mass spectrometric (HRMS) measurements, the mass analyzer is Fourier transform ion cyclotron resonance (FT-ICR).

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Unless otherwise noted, materials obtained from commercial suppliers were used without further purification.

Conjugated Ene-yne Ketones. The conjugated ene-yne ketones **1a–l** were prepared according to literature procedures.[13]

*3-(Oct-2-yn-1-ylidene)pentane-2,4-dione (**1a**).* The title compound[13a] was prepared as a yellow oil (2.43 g, 76%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.70 (t, J = 2.4 Hz, 1H), 2.47 (s, 3H), 2.44 (dt, J = 2.4, 7.1 Hz, 2H), 2.32 (s, 3H), 1.54–1.61 (m, 2H), 1.28–1.41 (m, 4H), 0.91 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.3, 195.7, 149.4, 123.2, 110.4, 76.8, 30.9, 30.9, 27.7, 27.1, 22.0, 20.1, 13.8.

*3-(4-Methylpent-2-yn-1-ylidene)pentane-2,4-dione (**1b**).* The title compound was prepared as a yellow oil (473 mg, 43%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.71 (d, J = 2.2 Hz, 1H), 2.74–2.85 (m, 1H), 2.48 (s, 3H), 2.31 (s, 3H), 1.22 (d, J = 6.9 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.2, 195.7, 149.4, 123.2, 115.2, 76.2, 30.9, 27.3, 22.2, 21.9. HRMS (ESI, m/z) calcd for $C_{11}H_{15}O_2$ $[M + H]^+$ 179.1067, found 179.1071. IR (film) 1249, 1665, 1692, 1716, 2215, 2917, 2973 cm^{-1}.

*3-(Hept-2-yn-1-ylidene)pentane-2,4-dione (**1c**).* The title compound[11g] was prepared as a yellow oil (679 mg, 71%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.70 (t, J = 2.4 Hz, 1H), 2.47 (s, 3H), 2.43–2.45 (m, 2H), 2.32 (s, 3H), 1.52–1.59 (m, 2H), 1.38–1.47 (m, 2H), 0.92 (t, J = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.2, 195.6, 149.4, 123.0, 110.2, 76.7, 30.7, 29.9, 27.0, 21.8, 19.7, 13.3.

*3-(5-Phenylpent-2-yn-1-ylidene)pentane-2,4-dione (**1d**).* The title compound was prepared as a yellow oil (1.55 g, 65%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29–7.32 (m, 2H), 7.19–7.24 (m, 3H), 6.66 (t, J = 2.4 Hz, 1H), 2.87 (t, J = 7.4 Hz, 2H), 2.73–2.77 (m, 2H), 2.35 (s, 3H), 2.29 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.2, 195.7, 149.7, 139.7, 128.5, 128.3, 126.5, 122.8, 108.9, 77.4, 34.2, 30.8, 27.2, 22.2. HRMS (ESI, m/z) calcd for $C_{16}H_{17}O_2$ $[M + H]^+$ 241.1223, found 241.1224. IR (film) 700, 1249, 1375, 1664, 1689, 1714, 2211 cm^{-1}.

*3-(3-Cyclopentylprop-2-yn-1-ylidene)pentane-2,4-dione (**1e**).* The title compound[13a] was prepared as a yellow oil (590 mg, 58%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.72 (d, J = 2.4 Hz, 1H), 2.82–2.90 (m, 1H), 2.48 (s, 3H), 2.31 (s, 3H), 1.92–2.02 (m, 2H), 1.58–1.74 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.3, 195.8, 149.2, 123.4, 114.7, 76.5, 33.4, 31.3, 30.8, 27.2, 25.0.

*3-(3-Cyclohexylprop-2-yn-1-ylidene)pentane-2,4-dione (**1f**).* The title compound was prepared as a yellow oil (885 mg, 81%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.72–6.73 (m, 1H), 2.60–2.64 (m, 1H), 2.48 (s, 3H), 2.31 (s, 3H), 1.81–1.84 (m, 2H), 1.69–1.71 (m, 2H), 1.45–1.56 (m, 3H), 1.34 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.3, 195.7, 149.3, 123.3, 114.2, 76.9, 31.8, 30.9, 30.3, 27.2, 25.6, 24.6. HRMS (ESI, m/z) calcd for $C_{14}H_{19}O_2$ $[M + H]^+$ 219.1380, found 219.1379. IR (film) 1249, 1665, 1691, 1715, 2206, 2855, 2932 cm^{-1}.

*3-[5-(Benzyloxy)pent-2-yn-1-ylidene]pentane-2,4-dione (**1g**).* The title compound was prepared as a yellow oil (422 mg, 31%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29–7.37 (m, 5H), 6.68 (t, J = 2.4 Hz, 1H), 4.54 (s, 2H), 3.62 (t, J = 6.6 Hz, 2H), 2.74 (dt, J = 2.4, 6.6 Hz, 2H), 2.45 (s, 3H), 2.30 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.2, 195.7, 149.8, 137.7, 128.4, 127.8, 127.6, 122.6, 106.6, 77.5, 73.0, 67.5, 30.9, 27.2, 21.6. HRMS (ESI, m/z) calcd for $C_{17}H_{19}O_3$ $[M + H]^+$ 271.1329, found 271.1326. IR (film) 1102, 1248, 1664, 1690, 1713, 2215, 2862 cm^{-1}.

*4-(Oct-2-yn-1-ylidene)heptane-3,5-dione (**1h**).* The title compound was prepared as a yellow oil (636 mg, 54%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.66 (t, J = 2.4 Hz, 1H), 2.78 (q, J = 7.3 Hz, 2H), 2.62 (q, J = 7.2 Hz, 2H), 2.41 (dt, J = 2.4, 7.0 Hz, 2H), 1.51–1.58 (m, 2H), 1.30–1.40 (m, 4H), 1.14 (t, J = 7.2 Hz, 3H), 1.09 (t, J = 7.2 Hz, 3H), 0.91 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.1, 198.3, 149.7, 121.3, 108.7, 76.6, 36.6, 32.4, 30.9, 27.8, 22.1, 20.0, 13.8, 7.8, 7.4. HRMS (ESI, m/z) calcd for $C_{15}H_{23}O_2$ $[M + H]^+$ 235.1693, found 235.1693. IR (film) 1209, 1667, 1693, 1713, 2210, 2937, 2957 cm^{-1}.

*(E)-Methyl 2-Acetylnon-2-en-4-ynoate (**1i**).* The title compound was prepared as a yellow oil (276 mg, 22%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.82 (t, J = 2.4 Hz, 1H), 3.80 (s, 3H), 2.45 (s, 3H), 2.40–2.44 (m, 2H), 1.51–1.58 (m, 2H), 1.37–1.46 (m, 2H), 0.92 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.0, 164.4, 141.6, 124.2, 108.6, 76.4, 52.4, 30.4, 30.0, 21.8, 19.7, 13.4. HRMS (ESI, m/z) calcd for $C_{12}H_{17}O_3$ $[M + H]^+$ 209.1172, found 209.1176. IR (film) 1161, 1258, 1713, 2212, 2957 cm^{-1}.

*(E)-tert-Butyl 2-Acetylnon-2-en-4-ynoate (**1j**).* The title compound was prepared as a yellow oil (394 mg, 26%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.68 (t, J = 2.4 Hz, 1H), 2.38–2.42 (m, 5H), 1.52–1.57 (m, 2H), 1.49 (s, 9H), 1.37–1.46 (m, 2H), 0.92 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.6, 163.0, 143.9, 122.7, 107.2, 82.3, 76.4, 30.2, 30.1, 27.9, 21.8, 19.7, 13.4. HRMS (ESI, m/z) calcd for $C_{15}H_{23}O_3$ $[M + H]^+$ 251.1642, found 251.1644. IR (film) 1154, 1256, 1273, 1707, 2212, 2934 cm^{-1}.

*Methyl 2-Propionylnon-2-en-4-ynoate (E/Z mixture) (**1k**).* The title compound was prepared as a yellow oil (1.02 g, 77%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.79 (t, J = 2.4 Hz, 2.3H), 3.86 (s, 3H), 3.78 (s, 4.1H), 2.76 (q, J = 7.3 Hz, 3.3H), 2.68 (q, J = 7.2 Hz, 2.3 H), 2.38–2.46 (m, 5.4H), 1.48–1.59 (m, 6.2H), 1.36–1.46 (m, 5.8H), 1.14 (t, J = 7.2 Hz, 4.5H), 1.10 (t, J = 7.4 Hz, 3.5H), 0.90–0.95 (m, 8H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.7, 196.7, 166.2, 164.4, 142.1, 141.1, 124.8, 123.6, 109.2, 107.6, 76.8, 76.3, 52.4, 52.2, 36.2, 32.8, 30.2, 30.1, 21.8, 21.8, 19.8, 19.6, 13.4, 13.4, 7.8, 7.4. HRMS (ESI, m/z) calcd for $C_{13}H_{19}O_3$ $[M + H]^+$ 223.1329, found 223.1329. IR (film) 1238, 1262, 1600, 1723, 2212, 2875, 2959 cm^{-1}.

*3-(3-Phenylprop-2-yn-1-ylidene)pentane-2,4-dione (**1l**).* The title compound[13a] was prepared as a yellow solid (887 mg, 83%,). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47–7.49 (m, 2H), 7.35–7.44 (m, 3H), 6.94 (s, 1H), 2.57 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.8, 195.5, 149.4, 132.1, 130.1, 128.6, 122.2, 121.6, 107.0, 85.3, 31.0, 27.4.

Typical Experimental Procedure of Cu(I)-Catalyzed Cross-Coupling of Conjugated Ene-yne Ketones with Terminal Alkynes. CuI (4.0 mg, 10 mol %) was added to a 25 mL Schlenk reaction flask. The reaction flask was then degassed two times with nitrogen, and MeCN (4 mL) was added via syringe. Next, conjugated ene-yne ketone **1a** (45.3 mg, 0.22 mmol), phenylacetylene **2a** (20.4 mg, 0.20 mmol), and ethyldiisopropylamine (5.2 mg, 20 mol %) were successively added to the reaction solution via syringe. The resulting solution was stirred at 45 °C for 10 h. The mixture was then cooled to room temperature and filtered through a short plug of silica gel (washed with petroleum ether/EtOAc = 3:1). Solvent was then removed in vacuo to provide a crude mixture, which was purified by silica gel column chromatography to afford pure product **4a** (52.2 mg, 85%) as a colorless oil.

*1-[2-Methyl-5-(1-phenylocta-1,2-dien-3-yl)furan-3-yl]ethanone (**4a**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 40:1), the product was isolated as a colorless oil (52 mg, 85%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30–7.33 (m, 4H), 7.21–7.25 (m, 1H), 6.59 (s, 1H), 6.49 (s, 1H), 2.56 (s, 3H), 2.38–2.45 (m, 5H), 1.56–1.61 (m, 2H), 1.29–1.41 (m, 4H), 0.87 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.4, 193.9, 158.1, 148.0, 134.2, 128.7, 127.2, 127.1, 123.0, 106.6, 101.7, 99.1, 31.5, 29.4, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{21}H_{25}O_2$ $[M + H]^+$ 309.1849, found 309.1844. IR (film) 694, 948, 1233, 1677, 2931, 2955 cm^{-1}.

*1-{2-Methyl-5-[1-(p-tolyl)octa-1,2-dien-3-yl]furan-3-yl}ethanone (**4b**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 40:1), the product was isolated as a colorless oil (50 mg, 77%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22 (d, J = 8.1 Hz, 2H), 7.13 (d, J = 7.9 Hz, 2H), 6.56 (t, J = 2.4 Hz, 1H), 6.47 (s, 1H), 2.55 (s, 3H), 2.38–2.44 (m, 5H), 2.34 (s, 3H), 1.55–1.64 (m, 2H), 1.28–1.41 (m, 4H), 0.87 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.1, 194.0, 158.0, 148.2, 137.1, 131.2, 129.4, 127.0, 123.0, 106.4, 101.6, 98.9, 31.5, 29.5, 29.1, 27.6, 22.4, 21.2, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{22}H_{27}O_2$ $[M + H]^+$ 323.2006, found 323.2008. IR (film) 652, 948, 1232, 1678, 2928, 2955 cm^{-1}.

*1-(5-{1-[4-(Dimethylamino)phenyl]octa-1,2-dien-3-yl}-2-methylfuran-3-yl)ethanone (**4c**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 25:1–15:1), the product was isolated as a yellow oil (51 mg, 73%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20 (d, J = 8.8 Hz, 2H), 6.70 (d, J = 8.7 Hz, 2H), 6.54 (t, J = 2.4 Hz, 1H), 6.45 (s, 1H), 2.95 (s, 6H), 2.55 (s, 3H), 2.36–2.43 (m, 5H), 1.56–1.63 (m, 2H), 1.29–1.39 (m, 4H), 0.87 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.4, 194.0, 157.8, 149.9, 148.7, 127.9, 122.9, 121.7, 112.7,

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106.0, 101.3, 98.8, 40.5, 31.6, 29.6, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{23}H_{30}NO_2$ $[M + H]^+$ 352.2271, found 352.2267. IR (film) 948, 1521, 1609, 1677, 2849, 2917 cm^{-1}.

*1-{5-[1-(4-Fluorophenyl)octa-1,2-dien-3-yl]-2-methylfuran-3-yl}-ethanone (**4d**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−50:1), the product was isolated as a colorless oil (50 mg, 76%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.26−7.30 (m, 2H), 6.98−7.04 (m, 2H), 6.56 (t, J = 2.6 Hz, 1H), 6.49 (s, 1H), 2.56 (s, 3H), 2.39−2.44 (m, 5H), 1.54−1.63 (m, 2H), 1.28−1.40 (m, 4H), 0.87 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.1, 193.9, 162.1 (d, J_{CF} = 246.7 Hz), 158.1, 147.8, 130.1 (d, J_{CF} = 3.1 Hz), 128.5 (d, J_{CF} = 8.0 Hz), 123.1, 115.6 (d, J_{CF} = 21.6 Hz), 106.7, 101.9, 98.1, 31.5, 29.4, 29.1, 27.5, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{21}H_{24}FO_2$ $[M + H]^+$ 327.1755, found 327.1753. IR (film) 850, 1229, 1507, 1677, 2928, 2957 cm^{-1}.

*Methyl 4-[3-(4-Acetyl-5-methylfuran-2-yl)octa-1,2-dien-1-yl]-benzoate (**4e**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 20:1−15:1), the product was isolated as a pale yellow oil (58 mg, 79%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.99 (d, J = 8.4 Hz, 2H), 7.38 (d, J = 8.4 Hz, 2H), 6.62 (t, J = 2.5 Hz, 1H), 6.52 (s, 1H), 3.91 (s, 3H), 2.56 (s, 3H), 2.42−2.47 (m, 2H), 2.41 (s, 3H), 1.55−1.64 (m, 2H), 1.28−1.41 (m, 4H), 0.86 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.8, 193.8, 166.8, 158.2, 147.2, 139.1, 130.0, 128.7, 126.9, 123.1, 107.1, 102.2, 98.7, 52.0, 31.5, 29.3, 29.1, 27.5, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{23}H_{27}O_4$ $[M + H]^+$ 367.1904, found 367.1910. IR (film) 1110, 1277, 1677, 1721, 2850, 2918 cm^{-1}.

*1-{2-Methyl-5-[1-(thiophen-3-yl)octa-1,2-dien-3-yl]furan-3-yl}-ethanone (**4f**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−40:1), the product was isolated as a colorless oil (40 mg, 64%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.26−7.28 (m, 1H), 7.14−7.15 (m, 1H), 7.06−7.08 (m, 1H), 6.65 (s, 1H), 6.47 (s, 1H), 2.56 (s, 3H), 2.37−2.42 (m, 5H), 1.55−1.62 (m, 2H), 1.29−1.41 (m, 4H), 0.87 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.4, 193.9, 158.0, 148.0, 135.5, 126.4, 125.9, 123.0, 121.4, 106.6, 100.8, 93.6, 31.5, 29.5, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{19}H_{23}O_2S$ $[M + H]^+$ 315.1413, found 315.1416. IR (film) 770, 950, 1233, 1677, 2929, 2956 cm^{-1}.

*1-{5-[1-(6-Methoxynaphthalen-2-yl)octa-1,2-dien-3-yl]-2-methyl-furan-3-yl}ethanone (**4g**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 25:1−15:1), the product was isolated as a pale yellow solid (48 mg, 62%), mp 106−107 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 7.64−7.69 (m, 3H), 7.44 (dd, J = 8.5, 1.7 Hz, 1H), 7.10−7.14 (m, 2H), 6.73 (t, J = 2.4 Hz, 1H), 6.51 (s, 1H), 3.90 (s, 3H), 2.55 (s, 3H), 2.42−2.48 (m, 2H), 2.40 (s, 3H), 1.58−1.67 (m, 2H), 1.29−1.43 (m, 4H), 0.87 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.6, 193.9, 158.0, 157.7, 148.1, 133.9, 129.3, 129.2, 129.1, 127.2, 125.8, 125.4, 123.0, 118.9, 106.6, 105.9, 101.8, 99.4, 55.2, 31.5, 29.5, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{26}H_{29}O_3$ $[M + H]^+$ 389.2111, found 389.2109. IR (film) 732, 1234, 1266, 1675, 2929, 2955 cm^{-1}.

*1-[5-(Dodeca-6,7-dien-6-yl)-2-methylfuran-3-yl]ethanone (**4h**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1), the product was isolated as a colorless oil (46 mg, 80%). ^1H NMR (400 MHz, $CDCl_3$) δ 6.36 (s, 1H), 5.54−5.58 (m, 1H), 2.57 (s, 3H), 2.40 (s, 3H), 2.23−2.27 (m, 2H), 2.11 (q, J = 6.9 Hz, 2H), 1.49−1.56 (m, 2H), 1.33−1.46 (m, 8H), 0.89−0.93 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.6, 194.1, 157.5, 149.5, 122.9, 105.4, 97.6, 95.8, 31.4, 31.2, 29.2, 29.1, 28.8, 27.6, 22.5, 22.1, 14.5, 14.0, 13.9. HRMS (ESI, m/z) calcd for $C_{19}H_{29}O_2$ $[M + H]^+$ 289.2162, found 289.2166. IR (film) 949, 1233, 1679, 2858, 2927, 2956 cm^{-1}.

*1-[2-Methyl-5-(2-methyldeca-3,4-dien-5-yl)furan-3-yl]ethanone (**4i**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−50:1), the product was isolated as a colorless oil (37 mg, 68%). ^1H NMR (400 MHz, $CDCl_3$) δ 6.36 (s, 1H), 5.59 (quint, J = 2.8 Hz, 1H), 2.57 (s, 3H), 2.41−2.44 (m, 1H), 2.40 (s, 3H), 2.24−2.28 (m, 2H), 1.49−1.56 (m, 2H), 1.34−1.37 (m, 4H), 1.08 (d, J = 1.4 Hz, 3H), 1.06 (d, J = 1.4 Hz, 3H), 0.89−0.92 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.0, 194.1, 157.4, 149.6, 122.9, 105.3, 103.2, 98.9, 31.5, 29.2, 29.1, 28.8, 27.6, 22.6, 22.5, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{18}H_{27}O_2$ $[M + H]^+$ 275.2006, found 275.2002. IR (film) 951, 1233, 1560, 1679, 2929, 2959 cm^{-1}.

*1-[5-(2,2-Dimethyldeca-3,4-dien-5-yl)-2-methylfuran-3-yl]-ethanone (**4j**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 40:1), the product was isolated as a colorless oil (32 mg, 55%). ^1H NMR (400 MHz, $CDCl_3$) δ 6.36 (s, 1H), 5.56 (t, J = 2.6 Hz, 1H), 2.57 (s, 3H), 2.40 (s, 3H), 2.24−2.28 (m, 2H), 1.49−1.56 (m, 2H), 1.34−1.38 (m, 4H), 1.10 (s, 9H), 0.90 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.8, 194.1, 157.4, 149.7, 122.9, 107.6, 105.2, 99.4, 33.0, 31.6, 30.2, 29.2, 29.1, 27.6, 22.5, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{19}H_{29}O_2$ $[M + H]^+$ 289.2162, found 289.2159. IR (film) 949, 1234, 1679, 2860, 2929, 2958 cm^{-1}.

*1-[5-(1-Cyclopropylocta-1,2-dien-3-yl)-2-methylfuran-3-yl]-ethanone (**4k**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−50:1), the product was isolated as a colorless oil (47 mg, 86%). ^1H NMR (400 MHz, $CDCl_3$) δ 6.38 (s, 1H), 5.46−5.48 (m, 1H), 2.58 (s, 3H), 2.40 (s, 3H), 2.24−2.28 (m, 2H), 1.48−1.54 (m, 2H), 1.31−1.35 (m, 5H), 0.90 (t, J = 6.8 Hz, 3H), 0.74 (dd, J = 8.1, 2.0 Hz, 2H), 0.42−0.45 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.0, 194.0, 157.6, 149.2, 122.9, 105.7, 100.2, 99.4, 31.4, 29.4, 29.1, 27.5, 22.5, 14.5, 14.0, 9.7, 7.0, 6.9. HRMS (ESI, m/z) calcd for $C_{18}H_{25}O_2$ $[M + H]^+$ 273.1849, found 273.1850. IR (film) 945, 1234, 1560, 1678, 2929, 2956 cm^{-1}.

*1-[5-(1-Cyclohexylocta-1,2-dien-3-yl)-2-methylfuran-3-yl]-ethanone (**4l**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 40:1), the product was isolated as a colorless oil (50 mg, 80%). ^1H NMR (400 MHz, $CDCl_3$) δ 6.36 (s, 1H), 5.54−5.57 (m, 1H), 2.57 (s, 3H), 2.39 (s, 3H), 2.23−2.27 (m, 2H), 2.06−2.14 (m, 1H), 1.72−1.83 (m, 4H), 1.62−1.67 (m, 1H), 1.49−1.55 (m, 2H), 1.32−1.37 (m, 5H), 1.22−1.29 (m, 2H), 1.14−1.21 (m, 2H), 0.89−0.92 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.5, 194.1, 157.4, 149.6, 122.9, 105.3, 101.8, 98.6, 37.9, 33.1, 33.0, 31.5, 29.2, 29.1, 27.6, 26.1, 26.0, 22.5, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{21}H_{31}O_2$ $[M + H]^+$ 315.2319, found 315.2321. IR (film) 946, 1235, 1558, 1679, 2852, 2925 cm^{-1}.

*1-{5-[1-(Benzyloxy)deca-3,4-dien-5-yl]-2-methylfuran-3-yl}-ethanone (**4m**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 50:1−40:1), the product was isolated as a colorless oil (43 mg, 58%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.26−7.33 (m, 5H), 6.37 (s, 1H), 5.60−5.64 (m, 1H), 4.53 (s, 2H), 3.61 (t, J = 6.7 Hz, 2H), 2.54 (s, 3H), 2.44 (q, J = 6.7 Hz, 2H), 2.37 (s, 3H), 2.23−2.28 (m, 2H), 1.48−1.55 (m, 2H), 1.31−1.35 (m, 4H), 0.88−0.91 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.1, 194.0, 157.6, 149.1, 138.4, 128.3, 127.5, 127.5, 122.9, 105.8, 98.1, 92.5, 72.9, 69.6, 31.4, 29.6, 29.1, 29.1, 27.5, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{24}H_{31}O_3$ $[M + H]^+$ 367.2268, found 367.2267. IR (film) 736, 1103, 1677, 2849, 2918, 2958 cm^{-1}.

*1-[5-(1-Hydroxydeca-3,4-dien-5-yl)-2-methylfuran-3-yl]ethanone (**4n**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 10:1−4:1), the product was isolated as a pale yellow oil (44 mg, 80%). ^1H NMR (400 MHz, $CDCl_3$) δ 6.41 (s, 1H), 5.58−5.61 (m, 1H), 3.68−3.81 (m, 2H), 2.57 (s, 3H), 2.40 (s, 3H), 2.35−2.38 (m, 2H), 2.25−2.29 (m, 2H), 2.06 (s, 1H), 1.51−1.56 (m, 2H), 1.34−1.37 (m, 4H), 0.90 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.6, 193.9, 157.7, 148.7, 123.1, 106.1, 98.4, 92.3, 61.4, 32.5, 31.4, 29.1, 29.0, 27.5, 22.4, 14.4, 14.0. HRMS (ESI, m/z) calcd for $C_{17}H_{25}O_3$ $[M + H]^+$ 277.1798, found 277.1800. IR (film) 950, 1234, 1674, 2927, 2954, 3426 cm^{-1}.

*1-[5-(2-Hydroxy-2-methyldeca-3,4-dien-5-yl)-2-methylfuran-3-yl]ethanone (**4o**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography

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(petroleum ether/EtOAc = 10:1−4:1), the product was isolated as a pale yellow oil (52 mg, 89%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.42 (s, 1H), 5.79 (t, J = 2.7 Hz, 1H), 2.57 (s, 3H), 2.40 (s, 3H), 2.28−2.32 (m, 2H), 1.85 (s, 1H), 1.50−1.58 (m, 2H), 1.41 (s, 6H), 1.34−1.38 (m, 4H), 0.91 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.3, 193.9, 157.8, 148.5, 123.0, 106.2, 105.9, 101.3, 70.4, 31.5, 30.1, 29.9, 29.2, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{18}H_{27}O_3$ $[M + H]^+$ 291.1955, found 291.1962. IR (film) 950, 1150, 1668, 2929, 2966, 3418 cm^{-1}.

*1-(2-Methyl-5-{1-[(tetrahydro-2H-pyran-2-yl)oxy]nona-2,3-dien-4-yl}furan-3-yl)ethanone (**4p**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 25:1−15:1), the product was isolated as a colorless oil (58 mg, 83%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.41 (s, 1H), 5.67−5.71 (m, 1H), 4.80 (t, J = 3.4 Hz, 0.5 H), 4.75 (t, J = 3.2 Hz, 0.5H), 4.26−4.34 (m, 1H), 4.13−4.18 (m, 1H), 3.86−3.93 (m, 1H), 3.47−3.54 (m, 1H), 2.57 (s, 3H), 2.40 (s, 3H), 2.26−2.32 (m, 2H), 1.81−1.88 (m, 1H), 1.68−1.75 (m, 1H), 1.50−1.64 (m, 6H), 1.32−1.37 (m, 4H), 0.89−0.92 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.8, 203.3, 194.0, 157.8, 157.7, 148.4, 123.0, 106.3, 106.3, 99.0, 98.7, 97.5, 97.2, 93.6, 93.2, 64.8, 64.6, 62.3, 62.2, 31.4, 30.6, 30.5, 29.14, 29.08, 29.0, 27.54, 27.47, 25.4, 22.4, 19.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{21}H_{31}O_4$ $[M + H]^+$ 347.2217, found 347.2226. IR (film) 948, 1024, 1119, 1678, 2871, 2935 cm^{-1}.

*1-[2-Methyl-5-(4-methyl-1-phenylpenta-1,2-dien-3-yl)furan-3-yl]-ethanone (**5a**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 50:1−40:1), the product was isolated as a pale yellow oil (51 mg, 91%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.34 (m, 4H), 7.20−7.25 (m, 1H), 6.64 (d, J = 0.9 Hz, 1H), 6.51 (s, 1H), 2.73−2.81 (m, 1H), 2.56 (s, 3H), 2.40 (s, 3H), 1.23 (d, J = 6.8 Hz, 3H), 1.20 (d, J = 6.7 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.3, 193.9, 158.0, 147.6, 134.2, 128.7, 127.3, 126.9, 123.0, 108.8, 106.7, 100.3, 29.1, 29.0, 22.5, 22.2, 14.5. HRMS (ESI, m/z) calcd for $C_{19}H_{21}O_2$ $[M + H]^+$ 281.1536, found 281.1538. IR (film) 695, 948, 1231, 1678, 2925, 2964 cm^{-1}.

*1-[2-Methyl-5-(1-phenylhepta-1,2-dien-3-yl)furan-3-yl]ethanone (**5b**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−40:1), the product was isolated as a colorless oil (49 mg, 82%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.33 (m, 4H), 7.20−7.26 (m, 1H), 6.59 (t, J = 2.7 Hz, 1H), 6.49 (s, 1H), 2.56 (s, 3H), 2.41−2.46 (m, 2H), 2.40 (s, 3H), 1.54−1.62 (m, 2H), 1.37−1.46 (m, 2H), 0.92 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.4, 193.9, 158.0, 147.9, 134.2, 128.7, 127.2, 127.0, 123.0, 106.6, 101.7, 99.1, 30.0, 29.2, 29.1, 22.4, 14.5, 13.8. HRMS (ESI, m/z) calcd for $C_{20}H_{23}O_2$ $[M + H]^+$ 295.1693, found 295.1694. IR (film) 694, 948, 1232, 1677, 2929, 2959 cm^{-1}.

*1-[5-(1,5-Diphenylpenta-1,2-dien-3-yl)-2-methylfuran-3-yl]-ethanone (**5c**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 20:1−15:1), the product was isolated as a colorless oil (51 mg, 74%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.17−7.31 (m, 10H), 6.58 (s, 1H), 6.49 (s, 1H), 2.85−2.96 (m, 2H), 2.70−2.83 (m, 2H), 2.56 (s, 3H), 2.38 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.3, 193.9, 158.2, 147.6, 141.3, 133.8, 128.6, 128.43, 128.38, 127.3, 127.1, 126.0, 123.0, 106.8, 101.1, 99.6, 34.0, 31.2, 29.1, 14.5. HRMS (ESI, m/z) calcd for $C_{24}H_{23}O_2$ $[M + H]^+$ 343.1693, found 343.1694. IR (film) 696, 732, 910, 949, 1233, 1676 cm^{-1}.

*1-[5-(1-Cyclopentyl-3-phenylpropa-1,2-dien-1-yl)-2-methylfuran-3-yl]ethanone (**5d**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−40:1), the product was isolated as a colorless oil (54 mg, 88%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.32 (m, 4H), 7.20−7.25 (m, 1H), 6.61 (s, 1H), 6.52 (s, 1H), 2.89−2.94 (m, 1H), 2.55 (s, 3H), 2.40 (s, 3H), 1.95−2.06 (m, 2H), 1.61−1.69 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.0, 193.9, 157.9, 148.1, 134.2, 128.7, 127.2, 126.9, 123.0, 107.0, 106.7, 100.1, 39.3, 32.6, 32.3, 29.1, 25.1, 25.0, 14.5. HRMS (ESI, m/z) calcd for $C_{21}H_{23}O_2$ $[M + H]^+$ 307.1693, found 307.1696. IR (film) 694, 949, 1231, 1677, 2866, 2954 cm^{-1}.

*1-[5-(1-Cyclohexyl-3-phenylpropa-1,2-dien-1-yl)-2-methylfuran-3-yl]ethanone (**5e**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−50:1), the product was isolated as a pale yellow oil (56 mg, 88%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.35 (m, 4H), 7.20−7.25 (m, 1H), 6.61 (s, 1H), 6.50 (s, 1H), 2.55 (s, 3H), 2.40 (s, 3H), 1.95−2.04 (m, 2H), 1.77−1.81 (m, 2H), 1.68−1.72 (m, 1H), 1.14−1.43 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.9, 193.9, 158.0, 147.5, 134.2, 128.7, 127.2, 126.9, 123.0, 107.9, 106.5, 100.0, 38.6, 33.2, 32.8, 29.2, 26.5, 26.0, 14.6. HRMS (ESI, m/z) calcd for $C_{22}H_{25}O_2$ $[M + H]^+$ 321.1849, found 321.1844. IR (film) 693, 948, 1232, 1677, 2852, 2927 cm^{-1}.

*1-{5-[5-(Benzyloxy)-1-phenylpenta-1,2-dien-3-yl]-2-methylfuran-3-yl}ethanone (**5f**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 30:1−10:1), the product was isolated as a colorless oil (46 mg, 61%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28−7.34 (m, 8H), 7.20−7.25 (m, 2H), 6.60 (s, 1H), 6.50 (s, 1H), 4.48 (s, 2H), 3.71−3.76 (m, 2H), 2.70−2.83 (m, 2H), 2.54 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.5, 193.9, 158.2, 147.4, 138.2, 133.7, 128.7, 128.3, 127.6, 127.5, 127.4, 127.2, 123.0, 106.9, 99.4, 98.7, 73.0, 68.4, 30.0, 29.1, 14.5. HRMS (ESI, m/z) calcd for $C_{25}H_{25}O_3$ $[M + H]^+$ 373.1798, found 373.1799. IR (film) 696, 746, 949, 1676, 2856, 2922 cm^{-1}.

*1-[2-Ethyl-5-(1-phenylocta-1,2-dien-3-yl)furan-3-yl]propan-1-one (**5g**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 100:1), the product was isolated as a yellow oil (54 mg, 80%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.34 (m, 4H), 7.20−7.25 (m, 1H), 6.58 (t, J = 2.7 Hz, 1H), 6.49 (s, 1H), 2.98 (q, J = 7.5 Hz, 2H), 2.74 (q, J = 7.3 Hz, 2H), 2.38−2.48 (m, 2H), 1.56−1.63 (m, 2H), 1.29−1.41 (m, 4H), 1.20 (t, J = 7.5 Hz, 3H), 1.15 (t, J = 7.3 Hz, 3H), 0.87 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.4, 196.9, 162.9, 147.8, 134.3, 128.6, 127.2, 127.0, 121.4, 106.2, 101.8, 99.0, 34.4, 31.5, 29.4, 27.6, 22.4, 21.7, 14.0, 12.1, 7.8. HRMS (ESI, m/z) calcd for $C_{23}H_{29}O_2$ $[M + H]^+$ 337.2162, found 337.2156. IR (film) 693, 799, 924, 1679, 2871, 2933 cm^{-1}.

*Methyl 2-Methyl-5-(1-phenylhepta-1,2-dien-3-yl)furan-3-carboxylate (**5h**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 130:1−80:1), the product was isolated as a colorless oil (45 mg, 73%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29−7.32 (m, 4H), 7.20−7.25 (m, 1H), 6.58 (s, 1H), 6.52 (s, 1H), 3.81 (s, 3H), 2.54 (s, 3H), 2.38−2.44 (m, 2H), 1.53−1.61 (m, 2H), 1.36−1.45 (m, 2H), 0.90 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.3, 164.4, 159.0, 148.0, 134.2, 128.6, 127.2, 127.0, 114.8, 106.9, 101.8, 99.0, 51.3, 30.1, 29.2, 22.4, 13.8. HRMS (ESI, m/z):calcd for $C_{20}H_{23}O_3$ $[M + H]^+$ 311.1642, found 311.1641. IR (film) 694, 1087, 1232, 1719, 2860, 2955 cm^{-1}.

*tert-Butyl 2-Methyl-5-(1-phenylhepta-1,2-dien-3-yl)furan-3-carboxylate (**5i**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 200:1−160:1), the product was isolated as a colorless oil (57 mg, 81%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29−7.32 (m, 4H), 7.19−7.24 (m, 1H), 6.57 (s, 1H), 6.48 (s, 1H), 2.51 (s, 3H), 2.38−2.44 (m, 2H), 1.56−1.60 (m, 2H), 1.55 (s, 9H), 1.36−1.45 (m, 2H), 0.90 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.2, 163.4, 158.1, 147.6, 134.4, 128.6, 127.0, 116.5, 107.3, 101.9, 98.9, 80.5, 30.1, 29.2, 28.3, 22.4, 13.9, 13.8. HRMS (ESI, m/z) calcd for $C_{23}H_{29}O_3$ $[M + H]^+$ 353.2111, found 353.2109. IR (film) 693, 1084, 1169, 1710, 2930, 2960 cm^{-1}.

*Methyl 2-Ethyl-5-(1-phenylhepta-1,2-dien-3-yl)furan-3-carboxylate (**5j**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 160:1), the product was isolated as a pale yellow oil (39 mg, 60%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29−7.34 (m, 4H), 7.20−7.25 (m, 1H), 6.57 (t, J = 2.7 Hz, 1H), 6.52 (s, 1H), 3.81 (s, 3H), 2.97 (dq, J = 1.6, 7.5 Hz, 2H), 2.35−2.48 (m, 2H), 1.54−1.61 (m, 2H), 1.36−1.45 (m, 2H), 1.21 (t, J = 7.5 Hz, 3H), 0.90 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.4, 164.3, 163.8, 148.0, 134.3, 128.6,

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127.2, 127.0, 113.8, 106.9, 101.8, 99.0, 51.2, 30.1, 29.2, 22.4, 21.2, 13.8, 12.3. HRMS (ESI, m/z) calcd for $C_{21}H_{25}O_3$ $[M + H]^+$ 325.1798, found 325.1798. IR (film) 694, 1043, 1232, 1719, 2859, 2953 cm^{-1}.

Typical Experimental Procedure of Cu(I)-Catalyzed Cross-Coupling of Conjugated Ene-yne Ketones, Terminal Alkynes, and Allyl Halides. CuI (4.0 mg, 10 mol %) and K_2CO_3 (33.2 mg, 0.24 mmol) were added to a 25 mL Schlenk reaction flask. The reaction flask was then degassed two times with nitrogen, and MeCN (3 mL) was added via syringe. Next, the conjugated ene-yne ketone **1a** (41.2 mg, 0.20 mmol), phenylacetylene **2a** (24.5 mg, 0.24 mmol), and allyl bromide **3a** (48.4 mg, 0.40 mmol) were successively added to the reaction solution via syringe. The resulting solution was stirred at 70 °C for 11 h. The mixture was then cooled to room temperature and filtered through a short plug of silica gel (washed with petroleum ether/EtOAc = 3:1). Solvent was removed in vacuo to provide a crude mixture, which was purified by silica gel column chromatography to afford pure product **6a** (58.0 mg, 83%) as a colorless oil.

*1-[2-Methyl-5-(4-phenylundeca-1,4,5-trien-6-yl)furan-3-yl]-ethanone (**6a**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a colorless oil (58 mg, 83%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.41−7.43 (m, 2H), 7.30−7.34 (m, 2H), 7.20−7.24 (m, 1H), 6.45 (s, 1H), 5.91−6.01 (m, 1H), 5.21 (dd, J = 17.1, 1.6 Hz, 1H), 5.08 (dd, J = 10.1, 1.4 Hz, 1H), 3.28−3.35 (m, 2H), 2.55 (s, 3H), 2.37−2.42 (m, 5H), 1.53−1.60 (m, 2H), 1.29−1.37 (m, 4H), 0.86 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.6, 194.0, 157.8, 148.6, 136.2, 135.6, 128.4, 127.0, 126.2, 123.0, 116.4, 108.6, 106.1, 101.1, 35.2, 31.6, 29.6, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{24}H_{29}O_2$ $[M + H]^+$ 349.2162, found 349.2166. IR (film) 693, 951, 1678, 2928, 2955 cm^{-1}.

*1-{2-Methyl-5-[4-(p-tolyl)undeca-1,4,5-trien-6-yl]furan-3-yl}-ethanone (**6b**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a colorless oil (59 mg, 81%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.31 (d, J = 8.2 Hz, 2H), 7.13 (d, J = 8.0 Hz, 2H), 6.44 (s, 1H), 5.90−6.00 (m, 1H), 5.20 (dd, J = 17.1, 1.6 Hz, 1H), 5.07 (dd, J = 10.1, 1.4 Hz, 1H), 3.29−3.30 (m, 2H), 2.54 (s, 3H), 2.36−2.41 (m, 5H), 2.33 (s, 3H), 1.52−1.60 (m, 2H), 1.29−1.37 (m, 4H), 0.86 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.3, 194.0, 157.7, 148.8, 136.8, 135.6, 133.2, 129.1, 126.1, 123.0, 116.2, 108.5, 105.9, 101.0, 35.2, 31.6, 29.6, 29.1, 27.6, 22.4, 21.0, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{25}H_{31}O_2$ $[M + H]^+$ 363.2319, found 363.2322. IR (film) 816, 951, 1678, 2924, 2956 cm^{-1}.

*1-{5-[4-(4-Methoxyphenyl)undeca-1,4,5-trien-6-yl]-2-methylfuran-3-yl}ethanone (**6c**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−40:1), the product was isolated as a colorless oil (46 mg, 61%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, J = 8.7 Hz, 2H), 6.86 (d, J = 8.7 Hz, 2H), 6.44 (s, 1H), 5.90−6.00 (m, 1H), 5.20 (dd, J = 17.1, 1.4 Hz, 1H), 5.07 (dd, J = 10.1, 1.1 Hz, 1H), 3.80 (s, 3H), 3.24−3.34 (m, 2H), 2.55 (s, 3H), 2.36−2.39 (m, 5H), 1.52−1.57 (m, 2H), 1.29−1.36 (m, 4H), 0.86 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.0, 194.0, 158.8, 157.7, 148.9, 135.7, 128.4, 127.4, 123.0, 116.2, 113.8, 108.2, 105.9, 100.9, 55.3, 35.4, 31.6, 29.6, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{25}H_{31}O_3$ $[M + H]^+$ 379.2268, found 379.2271. IR (film) 831, 1247, 1510, 1677, 2929 cm^{-1}.

*1-(2-Methyl-5-{4-[4-(trifluoromethyl)phenyl]undeca-1,4,5-trien-6-yl}furan-3-yl)ethanone (**6d**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 90:1−50:1), the product was isolated as a colorless oil (51 mg, 61%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.54 (AB quart, J = 8.5 Hz, 4H), 6.49 (s, 1H), 5.90−6.00 (m, 1H), 5.22 (dd, J = 17.1, 1.6 Hz, 1H), 5.11 (dd, J = 10.1, 1.4 Hz, 1H), 3.32−3.34 (m, 2H), 2.56 (s, 3H), 2.38−2.44 (m, 5H), 1.52−1.60 (m, 2H), 1.28−1.37 (m, 4H), 0.86 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.5, 193.8, 158.1, 147.9, 140.0, 135.0, 128.9 (q, J_{CF} = 32.9 Hz), 126.4, 125.3 (q, J_{CF} = 3.7 Hz), 124.2 (q, J_{CF} = 272.0 Hz), 123.1, 116.8, 107.9, 106.7, 101.8, 35.1, 31.6, 29.5, 29.1, 27.6, 22.4, 14.5, 13.9. HRMS (ESI, m/z) calcd for $C_{25}H_{28}F_3O_2$ $[M + H]^+$ 417.2036, found 417.2036. IR (film) 1069, 1124, 1326, 1679, 2928 cm^{-1}.

*Methyl 4-[6-(4-Acetyl-5-methylfuran-2-yl)undeca-1,4,5-trien-4-yl]benzoate (**6e**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 60:1−20:1), the product was isolated as a colorless oil (49 mg, 60%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.98 (d, J = 8.5 Hz, 2H), 7.47 (d, J = 8.5 Hz, 2H), 6.48 (s, 1H), 5.90−6.00 (m, 1H), 5.21 (dd, J = 17.1, 1.6 Hz, 1H), 5.10 (dd, J = 10.1, 1.4 Hz, 1H), 3.90 (s, 3H), 3.32−3.34 (m, 2H), 2.56 (s, 3H), 2.40−2.44 (m, 5H), 1.52−1.60 (m, 2H), 1.29−1.37 (m, 4H), 0.85 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.8, 193.8, 166.8, 158.0, 148.0, 141.0, 135.1, 129.7, 128.5, 126.1, 123.1, 116.7, 108.3, 106.6, 101.6, 52.0, 35.0, 31.5, 29.5, 29.1, 27.6, 22.4, 14.5, 13.9. HRMS (ESI, m/z) calcd for $C_{26}H_{31}O_4$ $[M + H]^+$ 407.2217, found 407.2219. IR (film) 1110, 1277, 1678, 1722, 2927 cm^{-1}.

*1-{2-Methyl-5-[4-(thiophen-2-yl)undeca-1,4,5-trien-6-yl]furan-3-yl}ethanone (**6f**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a pale yellow oil (45 mg, 64%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.17 (dd, J = 4.7, 1.3 Hz, 1H), 6.97−7.00 (m, 2H), 6.47 (s, 1H), 5.90−6.00 (m, 1H), 5.22 (dd, J = 17.1, 1.5 Hz, 1H), 5.09 (dd, J = 10.1, 1.3 Hz, 1H), 3.24−3.34 (m, 2H), 2.56 (s, 3H), 2.37−2.42 (m, 5H), 1.54−1.61 (m, 2H), 1.31−1.39 (m, 4H), 0.87 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.6, 194.0, 158.0, 148.2, 141.4, 135.1, 127.4, 124.6, 123.4, 123.0, 116.6, 106.6, 104.6, 101.6, 36.4, 31.6, 29.7, 29.1, 27.6, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{22}H_{27}O_2S$ $[M + H]^+$ 355.1726, found 355.1731. IR (film) 696, 951, 1233, 1678, 2928 cm^{-1}.

*1-{2-Methyl-5-[4-(thiophen-3-yl)undeca-1,4,5-trien-6-yl]furan-3-yl}ethanone (**6g**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 85:1−50:1), the product was isolated as a pale yellow oil (56 mg, 79%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.23−7.25 (m, 1H), 7.16−7.17 (m, 1H), 7.07−7.08 (m, 1H), 6.44 (s, 1H), 5.90−6.00 (m, 1H), 5.51 (dd, J = 17.1, 1.5 Hz, 1H), 5.08 (dd, J = 10.1, 1.3 Hz, 1H), 3.22−3.32 (m, 2H), 2.55 (s, 3H), 2.36−2.39 (m, 5H), 1.52−1.59 (m, 2H), 1.30−1.37 (m, 4H), 0.86 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.3, 194.0, 157.8, 148.6, 138.0, 135.5, 127.0, 125.3, 123.0, 119.7, 116.4, 106.2, 104.9, 100.6, 36.0, 31.6, 29.6, 29.1, 27.7, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{22}H_{27}O_2S$ $[M + H]^+$ 355.1726, found 355.1730. IR (film) 779, 952, 1232, 1677, 2928 cm^{-1}.

*1-{5-[4-(6-Methoxynaphthalen-2-yl)undeca-1,4,5-trien-6-yl]-2-methylfuran-3-yl}ethanone (**6h**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 75:1−25:1), the product was isolated as a pale yellow solid (67 mg, 78%), mp 90−92 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 7.69−7.73 (m, 2H), 7.63−7.65 (m, 1H), 7.51−7.54 (m, 1H), 7.09−7.14 (m, 2H), 6.48 (s, 1H), 5.97−6.07 (m, 1H), 5.25 (dd, J = 17.1, 1.3 Hz, 1H), 5.10 (dd, J = 10.1, 1.2 Hz, 1H), 3.90 (s, 3H), 3.37−3.48 (m, 2H), 2.55 (s, 3H), 2.41−2.46 (m, 2H), 2.40 (s, 3H), 1.55−1.63 (m, 2H), 1.30−1.39 (m, 4H), 0.85 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.0, 194.0, 157.8, 157.7, 148.7, 135.6, 133.7, 131.2, 129.5, 129.0, 126.7, 125.9, 123.9, 123.0, 118.8, 116.4, 108.9, 106.1, 105.8, 101.3, 55.3, 35.2, 31.6, 29.7, 29.1, 27.7, 22.4, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{29}H_{33}O_3$ $[M + H]^+$ 429.2424, found 429.2419. IR (film) 732, 1232, 1267, 1677, 2928 cm^{-1}.

*1-[5-(8-Allyldodeca-6,7-dien-6-yl)-2-methylfuran-3-yl]ethanone (**6i**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 110:1−90:1), the product was isolated as a pale yellow oil (53 mg, 80%). ^1H NMR (400 MHz, $CDCl_3$) δ 6.33 (s, 1H), 5.77−5.87 (m, 1H), 5.10 (dd, J = 17.0, 1.6 Hz, 1H), 5.02 (dd, J = 10.0, 1.5 Hz, 1H), 2.76−2.86 (m, 2H), 2.56 (s, 3H), 2.39 (s, 3H), 2.24 (t, J = 7.3 Hz, 2H), 2.06 (t, J = 6.8 Hz, 2H), 1.48−1.54 (m, 2H), 1.33−1.44 (m, 8H), 0.87−0.92 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.3, 194.1, 157.2, 150.2, 136.0, 122.9, 115.8, 107.5, 105.0, 98.3, 37.8, 32.2, 31.5, 29.7, 29.6, 29.1, 27.7, 22.5, 22.3, 14.5, 14.0, 13.9. HRMS (ESI, m/z) calcd for $C_{22}H_{33}O_2$ $[M + H]^+$ 329.2475, found 329.2478. IR (film) 913, 944, 1231, 1679, 2927 cm^{-1}.

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*1-[5-(4-Cyclopropylundeca-1,4,5-trien-6-yl)-2-methylfuran-3-yl]-ethanone (**6j**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 120:1−110:1), the product was isolated as a colorless oil (55 mg, 87%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.32 (s, 1H), 5.82−5.92 (m, 1H), 5.14 (dd, J = 17.1, 1.5 Hz, 1H), 5.03 (dd, J = 10.1, 1.2 Hz, 1H), 2.93 (dd, J = 6.6, 1.0 Hz, 2H), 2.56 (s, 3H), 2.38 (s, 3H), 2.22 (t, J = 7.2 Hz, 2H), 1.42−1.49 (m, 2H), 1.32−1.35 (m, 4H), 1.19−1.24 (m, 1H), 0.90 (t, J = 6.9 Hz, 3H), 0.65−0.71 (m, 2H), 0.38−0.46 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.0, 194.1, 157.3, 149.8, 136.0, 122.9, 115.8, 111.2, 105.2, 99.9, 38.0, 31.5, 29.5, 29.1, 27.7, 22.5, 14.5, 14.0, 12.6, 7.1, 6.8. HRMS (ESI, m/z) calcd for $C_{21}H_{29}O_2$ $[M + H]^+$ 313.2162, found 313.2168. IR (film) 914, 951, 1231, 1678, 2929 cm^{-1}.

*1-[5-(4-Cyclohexylundeca-1,4,5-trien-6-yl)-2-methylfuran-3-yl]-ethanone (**6k**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 120:1−100:1), the product was isolated as a colorless oil (47 mg, 66%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.33 (s, 1H), 5.76−5.86 (m, 1H), 5.09 (dd, J = 17.1, 1.7 Hz, 1H), 5.00 (d, J = 10.0 Hz, 1H), 2.84 (d, J = 6.6 Hz, 2H), 2.56 (s, 3H), 2.39 (s, 3H), 2.24 (t, J = 7.4 Hz, 2H), 1.85−1.92 (m, 3H), 1.63−1.75 (m, 4H), 1.46−1.54 (m, 2H), 1.31−1.37 (m, 4H), 1.05−1.23 (m, 4H), 0.90 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.0, 194.1, 157.2, 150.3, 136.3, 122.9, 115.6, 113.1, 104.8, 99.4, 41.2, 36.2, 32.4, 32.3, 31.6, 29.4, 29.1, 27.7, 26.45, 26.39, 26.3, 22.5, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{24}H_{35}O_2$ $[M + H]^+$ 355.2632, found 355.2637. IR (film) 951, 1232, 1679, 2852, 2926 cm^{-1}.

*1-{5-[4-(tert-Butyl)undeca-1,4,5-trien-6-yl]-2-methylfuran-3-yl}-ethanone (**6l**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 130:1−120:1), the product was isolated as a colorless oil (45 mg, 69%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.32 (s, 1H), 5.74−5.84 (m, 1H), 5.05 (dd, J = 17.0, 1.6 Hz, 1H), 4.95 (dd, J = 10.0, 1.1 Hz, 1H), 2.79−2.92 (m, 2H), 2.55 (s, 3H), 2.39 (s, 3H), 2.23 (t, J = 7.5 Hz, 2H), 1.46−1.53 (m, 2H), 1.31−1.37 (m, 4H), 1.11 (s, 9H), 0.90 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.7, 194.1, 157.1, 150.4, 136.8, 122.9, 117.1, 115.1, 104.6, 99.7, 34.9, 32.8, 31.7, 29.4, 29.3, 29.1, 27.7, 22.5, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{22}H_{33}O_2$ $[M + H]^+$ 329.2475, found 329.2478. IR (film) 911, 952, 1232, 1679, 2959 cm^{-1}.

*1-{5-{4-[2-(Benzyloxy)ethyl]undeca-1,4,5-trien-6-yl}-2-methylfuran-3-yl)ethanone (**6m**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 100:1−50:1), the product was isolated as a pale yellow oil (38 mg, 46%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25−7.32 (m, 5H), 6.35 (s, 1H), 5.77−5.87 (m, 1H), 5.11 (dd, J = 17.1, 1.6 Hz, 1H), 5.03 (dd, J = 10.1, 1.1 Hz, 1H), 4.48 (s, 2H), 3.60 (t, J = 6.9 Hz, 2H), 2.85 (d, J = 6.7 Hz, 2H), 2.53 (s, 3H), 2.40 (t, J = 6.9 Hz, 2H), 2.36 (s, 3H), 2.24 (t, J = 7.4 Hz, 2H), 1.45−1.52 (m, 2H), 1.30−1.34 (m, 4H), 0.89 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.3, 194.1, 157.4, 149.7, 138.4, 135.6, 128.3, 127.5, 127.4, 122.9, 116.2, 105.4, 104.5, 98.8, 73.0, 68.8, 38.1, 32.7, 31.5, 29.5, 29.0, 27.7, 22.5, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{27}H_{35}O_3$ $[M + H]^+$ 407.2581, found 407.2584. IR (film) 698, 735, 1102, 1678, 2927 cm^{-1}.

*1-{5-[4-(2-Hydroxypropan-2-yl)undeca-1,4,5-trien-6-yl]-2-methylfuran-3-yl}ethanone (**6n**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 20:1−5:1), the product was isolated as a pale yellow oil (32 mg, 48%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.38 (s, 1H), 5.78−5.88 (m, 1H), 5.12 (dd, J = 17.0, 1.4 Hz, 1H), 5.00 (dd, J = 10.0, 1.1 Hz, 1H), 2.91−3.04 (m, 2H), 2.56 (s, 3H), 2.40 (s, 3H), 2.28 (t, J = 7.5 Hz, 2H), 1.79 (s, 1H), 1.47−1.52 (m, 2H), 1.41 (s, 6H), 1.33−1.37 (m, 4H), 0.90 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.5, 194.0, 157.5, 149.3, 136.4, 123.0, 116.2, 115.7, 105.6, 101.5, 72.1, 32.8, 31.6, 29.4, 29.1, 27.7, 22.5, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{21}H_{31}O_3$ $[M + H]^+$ 331.2268, found 331.2273. IR (film) 952, 1232, 1668, 2928, 3424 cm^{-1}.

*1-{5-[4-(Cyclohex-1-en-1-yl)undeca-1,4,5-trien-6-yl]-2-methylfuran-3-yl}ethanone (**6o**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 130:1−120:1), the product was isolated as a pale yellow oil (61 mg, 86%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.37 (s, 1H), 5.84−5.92 (m, 1H), 5.81−5.83 (m, 1H), 5.10 (dd, J = 17.1, 1.5 Hz, 1H), 5.00 (d, J = 10.1 Hz, 1H), 3.00−3.10 (m, 2H), 2.56 (s, 3H), 2.39 (s, 3H), 2.29 (t, J = 7.5 Hz, 2H), 2.16−2.17 (m, 2H), 2.05 (s, 2H), 1.57−1.66 (m, 4H), 1.47−1.52 (m, 2H), 1.32−1.37 (m, 4H), 0.89 (t, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.1, 194.1, 157.5, 149.4, 136.3, 132.5, 123.4, 122.9, 115.6, 110.6, 105.4, 100.5, 34.2, 31.6, 29.8, 29.1, 27.7, 27.2, 26.0, 22.8, 22.5, 22.3, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{24}H_{33}O_2$ $[M + H]^+$ 353.2475, found 353.2480. IR (film) 733, 914, 1232, 1678, 2927 cm^{-1}.

*1-{2-Methyl-5-[4-(trimethylsilyl)undeca-1,4,5-trien-6-yl]furan-3-yl}ethanone (**6p**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 150:1), the product was isolated as a colorless oil (44 mg, 64%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.26 (s, 1H), 5.81−5.91 (m, 1H), 5.10 (dq, J = 17.0, 1.7 Hz, 1H), 5.00 (dd, J = 10.0, 1.7 Hz, 1H), 2.80−2.92 (m, 2H), 2.55 (s, 3H), 2.39 (s, 3H), 2.15−2.28 (m, 2H), 1.46−1.53 (m, 2H), 1.33−1.38 (m, 4H), 0.90 (t, J = 7.0 Hz, 3H), 0.13 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.8, 194.1, 156.9, 150.2, 137.0, 123.0, 115.3, 104.2, 100.5, 93.5, 34.6, 31.6, 29.1, 28.8, 27.9, 22.5, 14.5, 14.0, −1.2. HRMS (ESI, m/z) calcd for $C_{21}H_{33}O_2Si$ $[M + H]^+$ 345.2244, found 345.2248. IR (film) 839, 1248, 1679, 1925, 2957 cm^{-1}.

*1-[2-Methyl-5-(2-methyl-5-phenylocta-3,4,7-trien-3-yl)furan-3-yl]ethanone (**7a**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 90:1−50:1), the product was isolated as a colorless oil (52 mg, 81%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43−7.45 (m, 2H), 7.32 (t, J = 7.4 Hz, 2H), 7.20−7.24 (m, 1H), 6.47 (s, 1H), 5.90−6.00 (m, 1H), 5.20 (dd, J = 17.1, 1.6 Hz, 1H), 5.08 (dd, J = 10.1, 1.5 Hz, 1H), 3.27−3.38 (m, 2H), 2.72−2.79 (m, 1H), 2.55 (s, 3H), 2.39 (s, 3H), 1.20 (d, J = 6.8 Hz, 3H), 1.18 (d, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.4, 194.0, 157.7, 148.3, 136.0, 135.6, 128.4, 127.0, 126.0, 123.0, 116.4, 110.0, 108.2, 106.2, 35.2, 29.2, 29.1, 22.5, 22.4, 14.5. HRMS (ESI, m/z) calcd for $C_{22}H_{25}O_2$ $[M + H]^+$ 321.1849, found 321.1851. IR (film) 693, 950, 1232, 1678, 2963 cm^{-1}.

*1-[2-Methyl-5-(7-phenyldeca-5,6,9-trien-5-yl)furan-3-yl]-ethanone (**7b**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a colorless oil (57 mg, 85%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41−7.43 (m, 2H), 7.32 (t, J = 7.5 Hz, 2H), 7.20−7.24 (m, 1H), 6.45 (s, 1H), 5.91−6.01 (m, 1H), 5.21 (dd, J = 17.1, 1.6 Hz, 1H), 5.08 (dd, J = 10.1, 1.3 Hz, 1H), 3.31−3.33 (m, 2H), 2.55 (s, 3H), 2.38−2.43 (m, 5H), 1.51−1.59 (m, 2H), 1.35−1.44 (m, 2H), 0.90 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.6, 194.0, 157.8, 148.6, 136.2, 135.5, 128.4, 127.0, 126.2, 123.0, 116.4, 108.6, 106.1, 101.1, 35.2, 30.1, 29.3, 29.1, 22.5, 14.5, 13.9. HRMS (ESI, m/z) calcd for $C_{23}H_{27}O_2$ $[M + H]^+$ 335.2006, found 335.2008. IR (film) 694, 759, 949, 1678, 2928 cm^{-1}.

*1-[5-(1-Cyclopentyl-3-phenylhexa-1,2,5-trien-1-yl)-2-methylfuran-3-yl]ethanone (**7c**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a pale yellow oil (49 mg, 70%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41−7.43 (m, 2H), 7.32 (t, J = 7.4 Hz, 2H), 7.20−7.23 (m, 1H), 6.48 (s, 1H), 5.90−6.00 (m, 1H), 5.20 (dd, J = 17.1, 1.5 Hz, 1H), 5.07 (dd, J = 10.1, 1.0 Hz, 1H), 3.26−3.37 (m, 2H), 2.86−2.93 (m, 1H), 2.55 (s, 3H), 2.39 (s, 3H), 1.94−2.01 (m, 2H), 1.54−1.68 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.2, 194.0, 157.7, 148.8, 136.1, 135.5, 128.4, 127.0, 126.1, 123.0, 116.4, 109.6, 106.5, 106.2, 39.6, 35.2, 32.6, 32.4, 29.1, 25.12, 25.08, 14.6. HRMS (ESI, m/z) calcd for $C_{24}H_{27}O_2$ $[M + H]^+$ 347.2006, found 347.2008. IR (film) 693, 759, 952, 1677, 2956 cm^{-1}.

*1-[5-(1-Cyclohexyl-3-phenylhexa-1,2,5-trien-1-yl)-2-methylfuran-3-yl]ethanone (**7d**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a pale yellow oil (55 mg, 76%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43−7.46 (m, 2H), 7.32 (t, J = 7.4 Hz, 2H), 7.20−7.23 (m, 1H), 6.46 (s, 1H), 5.91−6.01 (m, 1H), 5.21 (dd, J = 17.1, 1.6 Hz, 1H), 5.08 (dd,

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J = 10.1, 1.4 Hz, 1H), 3.26−3.36 (m, 2H), 2.55 (s, 3H), 2.40 (s, 3H), 1.98 (t, J = 14.5 Hz, 2H), 1.75−1.79 (m, 2H), 1.65−1.71 (m, 1H), 1.15−1.42 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.1, 194.0, 157.7, 148.2, 136.1, 135.6, 128.4, 127.0, 126.0, 123.0, 116.4, 109.5, 107.3, 106.1, 38.9, 35.2, 33.09, 33.06, 29.1, 26.6, 26.1, 14.6. HRMS (ESI, m/z) calcd for $C_{25}H_{29}O_2$ $[M + H]^+$ 361.2162, found 361.2167. IR (film) 693, 760, 950, 1677, 2926 cm^{-1}.

*1-[5-(1,5-Diphenylocta-3,4,7-trien-3-yl)-2-methylfuran-3-yl]-ethanone (**7e**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a pale yellow oil (69 mg, 90%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35−7.37 (m, 2H), 7.16−7.32 (m, 8H), 6.46 (s, 1H), 5.85−5.95 (m, 1H), 5.19 (d, J = 17.1 Hz, 1H), 5.07 (d, J = 10.2 Hz, 1H), 3.19−3.32 (m, 2H), 2.82−2.94 (m, 2H), 2.68−2.80 (m, 2H), 2.56 (s, 3H), 2.38 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.6, 194.0, 157.9, 148.3, 141.4, 135.9, 135.5, 128.4, 128.38, 128.36, 127.1, 126.3, 126.0, 123.0, 116.4, 109.3, 106.3, 100.6, 35.2, 34.1, 31.4, 29.1, 14.5. HRMS (ESI, m/z) calcd for $C_{27}H_{27}O_2$ $[M + H]^+$ 383.2006, found 383.2007. IR (film) 695, 760, 951, 1677, 2926 cm^{-1}.

*1-{5-[1-(Benzyloxy)-5-phenylocta-3,4,7-trien-3-yl]-2-methylfuran-3-yl}ethanone (**7f**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 50:1−15:1), the product was isolated as a colorless oil (59 mg, 71%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42−7.44 (m, 2H), 7.19−7.31 (m, 8H), 6.46 (s, 1H), 5.89−5.99 (m, 1H), 5.18 (dd, J = 17.1, 1.6 Hz, 1H), 5.05 (dd, J = 10.1, 1.5 Hz, 1H), 4.47 (s, 2H), 3.66−3.75 (m, 2H), 3.24−3.35 (m, 2H), 2.68−2.80 (m, 2H), 2.54 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.7, 193.9, 158.0, 148.1, 138.2, 135.8, 135.4, 128.4, 128.3, 127.6, 127.5, 127.1, 126.3, 123.0, 116.4, 109.1, 106.4, 98.0, 73.0, 68.6, 35.1, 30.1, 29.1, 14.5. HRMS (ESI, m/z) calcd for $C_{28}H_{29}O_3$ $[M + H]^+$ 413.2111, found 413.2114. IR (film) 696, 736, 1103, 1677, 2857 cm^{-1}.

*1-[5-(1,3-diphenylhexa-1,2,5-trien-1-yl)-2-methylfuran-3-yl]-ethanone (**7g**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 80:1−50:1), the product was isolated as a pale yellow oil (22 mg, 31%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48−7.50 (m, 4H), 7.31−7.39 (m, 5H), 7.22−7.25 (m, 1H), 6.51 (s, 1H), 5.97−6.07 (m, 1H), 5.25 (dd, J = 17.1, 1.6 Hz, 1H), 5.12 (dd, J = 10.1, 1.4 Hz, 1H), 3.41 (dd, J = 6.3, 1.3 Hz, 2H), 2.60 (s, 3H), 2.38 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.3, 194.0, 158.4, 147.4, 135.3, 135.1, 134.7, 128.6, 128.0, 127.9, 127.4, 126.4, 123.0, 116.9, 109.2, 109.0, 104.4, 35.1, 29.1, 14.6. HRMS (ESI, m/z) calcd for $C_{25}H_{23}O_2$ $[M + H]^+$ 355.1693, found 355.1694. IR (film) 694, 760, 1232, 1678, 2918 cm^{-1}.

*Methyl 2-Methyl-5-(7-phenyldeca-5,6,9-trien-5-yl)furan-3-carboxylate (**7h**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 100:1−60:1), the product was isolated as a colorless oil (28 mg, 40%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41−7.43 (m, 2H), 7.31 (t, J = 7.4 Hz, 2H), 7.19−7.23 (m, 1H), 6.49 (s, 1H), 5.91−6.01 (m, 1H), 5.20 (dd, J = 17.1, 1.6 Hz, 1H), 5.07 (dd, J = 10.1, 1.4 Hz, 1H), 3.81 (s, 3H), 3.26−3.36 (m, 2H), 2.53 (s, 3H), 2.36−2.41 (m, 2H), 1.50−1.56 (m, 2H), 1.34−1.43 (m, 2H), 0.89 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.5, 164.5, 158.7, 148.7, 136.2, 135.6, 128.4, 127.0, 126.2, 116.3, 114.7, 108.5, 106.4, 101.2, 51.2, 35.2, 30.2, 29.4, 22.5, 13.9. HRMS (ESI, m/z) calcd for $C_{23}H_{27}O_3$ $[M + H]^+$ 351.1955, found 351.1958. IR (film) 775, 1088, 1230, 1719, 2955 cm^{-1}.

*tert-Butyl 2-Methyl-5-(7-phenyldeca-5,6,9-trien-5-yl)furan-3-carboxylate (**7i**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 200:1−120:1), the product was isolated as a colorless oil (39 mg, 50%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.43 (m, 2H), 7.31 (t, J = 7.4 Hz, 2H), 7.19−7.23 (m, 1H), 6.44 (s, 1H), 5.90−6.00 (m, 1H), 5.20 (dd, J = 17.1, 1.6 Hz, 1H), 5.06 (dd, J = 10.1, 1.5 Hz, 1H), 3.25−3.36 (m, 2H), 2.50 (s, 3H), 2.32−2.44 (m, 2H), 1.50−1.57 (m, 11H), 1.33−1.43 (m, 2H), 0.89 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.5, 163.5, 157.8, 148.3, 136.4, 135.6, 128.4, 126.9, 126.2, 116.3, 108.4, 106.8, 101.3, 80.4, 35.2, 30.2, 29.4, 28.3, 22.5, 13.94, 13.88. HRMS (ESI, m/z) calcd for $C_{26}H_{33}O_3$ $[M + H]^+$ 393.2424, found 393.2428. IR (film) 693, 1086, 1171, 1710, 2931 cm^{-1}.

*1-[2-Methyl-5-(2-methyl-4-phenylundeca-1,4,5-trien-6-yl)furan-3-yl]ethanone (**7j**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 90:1−50:1), the product was isolated as a colorless oil (27 mg, 37%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41−7.42 (m, 2H), 7.30 (t, J = 7.4 Hz, 2H), 7.19−7.22 (m, 1H), 6.45 (s, 1H), 4.92 (s, 1H), 4.85 (s, 1H), 3.23−3.31 (m, 2H), 2.54 (s, 3H), 2.37−2.42 (m, 5H), 1.81 (s, 3H), 1.55−1.62 (m, 2H), 1.29−1.37 (m, 4H), 0.85 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.2, 194.0, 157.7, 148.6, 142.9, 136.3, 128.3, 126.9, 126.4, 123.0, 112.6, 107.8, 106.1, 100.2, 39.9, 31.6, 29.6, 29.1, 27.7, 22.44, 22.39, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{25}H_{31}O_2$ $[M + H]^+$ 363.2319, found 363.2322. IR (film) 693, 951, 1232, 1678, 2928 cm^{-1}.

*(E)-1-[5-(1,4-Diphenylundeca-1,4,5-trien-6-yl)-2-methylfuran-3-yl]ethanone (**7k**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 100:1−60:1), the product was isolated as a yellow oil (34 mg, 40%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45−7.46 (m, 2H), 7.28−7.35 (m, 5H), 7.16−7.24 (m, 3H), 6.56 (d, J = 15.8 Hz, 1H), 6.45 (s, 1H), 6.32−6.41 (m, 1H), 3.42−3.52 (m, 2H), 2.54 (s, 3H), 2.38−2.42 (m, 2H), 2.37 (s, 3H), 1.53−1.60 (m, 2H), 1.26−1.34 (m, 4H), 0.82 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.8, 194.0, 157.8, 148.6, 137.5, 136.2, 131.5, 128.45, 128.42, 127.5, 127.0, 126.3, 126.0, 123.0, 108.8, 106.2, 101.3, 34.5, 31.6, 29.6, 29.1, 27.7, 22.4, 14.5, 13.9. HRMS (ESI, m/z) calcd for $C_{30}H_{33}O_2$ $[M + H]^+$ 425.2475, found 425.2473. IR (film) 693, 740, 951, 1677, 2927 cm^{-1}.

*1-{5-[1-(Cyclohex-2-en-1-yl)-1-phenylocta-1,2-dien-3-yl]-2-methylfuran-3-yl}ethanone (**7l**).* The title compound was prepared via the general procedure. After purification by silica gel column chromatography (petroleum ether/EtOAc = 90:1−60:1), the product was isolated as a pale yellow oil (39 mg, 50%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41−7.43 (m, 2H), 7.32 (t, J = 7.4 Hz, 2H), 7.20−7.24 (m, 1H), 6.42 (s, 1H), 5.69−5.75 (m, 2H), 3.48−3.52 (m, 1H), 2.55 (s, 3H), 2.35−2.40 (m, 5H), 1.92−2.05 (m, 3H), 1.74−1.86 (m, 1H), 1.52−1.69 (m, 5H), 1.29−1.37 (m, 4H), 0.82−0.88 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.8, 204.6, 194.0, 157.7, 157.6, 149.1, 148.9, 136.3, 136.1, 129.3, 129.0, 128.4, 127.8, 127.7, 126.9, 126.74, 126.72, 123.0, 114.7, 114.6, 105.8, 101.5, 36.7, 36.5, 31.65, 31.63, 29.8, 29.6, 29.1, 28.7, 28.2, 27.9, 27.7, 25.2, 22.50, 22.46, 21.2, 20.6, 14.6, 14.5, 14.0. HRMS (ESI, m/z) calcd for $C_{27}H_{33}O_2$ $[M + H]^+$ 389.2475, found 389.2476. IR (film) 694, 733, 949, 1677, 2930 cm^{-1}.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00236.

^{1}H and ^{13}C spectra for compounds **1a−l**, **4a−p**, **5a−j**, **6a−p**, and **7a−l** (PDF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For recent monographs, see (a) *Modern Allene Chemistry*; Krause, N., Hashmi, A. S. K., Eds.; Wiley−VCH: Weinheim, Germany, 2004; Vols. *1 and 2*; DOI: 10.1002/9783527619573. (b) Ma, S. Palladium-Catalyzed Two- or Three-Component Cyclization of Functionalized Allenes. In *Palladium in Organic Synthesis*; Tsuji, J., Ed.; Springer: Berlin, 2005; pp 183−210; DOI: 10.1007/b104131. (c) *Cumulenes and Allenes*; Science of Synthesis: Houben-Weyl Methods of Molecular

DOI: 10.1021/acs.joc.6b00236
J. Org. Chem. 2016, 81, 3275−3285

Transformations, Vol. *44*; Krause, N., Ed.; Georg Thieme Verlag: Stuttgart, Germany, 2008.
(2) For selected reviews, see (a) Bates, R. W.; Satcharoen, V. *Chem. Soc. Rev.* **2002**, *31*, 12. (b) Sydnes, L. K. *Chem. Rev.* **2003**, *103*, 1133. (c) Tius, M. A. *Acc. Chem. Res.* **2003**, *36*, 284. (d) Ma, S. *Chem. Rev.* **2005**, *105*, 2829. (e) Brasholz, M.; Reissig, H.-U.; Zimmer, R. *Acc. Chem. Res.* **2009**, *42*, 45. (f) Ma, S. *Acc. Chem. Res.* **2009**, *42*, 1679. (g) Yang, W.; Hashmi, A. S. K. *Chem. Soc. Rev.* **2014**, *43*, 2941.
(3) For reviews, see (a) Hoffmann-Röder, A.; Krause, N. *Angew. Chem., Int. Ed.* **2004**, *43*, 1196. (b) Kim, H.; Williams, L. J. *Curr. Opin. Drug Discovery Dev.* **2008**, *11* (6), 870. (c) Rivera-Fuentes, P.; Diederich, F. *Angew. Chem., Int. Ed.* **2012**, *51*, 2818.
(4) For reviews on the synthesis of allenes, see (a) Krause, N.; Hoffmann-Röder, A. *Tetrahedron* **2004**, *60*, 11671. (b) Brummond, K. M.; Deforrest, J. E. *Synthesis* **2007**, *2007*, 795. (c) Ogasawara, M. *Tetrahedron: Asymmetry* **2009**, *20*, 259. (d) Yu, S.; Ma, S. *Chem. Commun.* **2011**, *47*, 5384. (e) Neff, R. K.; Frantz, D. E. *ACS Catal.* **2014**, *4*, 519. For a recent example: (f) Blanco Jaimes, M. C.; Ahrens, A.; Pflästerer, D.; Rudolph, M.; Hashmi, A. S. K. *Chem. - Eur. J.* **2015**, *21*, 427.
(5) For selected reviews, see (a) Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18. (b) Jiménez-Núñez, E.; Echavarren, A. M. *Chem. Rev.* **2008**, *108*, 3326. For gold carbene, see (c) Nunes dos Santos Comprido, L.; Klein, J. E. M. N.; Knizia, G.; Kästner, J.; Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2015**, *54*, 10336.
(6) For selected reviews, see (a) Ye, T.; McKervey, M. A. *Chem. Rev.* **1994**, *94*, 1091. (b) Doyle, M. P.; McKervey, M. A.; Ye, T. *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds*; Wiley: New York, 1998. (c) Davies, H. M. L.; Beckwith, R. E. J. *Chem. Rev.* **2003**, *103*, 2861. (d) Zhang, Z.; Wang, J. *Tetrahedron* **2008**, *64*, 6577. (e) Braun, I.; Asiri, A. M.; Hashmi, A. S. K. *ACS Catal.* **2013**, *3*, 1902.
(7) (a) Zhang, Y.; Wang, J. *Eur. J. Org. Chem.* **2011**, *2011*, 1015. (b) Barluenga, J.; Valdés, C. *Angew. Chem., Int. Ed.* **2011**, *50*, 7486. (c) Shao, Z.; Zhang, H. *Chem. Soc. Rev.* **2012**, *41*, 560. (d) Xiao, Q.; Zhang, Y.; Wang, J. *Acc. Chem. Res.* **2013**, *46*, 236. (e) Liu, Z.; Wang, J. *J. Org. Chem.* **2013**, *78*, 10024. (f) Hu, F.; Xia, Y.; Ma, C.; Zhang, Y.; Wang, J. *Chem. Commun.* **2015**, *51*, 7986.
(8) (a) Xiao, Q.; Xia, Y.; Li, H.; Zhang, Y.; Wang, J. *Angew. Chem., Int. Ed.* **2011**, *50*, 1114. (b) Hossain, M. L.; Ye, F.; Zhang, Y.; Wang, J. *J. Org. Chem.* **2013**, *78*, 1236.
(9) Ye, F.; Hossain, M. L.; Xu, Y.; Ma, X.; Xiao, Q.; Zhang, Y.; Wang, J. *Chem. - Asian J.* **2013**, *8*, 1404.
(10) For reviews on conjugated ene-yne ketones as carbene precursors: (a) Miki, K.; Uemura, S.; Ohe, K. *Chem. Lett.* **2005**, *34*, 1068. (b) Kusama, H.; Iwasawa, N. *Chem. Lett.* **2006**, *35*, 1082. (c) Ohe, K.; Miki, K. *Yuki Gosei Kagaku Kyokaishi* **2009**, *67*, 1161. (d) Fürstner, A.; Davies, P. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 3410.
(11) For selected examples: (a) Miki, K.; Nishino, F.; Ohe, K.; Uemura, S. *J. Am. Chem. Soc.* **2002**, *124*, 5260. (b) Miki, K.; Washitake, Y.; Ohe, K.; Uemura, S. *Angew. Chem., Int. Ed.* **2004**, *43*, 1857. (c) Vicente, R.; González, J.; Riesgo, L.; González, J.; López, L. A. *Angew. Chem., Int. Ed.* **2012**, *51*, 8063. (d) González, J.; González, J.; Pérez-Calleja, C.; López, L. A.; Vicente, R. *Angew. Chem., Int. Ed.* **2013**, *52*, 5853. (e) Cao, H.; Zhan, H.; Cen, J.; Lin, J.; Lin, Y.; Zhu, Q.; Fu, M.; Jiang, H. *Org. Lett.* **2013**, *15*, 1080. (f) Yu, Y.; Yi, S.; Zhu, C.; Hu, W.; Gao, B.; Chen, Y.; Wu, W.; Jiang, H. *Org. Lett.* **2016**, *18*, 400. (g) Clark, J. S.; Boyer, A.; Aimon, A.; García, P. E.; Lindsay, D. M.; Symington, A. D. F.; Danoy, Y. *Angew. Chem., Int. Ed.* **2012**, *51*, 12128.
(12) González, M. J.; López, E.; Vicente, R. *Chem. Commun.* **2014**, *50*, 5379.
(13) (a) Xia, Y.; Qu, S.; Xiao, Q.; Wang, Z.-X.; Qu, P.; Chen, Li.; Liu, Z.; Tian, L.; Huang, Z.; Zhang, Y.; Wang, J. *J. Am. Chem. Soc.* **2013**, *135*, 13502. For other related reports: (b) Xia, Y.; Liu, Z.; Ge, R.; Xiao, Q.; Zhang, Y.; Wang, J. *Chem. Commun.* **2015**, *51*, 11233. (c) Xia, Y.; Ge, R.; Chen, L.; Liu, Z.; Xiao, Q.; Zhang, Y.; Wang, J. *J. Org. Chem.* **2015**, *80*, 7856.
(14) Hu, F.; Xia, Y.; Ma, C.; Zhang, Y.; Wang, J. *Org. Lett.* **2014**, *16*, 4082.
(15) For a detailed discussion on the effect of base on transition-metal-catalyzed coupling reactions, see Ouyang, K.; Xi, Z. *Huaxue Xuebao* **2013**, *71*, 13.
(16) For a recent paper on synthesis of allenyl-substituted furans, see Blanco Jaimes, M. C.; Ahrens, A.; Pflästerer, D.; Rudolph, M.; Hashmi, A. S. K. *Chem. - Eur. J.* **2015**, *21*, 427.
(17) For recent reports on transition-metal-catalyzed synthesis of 3-formylfurans, see (a) Wang, T.; Shi, S.; Hansmann, M. M.; Rettenmeier, E.; Rudolph, M.; Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2014**, *53*, 3715. (b) Wang, T.; Shi, S.; Rudolph, M.; Hashmi, A. S. K. *Adv. Synth. Catal.* **2014**, *356*, 2337. (c) Wang, T.; Huang, L.; Shi, S.; Rudolph, M.; Hashmi, A. S. K. *Chem. - Eur. J.* **2014**, *20*, 14868.

DOI: 10.1021/acs.joc.6b00236
J. Org. Chem. 2016, 81, 3275−3285