JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

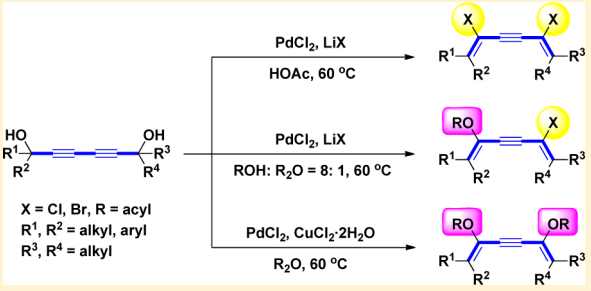
Palladium-Catalyzed Bond Reorganization of 1,3-Diynes: An Entry to Diverse Functionalized 1,5-Dien-3-ynes

Wanqing Wu, Yang Gao, Huanfeng Jiang,* and Yubing Huang

School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, People's Republic of China

Supporting Information

ABSTRACT: A mild and efficient method for the synthesis of functionalized 1,5-dien-3-ynes from 1,3-diynes under Pd^{II} catalysis is described. The process allows quick and atom-economical assembly of various dihalo-, haloacyl-, and diacyl-substituted 1,5-dien-3-ynes in high yields. The switch of selectivity in the formation of these dienyne products can be controlled by the choice of catalysis system and reaction conditions.



Among the challenges currently facing organic chemists is the development of efficient and elegant chemical processes that enable the rapid creation of complex skeletons.[1] One of the most effective ways of achieving this goal is to implement the synthesis with a nucleopalladation strategy, which allows multiple bond-forming events to occur in a single operation and thereby significantly increases resource efficiency for the overall process.[2] In addition, the development of complementary sets of catalysts or/and conditions that provide quick access to various functionalities of broad synthetic uses is valuable. Thus, the merging of these two topics would provide interesting possibilities for organic synthesis.

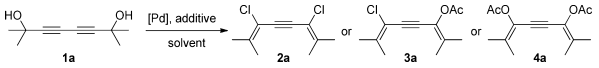
Conjugated molecules, such as enynes, enediynes, and 1,5-dien-3-ynes, are versatile building blocks for many naturally occurring biologically active compounds and functional materials.[3,4] In particular, the high π-electron delocalization behavior in these π-conjugated molecules allows their wide application in advanced organic materials, such as molecular wires, nonlinear optics, organic conductors, electroluminescence, etc.[3] Despite the significant progress that has been achieved in the synthesis of conjugated compounds,[5] further advances are still desirable, particularly with regard to the controlled incorporation of different functional groups by routine changes to the reaction conditions or/and catalyst system employed. As part of our continuing program on nucleopalladation chemistry,[6] we envisioned that functionalized 1,5-dien-3-ynes[7] could be obtained via bond reorganization of 1,3-diynes bearing propargylic alcohol moieties initiated by nucleopalladation of the triple bonds. Herein, we disclose a concise and convenient method for the synthesis of 1,5-dien-3-yne compounds. This protocol provides a diverse array of dihalo-, haloacyl-, and diacyl-substituted 1,5-dien-3-ynes that are suitable for further modifications and synthetic applications. The selectivity switch in these three kinds of products can be controlled efficiently by the choice of reaction conditions.

With the hypothesis mentioned above, initial studies were focused on using 2,7-dimethylocta-3,5-diyne-2,7-diol (**1a**) as a model substrate (Table 1). First, when **1a** was treated with $PdCl_2$ (5 mol %) in acetonitrile, no dichloro-1,5-dien-3-yne product **2a** could be detected and **1a** was recovered (entry 1). We then closely examined the influence of different additives on the reaction. To our delight, a clear improvement of the yield was observed when an excess amount of LiCl was added (entry 4), while other additives did not show apparent positive effects (entries 2 and 3). Further investigation of the solvent effects revealed that HOAc was the most suitable medium for this process (entries 4−8). Various palladium sources, including Pd^{II} and Pd^0, were also tested, and $PdCl_2$ proved to be optimal, which afforded **2a** in 93% yield (entries 8−12). However, the addition of ligands, such as triphenylphosphine and 1,10-phenanthroline, just led to a dramatic decrease in the yield (entries 13 and 14). After the reaction conditions initiated by chloropalladation were well-defined, the acetoxy anion was chosen as the nucleophile instead of the halide ion to perform this transformation. It was found that lowering the amount of LiCl and using HOAc/Ac_2O as solvent favored the formation of acetoxychlorination product **3a** (entries 16−19). The best result was obtained when the HOAc/Ac_2O ratio was 8/1 (v/v), giving an 85% yield of **3a** (entry 18). Interestingly, when the reaction was conducted in Ac_2O, the diacetoxy derivative **4a** was formed as the major product in 62% yield (entry 20), which was further improved to 91% with the use of a catalytic amount of $CuCl_2·2H_2O$ as additive (entry 22). Notably, the Pd source played an important role in the success of this transformation, since no desired products could be detected in the absence of the Pd catalyst (entries 15 and 23). Thus, the

Received: February 13, 2013
Published: April 16, 2013

dx.doi.org/10.1021/jo400276e | J. Org. Chem. 2013, 78, 4580−4586

Table 1. Optimization of the Pd-Catalyzed Synthesis of 1,5-Dien-3-ynes from 1a[a]



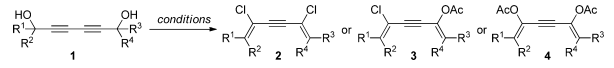
entry	[Pd]/ligand	additive (amt (equiv))	solvent (v/v)	product/ yield[b] (%)
1	$PdCl_2$		CH_3CN	n.r.
2	$PdCl_2$	KCl (4.0)	CH_3CN	**2a**/trace
3	$PdCl_2$	$CuCl_2{\cdot}2H_2O$ (4.0)	CH_3CN	**2a**/68
4	$PdCl_2$	LiCl (4.0)	CH_3CN	**2a**/82
5	$PdCl_2$	LiCl (4.0)	THF	**2a**/45
6	$PdCl_2$	LiCl (4.0)	DCE	**2a**/50
7	$PdCl_2$	LiCl (4.0)	DMSO	**2a**/n.d.
8	$PdCl_2$	LiCl (4.0)	HOAc	**2a**/96 (93)
9	$Pd(OAc)_2$	LiCl (4.0)	HOAc	**2a**/40
10	$Pd_2(dba)_3$	LiCl (4.0)	HOAc	**2a**/71
11	$Pd(PPh_3)_4$	LiCl (4.0)	HOAc	n.r.
12	Pd/C	LiCl (4.0)	HOAc	n.r.
13	$PdCl_2/PPh_3$	LiCl (4.0)	HOAc	**2a**/23
14	$PdCl_2$/1,10-Phen	LiCl (4.0)	HOAc	**2a**/31
15		LiCl (4.0)	HOAc	n.r.
16	$PdCl_2$	LiCl (1.0)	HOAc/Ac_2O (1/1)	**3a**/62
17	$PdCl_2$	LiCl (1.0)	HOAc/Ac_2O (4/1)	**3a**/70
18	$PdCl_2$	LiCl (1.0)	HOAc/Ac_2O (8/1)	**3a**/89 (85)
19	$PdCl_2$	LiCl (1.0)	HOAc/Ac_2O (10/1)	**3a**/58
20	$PdCl_2$	LiCl (1.0)	Ac_2O	**4a**/62
21	$PdCl_2$	$CuCl_2{\cdot}2H_2O$ (1.0)	Ac_2O	**4a**/76
22	$PdCl_2$	$CuCl_2{\cdot}2H_2O$ (0.1)	Ac_2O	**4a**/96 (91)
23		$CuCl_2{\cdot}2H_2O$ (0.1)	Ac_2O	**4a**/n.d.

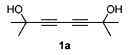
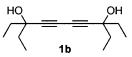
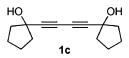
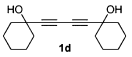
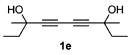
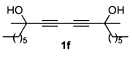
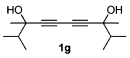
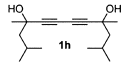
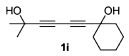
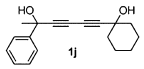
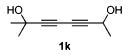
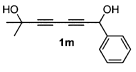
[a]Unless otherwise noted, all reactions were performed with **1a** (0.5 mmol), Pd catalyst (5 mol %), ligand (10 mol %) and additive in the indicated solvent (2.0 mL) at 60 °C for 12 h. n.r. = no reaction. n.d. = not detected. [b]Determined by GC using dodecane as the internal standard. Data in parentheses is the isolated yield.

complete selectivity and complementarity for accessing diverse 1,5-dien-3-ynes could be achieved through the employment of different additives and solvent systems.

To demonstrate the efficiency and generality of this process, we next examined the transformation of various 1,3-diynes under the optimized reaction conditions, and the representative results are summarized in Table 2. Pleasingly, the reactions of symmetrical (**1a**−**h**) and unsymmetrical diynes (**1i**,**j**) bearing tertiary propargyl alcohol moieties proceeded smoothly to afford the corresponding dichloro- (**2a**−**i**), acetoxychloro- (**3a**−**j**), and diacetoxy-1,5-dien-3-yne products (**4a**−**i**) in moderate to high yields (45−93%). The total number of isomers in the unsymmetrical dienyne products is typically three (*E*/*Z*, *Z*/*Z*, and *E*/*E*), and their ratios were determined by NMR analysis.[8] Generally, the relative rate conversion decreased from alkyl- to aryl-substituted diynes, indicating that the weak coordination effect of the aryl groups with the catalyst might have an influence on the reaction profile. For the phenyl-substituted diyne **1j**, the yield of the acetoxychlorination product **3j** was dropped dramatically to 45%, whereas the dichloro and diacetoxy products (**2j** and **4j**) could not be obtained.

Table 2. Pd-Catalyzed Synthesis of Various Functionalized 1,5-Dien-3-ynes



entry	1,3-diynes	cond.[a]	yield[b] (%) 2	3	4
1		**A**	93 (**2a**)	4 (**3a**)	-
		B	5 (**2a**)	85 (**3a**)	6 (**4a**)
		C	-	5 (**3a**)	91 (**4a**)
2		**A**	92 (**2b**)	4 (**3b**)	-
		B	7 (**2b**)	86 (**3b**)	4 (**4b**)
		C	-	7 (**3b**)	90 (**4b**)
3		**A**	90 (**2c**)	6 (**3c**)	-
		B	8 (**2c**)	83 (**3c**)	5 (**4c**)
		C	-	4 (**3c**)	90 (**4c**)
4		**A**	88 (**2d**)	7 (**3d**)	-
		B	10 (**2d**)	79 (**3d**)	6 (**4d**)
		C	-	5 (**3d**)	89 (**4d**)
5		**A**	91 (**2e**)	6 (**3e**)	-
		B	8 (**2e**)	83 (**3e**)	6 (**4e**)
		C	-	5 (**3e**)	90 (**4e**)
6		**A**	86 (**2f**)	10 (**3f**)	-
		B	9 (**2f**)	77 (**3f**)	8 (**4f**)
		C	-	7 (**3f**)	88 (**4f**)
7		**A**	83 (**2g**)	11 (**3g**)	-
		B	12 (**2g**)	72 (**3g**)	9 (**4g**)
		C	-	15 (**3g**)	80 (**4g**)
8		**A**	85 (**2h**)	6 (**3h**)	-
		B	10 (**2h**)	75 (**3h**)	6 (**4h**)
		C	-	8 (**3h**)	82 (**4h**)
9		**A**	92 (**2i**)	3 (**3i**)	-
		B	11 (**2i**)	83 (**3i**)	4 (**4i**)
		C	-	4 (**3i**)	92 (**4i**)
10[c]		**A**	-	-	-
		B	4 (**2j**)	45 (**3j**)	-
		C	-	-	-
11[d]		**A**	28 (**2k**)	5 (**3k**)	-
		B	3 (**2k**)	21 (**3k**)	4 (**4k**)
		C	-	6 (**3k**)	32 (**4k**)
12[d]		**A**	25 (**2l**)	7 (**3l**)	-
		B	5 (**2l**)	18 (**3l**)	3 (**4l**)
		C	-	4 (**3l**)	31 (**4l**)

[a]Conditions **A**: $PdCl_2$ (5 mol %), LiCl (4.0 equiv), HOAc, 60 °C. Conditions **B**: $PdCl_2$ (5 mol %), LiCl (1.0 equiv), HOAc/Ac_2O (8/1), 60 °C. Conditions **C**: $PdCl_2$ (5 mol %), $CuCl_2{\cdot}2H_2O$ (10 mol %), Ac_2O, 60 °C. [b]Unless otherwise noted, yields refer to isolated yields. [c]The stereochemistry was not determined. [d]Yields refer to GC yields.

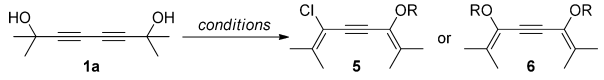
Furthermore, the unsymmetrical diynes **1k**−**l** having both tertiary and secondary propargyl alcohols could also participate in this catalytic process, though the yields were far from satisfactory (18−32%). However, when the diynes containing secondary or/and primary propargylic alcohols were subjected to the standard reaction conditions, the bond reorganization process did not occur at all. The reactivity difference observed in **1** suggested that the tertiary propargylic alcohol moieties were critical for this transformation, which was consistent with our

dx.doi.org/10.1021/jo400276e | J. Org. Chem. 2013, 78, 4580−4586

previous results that the tertiary propargyl alcohols were more liable to undergo the nucleopalladation process.[9] It is also possible that the alkyl substituents at the tertiary propargylic carbon would better stabilize the developing positive charge, thus facilitating the elimination pathway with the aid of acetic acid.[9a,c] Moreover, the increased steric repulsion of these alkyl groups at the propargylic position might also assist the rearrangement process to form the 1,5-dien-3-yne products. It is worth mentioning that both the vinyl halide and vinyl acetate moieties of these dienyne products are poised for subsequent functionalization, thus allowing for great structural diversity.

The scope of this transformation was further expanded to a range of carboxylate derivatives (Table 3). Other than acetyl,

Table 3. Pd-Catalyzed Synthesis of Various Diacyl-1,5-dien-3-ynes from 1a



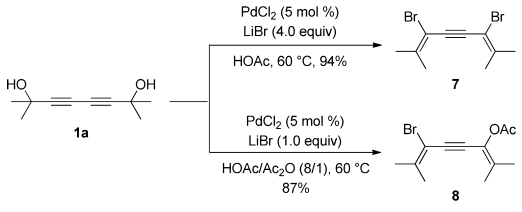
			yield[b] (%)	
entry	R	cond[a]	5	6
1	$COCH_3$	B	85 (**3a**)	8 (**4a**)
		C	5 (**3a**)	91 (**4a**)
2	$COCH_2CH_3$	B	80 (**5a**)	11 (**6a**)
		C	6 (**5a**)	90 (**6a**)
3	$CO(CH_2)_2CH_3$	B	82 (**5b**)	9 (**6b**)
		C	3 (**5b**)	94 (**6b**)
4	$CO(CH_2)_3CH_3$	B	84 (**5c**)	10 (**6c**)
		C	4 (**5c**)	90 (**6c**)
5	$COCH(CH_3)_2$	B	81 (**5d**)	9 (**6d**)
		C	8 (**5d**)	89 (**6d**)
6	$COC(CH_3)_3$	B	79 (**5e**)	12 (**6e**)
		C	5 (**5e**)	92 (**6e**)

[a]Conditions **B**: $PdCl_2$ (5 mol %), LiCl (1.0 equiv), ROH/R_2O (8/1), 60 °C. Conditions **C**: $PdCl_2$ (5 mol %), $CuCl_2{\cdot}2H_2O$ (10 mol %), R_2O, 60 °C. [b]Yields refer to isolated yields.

different acyl substituents could be incorporated successfully into the rearrangement sequence. In all the tested cases, the acyl groups with either elongated carbon chains (*n*-propionyl, *n*-butyryl, valeryl) or increased steric hindrance (*i*-butyryl, pivalyl) behaved similarly in terms of reactivity and selectivity, generating the corresponding chlorocarboxylate (**5a**–**e**) and dicarboxylate 1,5-dien-3-ynes (**6a**–**e**) in good to excellent yields (79–94%).

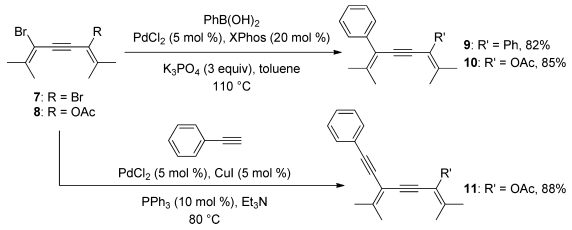
To our delight, this method could be successfully applied to the synthesis of bromide-incorporated products when switching the additive from LiCl to LiBr. Both the dibromo- and bromoacetoxy-1,5-dien-3-yne products (**7** and **8**) could be obtained under the standard conditions in good isolated yields (94% and 87%, respectively) (Scheme 1).

Scheme 1. Pd-Catalyzed Synthesis of Dibromo- and Acetoxybromo-1,5-dien-3-ynes



The utility of halo-substituted 1,5-dien-3-ynes produced by this chemistry as useful synthetic intermediates for further elaborations was demonstrated through Pd-catalyzed Suzuki–Miyaura and Sonogashira coupling reactions (Scheme 2). For

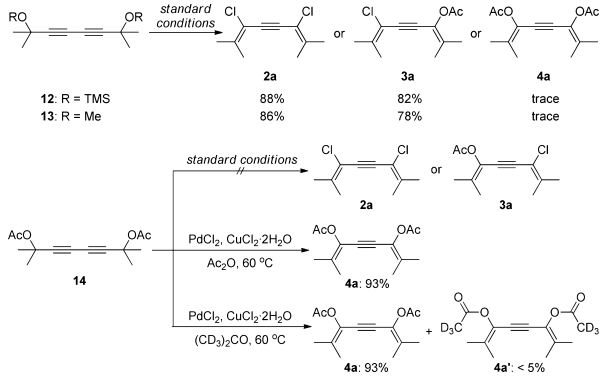
Scheme 2. Synthetic Applications of Halo-Substituted 1,5-Dien-3-ynes



instance, treatment of compound **7** or **8** with phenylboronic acid selectively afforded arylated products **9** and **10** in 82% and 85% yields, respectively. In addition, the coupling reaction of **7** with phenylacetylene furnished the conjugated enyne product **11** in 88% yield. The simplicity of this method should make it valuable to a diversity of dienynes and polyenynes, which may find potential utilities in materials science and natural product synthesis.

To shed light on the reaction mechanism, several control experiments were conducted (Scheme 3). Under the standard

Scheme 3. Control Experiments

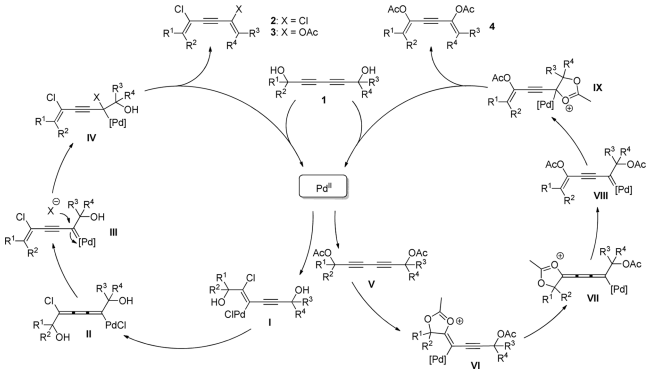


conditions, the reactions of silyloxy- and methoxy-substituted 1,3-diynes **12** and **13** could give the dichloro- and chloroacetoxy-1,5-dien-3-ynes **2a** and **3a** in high yields, while only a trace amount of diacetoxy product **4a** was detected, suggesting that the formation of these products might proceed via different pathways. Additionally, when using diyne **14** with propargylic acetates as the starting material, only **4a** could be obtained in 93% yield. These observations prompted us to further investigate the origin of the acetate moieties of the rearrangement products. An isotopic labeling study with deuterated acetic anhydride as the solvent was performed, and unlabeled **4a** was obtained as a major product, which clearly demonstrated that the acetate groups of **4a** originated from the substrate and an intramolecular acyl migration should be involved in the formation of **4**.

On the basis of the above results, a tentative mechanism for the switched selectivity in Pd-catalyzed bond reorganization of 1,3-diynes to synthesize functionalized 1,5-dienynes is proposed (Scheme 4). The pathway on the left was initiated by *trans*-halopalladation of the alkyne moiety in **1** to give vinylpalladium

dx.doi.org/10.1021/jo400276e | J. Org. Chem. 2013, 78, 4580–4586

Scheme 4. Proposed Mechanism



complex **I**, which could equilibrate to cumulene intermediate **II** through a 1,3-metal shift.[10] Then, **II** would transfer to enyne **III** with the elimination of −OH in the presence of acetic acid. Subsequent nucleophilic attack of halide or acyl anion to **III** gave intermediate **IV**, followed by *β*-OH elimination to afford the dihalo- and haloacyl-1,5-dien-yne products **2** and **3**.[9] For the pathway on the right, under the treatment of Pd catalyst and acetic anhydride, diyne **1** was first transformed to diacetate **V**, which would undergo 1,2-acyl migration to generate the acetoxonium species **VI**,[11] followed by isomerization to form **VII** and then **VIII**.[12] Finally, the migratory insertion of an acetate moiety onto the carbene center of **VIII** via the transient structure **IX** occurred to deliver the observed product **4**.

In summary, we have developed an efficient method for the synthesis of functionalized 1,5-dien-3-ynes via Pd-catalyzed bond reorganization of 1,3-diynes bearing propargylic alcohol moieties. This general protocol provides rapid access to a diversity of dihalo-, haloacyl-, and diacyl-1,5-dien-3-ynes in high yields. The selectivity in product formation can be switched by using different catalysis systems, and additional mechanistic studies are provided to rationalize the observed selectivity differences. Moreover, the 1,5-dien-3-yne derivatives constructed by this methodology are readily converted to different polyconjugated systems, which may have great promise for their potential applications in materials science and organic synthesis.

EXPERIMENTAL SECTION

General Procedure for the Pd-Catalyzed Synthesis of Dichloro-1,5-dien-3-ynes. A 20 mL Schlenk tube was charged with **1** (0.5 mmol), $PdCl_2$ (5 mol %), LiCl (2 mmol), and HOAc (2.0 mL). The resulting mixture was stirred at 60 °C until the starting material disappeared, as monitored by TLC. The reaction was then quenched with saturated aqueous Na_2CO_3. The aqueous phase was extracted with diethyl ether (×3), and the combined organic extracts were washed with brine. After the organic layer was dried over $MgSO_4$, the solvent was removed under reduced pressure. The residue was then purified by silica gel chromatography using light petroleum ether as eluent to afford the desired product **2**.

General Procedure for the Pd-Catalyzed Synthesis of Chloroacetoxy-1,5-dien-3-ynes. A 20 mL Schlenk tube was charged with **1** (0.5 mmol), $PdCl_2$ (5 mol %), LiCl (0.5 mmol), and HOAc/Ac_2O (8/1 v/v, 2.0 mL). The resulting mixture was stirred at 60 °C until the starting material disappeared, as monitored by TLC. The reaction was then quenched with saturated aqueous Na_2CO_3. The aqueous phase was extracted with diethyl ether (×3), and the combined organic extracts were washed with brine. After the organic layer was dried over $MgSO_4$, the solvent was removed under reduced pressure. The residue was then purified by silica gel chromatography using light petroleum ether/ethyl acetate as eluent to afford the desired product **3**.

General Procedure for the Pd-Catalyzed Synthesis of Diacetoxy-1,5-dien-3-ynes. A 20 mL Schlenk tube was charged with **1a** (0.5 mmol), $PdCl_2$ (5 mol %), $CuCl_2·2H_2O$ (10 mol %), and Ac_2O (2.0 mL). The resulting mixture was stirred at 60 °C until the starting material disappeared, as monitored by TLC. The reaction was then quenched with saturated aqueous Na_2CO_3. The aqueous phase was extracted with diethyl ether (×3), and the combined organic extracts were washed with brine. After the organic layer was dried over $MgSO_4$, the solvent was removed under reduced pressure. The residue was then purified by silica gel chromatography using light petroleum ether/ethyl acetate as eluent to afford the desired product **4**.

*3,6-Dichloro-2,7-dimethylocta-2,6-dien-4-yne (**2a**):* yellow oil (94 mg, 93%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.02 (s, 6H), 1.95 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.5, 107.6, 88.3, 23.0, 21.2; IR (KBr) 2926, 2856, 2189, 1730, 1462, 1375, 1266, 1123, 802, 740 cm^{-1}; HRMS (EI/$[M]^+$) calcd for $C_{10}H_{12}Cl_2$ 202.0316, found 202.0318.

*6-Chloro-2,7-dimethylocta-2,6-dien-4-yn-3-yl acetate (**3a**):* yellow oil (96 mg, 85%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.19 (s, 3H), 1.99 (s, 3H), 1.96 (s, 3H), 1.93 (s, 3H), 1.72 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 142.4, 134.0, 125.2, 107.7, 88.7, 85.5, 23.0, 21.2, 20.6, 20.6, 17.7; IR (KBr) 2976, 2873, 1714, 1624, 1464, 1372, 1281, 1168, 842, 607 cm^{-1}; HRMS (ESI/$[M + Na]^+$) calcd for $C_{12}H_{15}O_2ClNa$ 249.0653, found 249.0651.

*2,7-Dimethylocta-2,6-dien-4-yne-3,6-diyl diacetate (**4a**):*[7f,g] white solid (114 mg, 91%), mp 46−47 °C (lit.[1] mp 47.0−48.9 °C); ^1H NMR (400 MHz, $CDCl_3$) δ 2.15 (s, 6H), 1.91 (s, 6H), 1.68 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.5, 133.9, 125.3, 85.9, 20.6, 20.6, 17.6; IR (KBr) 2920, 2866, 1755, 1687, 1459, 1393, 1257, 1135, 967 cm^{-1}; HRMS (ESI/$[M + Na]^+$) calcd for $C_{14}H_{18}O_4Na$ 273.1097, found 273.1108.

*4,7-Dichloro-3,8-diethyldeca-3,7-dien-5-yne (**2b**):* yellow oil (119 mg, 92%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.37 (dq, J = 19.2, 7.6 Hz, 8H), 1.07 (dt, J = 9.3, 7.9 Hz, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.1, 107.5, 88.1, 27.7, 25.6, 12.5, 11.5; IR (KBr) 2968, 2873, 2184, 1725, 1619, 1459, 1376, 1241, 1127, 847 cm^{-1}; HRMS (EI/$[M]^+$) calcd for $C_{14}H_{20}Cl_2$ 258.0942, found 258.0942.

*7-Chloro-3,8-diethyldeca-3,7-dien-5-yn-4-yl acetate (**3b**):* yellow oil (121 mg, 86%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.37 (q, J = 7.5 Hz, 2H), 2.34 (q, J = 7.5 Hz, 4H), 2.18 (s, 3H), 2.12 (q, J = 7.6 Hz, 2H), 1.04 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.7, 152.9, 144.3, 125.0, 107.6, 88.5, 85.5, 27.7, 25.5, 25.0, 22.1, 20.6, 12.6, 12.5, 12.1, 11.5; IR (KBr) 2929, 2853, 2189, 1759, 1668, 1455, 1388, 1212, 1166, 817, 749 cm^{-1}; HRMS (ESI/$[M + Na]^+$) calcd for $C_{16}H_{23}O_2ClNa$ 305.1279, found 305.1278.

*3,8-Diethyldeca-3,7-dien-5-yne-4,7-diyl diacetate (**4b**):* colorless oil (138 mg, 90%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.31 (q, J = 7.5 Hz, 4H), 2.16 (s, 6H), 2.09 (q, J = 7.5 Hz, 4H), 1.06 (t, J = 7.5 Hz, 6H), 0.97 (t, J = 7.5 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 144.2, 125.1, 85.9, 24.9, 22.1, 20.6, 12.5, 12.0; IR (KBr) 2971, 2843, 2192, 1752, 1459, 1372, 1212, 849, 702 cm^{-1}; HRMS (ESI/$[M + Na]^+$) calcd for $C_{18}H_{26}O_4Na$ 329.1723, found 329.1723.

*1,4-Dichloro-1,4-dicyclopentylidenebut-2-yne (**2c**):* yellow oil (114 mg, 90%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.47 (m, 8H), 1.77 (m, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.5, 103.7, 88.2, 34.1, 33.5, 27.1, 26.3; IR (KBr) 2957, 2874, 2199, 1716, 1609, 1443, 1374, 1238, 1177, 869, 739 cm^{-1}; HRMS (EI/$[M]^+$) calcd for $C_{14}H_{16}Cl_2$ 254.0629, found 254.0630.

*4-Chloro-1,4-dicyclopentylidenebut-2-yn-1-yl acetate (**3c**):* yellow oil (115 mg, 83%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.48 (m, 6H), 2.31 (m 2H), 2.17 (s, 3H), 1.75 (m, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.4, 155.3, 146.2, 122.2, 103.7, 88.9, 85.6, 34.1, 33.5, 31.5, 30.0, 27.1, 26.4, 26.3, 26.3, 20.7; IR (KBr) 2935, 2823, 1765, 1658, 1455, 1395, 1216, 1158, 849, 725 cm^{-1}; HRMS (ESI/$[M + Na]^+$) calcd for $C_{16}H_{19}O_2ClNa$ 301.0966, found 301.0968.

*1,4-Dicyclopentylidenebut-2-yne-1,4-diyl diacetate (**4c**):* yellow oil (136 mg, 90%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.46 (m, 2H), 2.27 (m 2H), 2.14 (s, 3H), 1.70 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.4, 146.1, 122.3, 86.3, 31. 5, 30.0, 26.4, 26.3, 20.6; IR (KBr) 2950,

dx.doi.org/10.1021/jo400276e | J. Org. Chem. 2013, 78, 4580−4586

2871, 1761, 1655, 1429, 1369, 1201, 1135, 876 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{18}H_{22}O_4Na$ 325.1410, found 325.1429.

1,4-Dichloro-1,4-dicyclohexylidenebut-2-yne (**2d**): yellow oil (1247 mg, 88%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.46 (m, 8H), 1.60 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.2, 104.7, 88.3, 33.4, 31.0, 27.4, 26.9, 26.0; IR (KBr) 2932, 2856, 2186, 1729, 1658, 1522, 1445, 1328, 1235, 1135, 861 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{16}H_{20}Cl_2$ 282.0942, found 282.0940.

4-Chloro-1,4-dicyclohexylidenebut-2-yn-1-yl acetate (**3d**): yellow oil (121 mg, 79%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.43 (m, 6H), 2.18 (s, 3H), 2.16 (m, 2H), 1.64 (m, 2H), 1.57 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.7, 149.0, 140.8, 122.3, 104.8, 88.5, 85.7, 33.3, 30.9, 30.9, 27.9, 27.3, 27.2, 26.9, 26.8, 26.1, 26.0, 20.6; IR (KBr) 2936, 2858, 2180, 1752, 1449, 1372, 1227, 1135, 955, 758 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{18}H_{23}O_2ClNa$ 329.1279, found 329.1282.

1,4-Dicyclohexylidenebut-2-yne-1,4-diyl diacetate (**4d**):[7g] yellow oil (147 mg, 89%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.37 (m, 4H), 2.14 (s, 6H), 2.12 (m, 4H), 1.61 (m, 4H), 1.52 (m, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.7, 140.8, 122.4, 85.8, 30.8, 27.8, 27.1, 26.8, 26.1, 20.6; IR (KBr) 2933, 2856, 2184, 1764, 1445, 1368, 1193, 875 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{20}H_{26}O_4Na$ 353.1723, found 353.1730.

4,7-Dichloro-3,8-dimethyldeca-3,7-dien-5-yne (**2e**): yellow oil (105 mg, 91%, 26/54/20 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.40 (m, 2H), 2.35 (q, J = 7.5 Hz, 2H), 2.00 (d, J = 2.4 Hz, 3H), 1.93 (s, 3H), 1.06 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.9, 147.57, 147.54, 107.7, 107.6, 106.98, 106.95, 88.5, 88.4, 88.1, 87.9, 30.0, 27.9, 20.5, 20.45, 18.8, 18.7, 12.3, 11.3; IR (KBr) 2935, 2875, 2166, 1715, 1460, 1383, 1237, 1125, 849, 769 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{12}H_{16}Cl_2$ 230.0629, found 230.0625.

7-Chloro-3,8-dimethyldeca-3,7-dien-5-yn-4-yl acetate (**3e**): yellow oil (105 mg, 83%, 27/50/23 mixture of *EE*/(*EZ*,*ZE*)/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.35 (m, 3H), 2.18 (s, 3H), 2.10 (m, 1H), 1.95 (m, 2H), 1.91 (s, 1.5H), 1.70 (s, 1.5H), 1.05 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.8, 168.7, 168.5, 168.4, 147.8, 147.75, 147.4, 147.3, 139.2, 139.0, 138.9, 125.1, 125.0, 124.8, 124.7, 107.7, 107.6, 107.1, 107.0, 88.9, 88.8, 88.4, 88.3, 85.8, 85.7, 85.4, 85.3, 30.0, 27.9, 27.5, 24.53, 20.6, 20.5, 20.5, 20.4, 18.8, 18.7, 17.9, 17.7, 15.1, 15.0, 12.2, 12.1, 11.7, 11.2; IR (KBr) 2933, 2880, 2184, 1753, 1457, 1375, 1202, 1121, 840, 729 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{14}H_{19}O_2ClNa$ 277.0966, found 277.0973.

3,8-Dimethyldeca-3,7-dien-5-yne-4,7-diyl diacetate (**4e**): yellow oil (125 mg, 90%, 28/55/17 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.31 (dq, J = 7.5, 2.6 Hz, 2H), 2.16 (s, 6H), 2.08 (q, J = 7.6 Hz, 2H), 1.91 (d, J = 1.9 Hz, 3H), 1.68 (s, 3H), 1.05 (t, J = 7.5 Hz, 3H), 0.98 (t, J = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.7, 168.6, 168.4, 168.3, 139.1, 138.9, 138.8, 125.2, 125.1, 124.9, 124.82, 86.1, 86.0, 85.8, 85.7, 27.5, 24.5, 20.6, 20.5, 17.9, 17.8, 15.0, 15.0, 12.2, 12.1, 11.7; IR (KBr) 2978, 2876, 2170, 1755, 1489, 1395, 1222, 1143, 880, 755 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{16}H_{22}O_4Na$ 301.1410, found 301.1416.

8,11-Dichloro-7,12-dimethyloctadeca-7,11-dien-9-yne (**2f**): yellow oil (147 mg, 86%, 26/53/21 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.38 (t, J = 7.6 Hz, 2H), 2.32 (m, 2H), 2.00 (d, J = 2.2 Hz, 3H), 1.93 (s, 3H), 1.47 (m, 4H), 1.29 (m, 12H), 0.90 (d, J = 3.1 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.7, 146.5, 146.4, 146.3, 108.1, 108.0, 107.5, 107.4, 88.7, 88.5, 88.4, 88.2, 36.7, 34.7, 31.7, 31.6, 29.1, 28.9, 28.9, 27.7, 27.6, 26.9, 22.6, 22.5, 21.0, 20.9, 19.2, 19.1, 14.1; IR (KBr) 2928, 2861, 2184, 1714, 1601, 1460, 1376, 1256, 866, 727 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{20}H_{32}Cl_2$ 342.1881, found 342.1884.

11-Chloro-7,12-dimethyloctadeca-7,11-dien-9-yn-8-yl acetate (**3f**): yellow oil (141 mg, 77%, 31/47/22 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 3.32 (m, 3H), 2.17 (d, J = 3.5 Hz, 3H), 2.08 (m, 1H), 1.95 (m, 3H), 1.90 (s, 1.5H), 1.69 (s, 1.5H), 1.44 (m, 4H), 1.29 (m, 12H), 0.88 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 168.5, 168.4, 168.2, 146.4, 146.2, 146.1, 137.9, 137.7, 137.6, 137.5, 125.6, 125.5, 125.3, 125.2, 108.2, 108.1, 107.6, 107.5, 89.1, 88.8, 88.5, 85.9, 85.8, 85.7, 85.6, 36.8, 34.7, 34.2, 31.7, 31.6, 31.5, 31.4, 29.1, 29.0, 28.9, 28.8, 28.7, 27.8, 27.7, 27.6, 27.5, 27.1, 26.9, 22.6, 22.5, 22.4, 22.3, 21.0, 20.9, 20.6, 20.5, 19.2, 19.1, 18.4, 18.3, 15.5, 15.4, 14.0; IR (KBr) 2929, 2858, 2182, 1757, 1460, 1373, 1200, 1143, 875, 724 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{22}H_{35}O_2ClNa$ 389.2218, found 389.2217.

7,12-Dimethyloctadeca-7,11-dien-9-yne-8,11-diyl diacetate (**4f**): yellow oil (172 mg, 88%, 31/55/14 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.29 (m, 2H), 2.15 (d, J = 2.9 Hz, 6H), 2.05 (m, 2H), 1.90 (d, J = 2.4 Hz, 3H), 1.67 (s, 3H), 1.45 (m, 2H), 1.36 (m, 2H), 1.27 (m, 12H), 0.87 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.7, 168.6, 168.4, 168.3, 137.9, 137.8, 137.7, 137.6, 125.6, 125.5, 125.3, 125.2, 86.2, 86.1, 86.0, 85.8, 34.3, 34.2, 31.7, 31.6, 31.5, 31.4, 29.1, 28.9, 28.8, 27.6, 27.5, 27.0, 22.7, 22.6, 22.5, 20.6, 20.5, 18.5, 18.4, 15.5, 15.4, 14.1, 14.0; IR (KBr) 2928, 2859, 2186, 1767, 1460, 1371, 1204, 1123, 882, 728 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{24}H_{38}O_4Na$ 413.2662, found 413.2664.

4,7-Dichloro-2,3,8,9-tetramethyldeca-3,7-dien-5-yne (**2g**): yellow oil (107 mg, 83%, 23/60/17 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 3.21 (m, 2H), 1.91 (d, J = 4.4 Hz, 3H), 1.83 (s, 3H), 1.05 (d, J = 6.9 Hz, 6H), 1.02 (d, J = 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.4, 151.3, 150.6, 150.5, 107.3, 107.2, 106.2, 106.1, 89.1, 88.6, 88.3, 87.8, 34.0, 33.9, 31.2, 20.4, 20.4, 19.7, 15.8, 15.7, 14.0, 13.9; IR (KBr) 2959, 2872, 2185, 1721, 1462, 1376, 1247, 1167, 853, 751 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{14}H_{20}Cl_2$ 258.0942, found 258.0938.

7-Chloro-2,3,8,9-tetramethyldeca-3,7-dien-5-yn-4-yl acetate (**3g**): yellow oil (102 mg, 72%, 31/51/18 mixture of *EE*/(*EZ*,*ZE*)/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 3.15 (m, 1.6H), 2.85 (m, 0.4H), 2.18 (d, J = 1.3 Hz, 3H), 1.85 (m, 3H), 1.61 (s, 3H), 1.02 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.8, 168.7, 168.3, 168.2, 151.1, 150.4, 150.3, 142.6, 142.5, 142.3, 124.5, 124.4, 124.0, 123.9, 107.4, 107.3, 106.3, 106.2, 89.4, 88.9, 88.7, 88.1, 86.5, 86.0, 85.8, 85.3, 33.9, 31.4, 31.3, 31.1, 28.2, 20.6, 20.5, 20.4, 20.3, 20.1, 19.7, 15.8, 15.7, 13.9, 13.8, 13.4, 13.3, 10.4, 10.3; IR (KBr) 2968, 2875, 2187, 1766, 1463, 1370, 1283, 1202, 894, 782 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{16}H_{23}O_2ClNa$ 305.1279, found 305.1272.

2,3,8,9-Tetramethyldeca-3,7-dien-5-yne-4,7-diyl diacetate (**4g**): yellow oil (122 mg, 80%, 42/46/12 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 3.08 (m, 0.7H), 2.83 (q, J = 6.9 Hz, 1.3H), 2.16 (d, J = 3.1 Hz, 6H), 1.83 (d, J = 2.0 Hz, 3H), 1.59 (d, J = 8.0 Hz, 3H), 1.04 (d, J = 6.8 Hz, 4H), 0.97 (dd, J = 6.9, 1.7 Hz, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.8, 168.7, 168.4, 168.3, 142.6, 142.5, 142.3, 142.2, 124.5, 124.1, 124.0, 86.7, 86.2, 85.5, 31.4, 31.3, 28.2, 20.7, 20.6, 20.3, 20.0, 13.4, 13.3, 10.4, 10.3; IR (KBr) 2915, 2877, 2197, 1787, 1490, 1372, 1299, 1115, 878, 756 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{18}H_{26}O_4Na$ 329.1723, found 329.1721.

5,8-Dichloro-2,4,9,11-tetramethyldodeca-4,8-dien-6-yne (**2h**): yellow oil (122 mg, 85%, 23/59/18 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.28 (dd, J = 7.4, 1.8 Hz, 2H), 2.25 (dd, J = 7.4, 1.8 Hz, 2H), 2.00 (d, J = 3.2 Hz, 3H), 1.92 (d, J = 2.9 Hz, 3H), 1.90 (m, 2H), 0.94 (d, J = 6.6 Hz, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.8, 145.6, 145.5, 145.3, 108.8, 108.7, 108.4, 108.2, 89.0, 88.9, 88.5, 88.4, 45.8, 45.7, 43.6, 43.5, 27.5, 27.4, 27.2, 27.1, 22.5, 22.4, 22.3, 21.4, 21.3, 19.6, 19.5; IR (KBr) 2930, 2863, 1722, 1445, 1393, 1285, 1180, 866, 739 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{16}H_{24}Cl_2$ 286.1255, found 286.1256.

8-Chloro-2,4,9,11-tetramethyldodeca-4,8-dien-6-yn-5-yl acetate (**3h**): yellow oil (116 mg, 75%, 29/51/20 mixture of *EE*/(*EZ*,*ZE*)/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.21 (m, 6H), 1.96 (m, 2.4 H), 1.93 (m, 1.6 H), 1.89 (m, 1.6 H), 1.86 (m, 2H), 1.68 (m, 1.4 H), 0.91 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 168.4, 168.3, 168.2, 136.9, 136.7, 136.6, 136.4, 126.4, 126.3, 126.1, 126.0, 86.6, 86. 5, 86.0, 85.9, 43.4, 43.3, 40.6, 40.5, 27.1, 27.0, 26.7, 26.6, 22.6, 22.3, 20.7, 20.6, 20.5, 20.4, 18.7, 18.6, 15.9, 15.8; IR (KBr) 2988, 2898, 2153, 1754, 1687, 1422, 1381, 1222, 1150, 861, 745 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{18}H_{27}O_2ClNa$ 333.1592, found 333.1596.

2,4,9,11-Tetramethyldodeca-4,8-dien-6-yne-5,8-diyl diacetate (**4h**): yellow oil (137 mg, 82%, 34/53/13 mixture of *EE*/*EZ*/*ZZ* isomers); ^1H NMR (400 MHz, $CDCl_3$) δ 2.15 (m, 8H), 1.95 (d, J = 7.3, 2H), 1.89 (d, J = 3.7 Hz, 3H), 1.81 (m, 2H), 1.65 (s, 3H), 0.93 (d, J = 6.6 Hz, 6H), 0.86 (d, J = 6.6 Hz, 6H); ^{13}C NMR (100 MHz,

dx.doi.org/10.1021/jo400276e | J. Org. Chem. 2013, 78, 4580−4586

$CDCl_3$) δ 168.6, 168.4, 168.3, 168.2, 136.9, 136.7, 136.6, 136.4, 126.4, 126.3, 126.1, 126.0, 86.6, 86.5, 86.0, 85.9, 43.4, 43.3, 40.6, 40.5, 27.1, 27.0, 26.7, 26.6, 22.6, 22.3, 20.7, 20.6, 20.5, 20.4, 18.7, 18.6, 15.9, 15.8; IR (KBr) 2958, 2872, 2189, 1766, 1463, 1371, 1201, 1127, 888, 795 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{20}H_{30}O_4Na$ 357.2036, found 357.2039.

*(1,4-Dichloro-5-methylhex-4-en-2-yn-1-ylidene)cyclohexane (**2i**):* yellow oil (111 mg, 92%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.45 (m, 4H), 2.02 (s, 3H), 1.95 (s, 3H), 1.60 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.2, 142.5, 107.7, 104.6, 88.5, 88.0, 33.4, 31.0, 27.4, 26.9, 26.0, 23.0, 21.2; IR (KBr) 2935, 2883, 2189, 1715, 1463, 1369, 1257, 1177, 827, 732 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{13}H_{16}Cl_2$ 242.0629, found 242.0628.

*4-Chloro-1-cyclohexylidene-5-methylhex-4-en-2-yn-1-yl acetate (**3i**) and 6-chloro-6-cyclohexylidene-2-methylhex-2-en-4-yn-3-yl acetate (**3i′**):* yellow oil (110 mg, 83%, **3i**/**3i′** = 1/2); ^1H NMR (400 MHz, $CDCl_3$) δ 2.42 (m, 3H), 2.18 (m, 4H), 1.99 (s, 1.7H), 1.96 (s, 1.3H), 1.93 (s, 1.7H), 1.72 (s, 1.3H), 1.60 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 168.5, 149.0, 142.2, 140.8, 133.9, 125.3, 122.3, 107.7, 104.7, 88.7, 88.4, 85.8 85.4, 33.3, 30.9, 30.8, 27.8, 27.3, 27.2, 26.9, 26.8, 26.1, 26.0, 23.0, 21.2, 20.6, 20.5, 20.4, 17.7; IR (KBr) 2933, 2893, 2189, 1755, 1466, 1371, 1200, 1178, 880, 712 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{15}H_{19}O_2ClNa$ 289.0966, found 289.0964.

*1-Cyclohexylidene-5-methylhex-4-en-2-yne-1,4-diyl diacetate (**4i**):* yellow oil (133 mg, 92%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.37 (m, 2H), 2.14 (d, *J* = 3.2 Hz, 6H), 2.12 (m, 1.6H), 2.07 (br, 0.4H), 1.91 (s, 3H), 1.68 (s, 3H), 1.61 (m, 2H), 1.52 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 168.5, 140.8, 133.9, 125.3, 122.3, 85.9, 85.7, 30.8, 27.8, 27.1, 26.8, 26.1, 20.7, 20.6, 20.5, 17.7; IR (KBr) 2925, 2876, 2192, 1767, 1465, 1370, 1207, 1123, 869, 743 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{17}H_{22}O_4Na$ 313.1410, found 313.1412.

*4-Chloro-1-cyclohexylidene-5-phenylhex-4-en-2-yn-1-yl acetate (**3j**) and 6-chloro-6-cyclohexylidene-2-phenylhex-2-en-4-yn-3-yl acetate (**3j′**):* yellow oil (74 mg, 45%); ^1H NMR (400 MHz, $CDCl_3$) δ 7.32 (m, 5H), 2.48 (m, 4H), 2.30 (s, 3H), 1.99 (s, 3H), 1.61 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.3, 149.9, 138.0, 135.7, 129.3, 128.2, 128.0, 127.8, 127.5, 90.2, 86.3, 33.5, 31.0, 27.4, 26.9, 26.0, 20.7, 17.9; IR (KBr) 2189, 1755, 1510, 1371, 1200, 1176, 961, 880, 812 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{20}H_{21}O_2ClNa$ 351.1122, found 351.1120.

*6-Chloro-2,7-dimethylocta-2,6-dien-4-yn-3-yl propionate (**5a**):* yellow oil (96 mg, 80%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.46 (q, *J* = 7.6 Hz, 2H), 1.99 (s, 3H), 1.95 (s, 3H), 1.92 (s, 3H), 1.71 (s, 3H), 1.21 (t, *J* = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.0, 142.2, 133.7, 125.3, 107.7, 88.6, 85.7, 27.4, 23.0, 21.2, 20.6, 17.6, 9.1; IR (KBr) 2981, 2873, 1752, 1634, 1468, 1380, 1271, 1159, 845, 707 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{13}H_{17}O_2ClNa$ 263.0809, found 263.0806.

*2,7-Dimethylocta-2,6-dien-4-yne-3,6-diyl dipropionate (**6a**):* yellow oil (125 mg, 90%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.45 (q, *J* = 7.6 Hz, 4H), 1.93 (s, 6H), 1.68 (s, 6H), 1.19 (t, *J* = 7.6 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.9, 133.6, 125.4, 86.0, 27.3, 20.6, 17.6, 9.1; IR (KBr) 2972, 2910, 2210, 1751, 1450, 1395, 1308, 1266, 1212, 1103, 862, 767 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{16}H_{22}O_4Na$ 301.1410, found 301.1410.

*6-Chloro-2,7-dimethylocta-2,6-dien-4-yn-3-yl butyrate (**5b**):* yellow oil (104 mg, 82%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.40 (t, *J* = 7.4 Hz, 2H), 1.97 (s, 3H), 1.94 (s, 3H), 1.91 (s, 3H), 1.72 (m, 2H), 1.70 (s, 3H), 0.99 (t, *J* = 7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.1, 142.1, 133.6, 125.3, 107.7, 88.6, 85.7, 35.8, 22. 9, 21.1, 20. 6, 18.5, 17.6, 13.6; IR (KBr) 2988, 2868, 1755, 1645, 1480, 1368, 1277, 1171, 882, 756 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{14}H_{19}O_2ClNa$ 277.0966, found 277.0960.

*2,7-Dimethylocta-2,6-dien-4-yne-3,6-diyl dibutyrate (**6b**):* yellow oil (144 mg, 94%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.37 (t, *J* = 7.4 Hz, 4H), 1.89 (s, 6H), 1.66 (m, 10H), 0.95 (t, *J* = 7.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.3, 133.5, 125.3, 85.9, 35.9, 20.5, 18.4, 17.5, 13.5; IR (KBr) 2936, 2888, 1761, 1667, 1479, 1375, 1266, 1125, 956 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{18}H_{26}O_4Na$ 329.1723, found 329.1725.

*6-Chloro-2,7-dimethylocta-2,6-dien-4-yn-3-yl pentanoate (**5c**):* yellow oil (113 mg, 84%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.43 (t, *J* = 7.4 Hz, 2H), 1.98 (s, 3H), 1.95 (s, 3H), 1.92 (s, 3H), 1.71 (s, 3H), 1.68 (m, 2H), 1.39 (m, 2H), 0.93 (t, *J* = 7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.4, 142.1, 133.6, 125.3, 107.7, 88.6, 85.7, 33.7, 27.0, 22.9, 22.2, 21.1, 20.6, 17.6, 13.7; IR (KBr) 2968, 2852, 1758, 1650, 1473, 1355, 1261, 1158, 868, 742 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{15}H_{21}O_2ClNa$ 291.1122, found 291.1126.

*2,7-Dimethylocta-2,6-dien-4-yne-3,6-diyl dipentanoate (**6c**):* yellow oil (150 mg, 90%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.41 (t, *J* = 7.4 Hz, 4H), 1.92 (s, 6H), 1.68 (s, 6H), 1.66 (m, 4H), 1.40 (m, 4H), 0.92 (t, *J* = 7.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.2, 133.4, 125.4, 86.0, 33.7, 27.0, 22.2, 20.6, 17.6, 13.7; IR (KBr) 2930, 2876, 1764, 1682 1475, 1382, 1268, 1142, 946 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{20}H_{30}O_4Na$ 357.2036, found 357.2034.

*6-Chloro-2,7-dimethylocta-2,6-dien-4-yn-3-yl isobutyrate (**5d**):* yellow oil (10 mg, 81%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.69 (m, 1H), 1.98 (s, 3H), 1.96 (s, 3H), 1.92 (s, 3H), 1.71 (s, 3H), 1.25 (d, *J* = 7.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 142.1, 133.5, 125.3, 107.8, 88.5, 85.8, 33.9, 22.9, 21.2, 20.7, 18.9, 17.5; IR (KBr) 2980, 2946, 2902, 2235, 1751, 1461, 1442, 1375, 1339, 1317, 1235, 1112, 881, 759 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{14}H_{19}O_2ClNa$ 277.0966, found 277.0968.

*2,7-Dimethylocta-2,6-dien-4-yne-3,6-diyl bis(2-methylpropanoate) (**6d**):* yellow oil (136 mg, 89%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.65 (m, 2H), 1.91 (s, 6H), 1.67 (s, 6H), 1.92 (s, 3H), 1.22 (d, *J* = 7.0 Hz, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 133.1, 125.4, 85.9, 33.9, 20.6, 18.8, 17.4; IR (KBr) 2966, 2931, 2925, 2218, 1750, 1473, 1441, 1385, 1331, 1300, 1245, 1108, 857 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{18}H_{26}O_4Na$ 329.1723, found 329.1722.

*6-Chloro-2,7-dimethylocta-2,6-dien-4-yn-3-yl pivalate (**5e**):* yellow oil (106 mg, 79%); ^1H NMR (400 MHz, $CDCl_3$) δ 1.97 (d, *J* = 8.0 Hz, 6H), 1.92 (s, 3H), 1.70 (s, 3H), 1.24 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 175.9, 141.8, 133.2, 125.5, 107.8, 88.4, 85.8, 38.9, 26.5, 22.9, 21.1, 20.6, 17.4; IR (KBr) 2995, 2956, 2908, 2240, 1766, 1489, 1452, 1399, 1351, 1302, 1255, 1119, 892, 782 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{15}H_{21}O_2ClNa$ 291.1122, found 291.1120.

*2,7-Dimethylocta-2,6-dien-4-yne-3,6-diyl bis(2,2-dimethylpropanoate) (**6e**):*[7g] White solid (154 mg, 92%), mp =75−76 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 1.89 (s, 6H), 1.66 (s, 6H), 1.21 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 175.7, 132.6, 125.6, 85.8, 38.8, 26.9, 20.5, 17.3; IR (KBr) 2972, 2936, 2910, 2210, 1760, 1468, 1450, 1395, 1355, 1308, 1266, 1103, 862 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{20}H_{30}O_4$ 334.2144, found 334.2146.

*3,6-Dibromo-2,7-dimethylocta-2,6-dien-4-yne (**7**):* light yellow solid (137 mg, 94%), mp 88−89 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 2.04 (s, 6H), 1.97 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.1, 95.8, 90.1, 24.2, 23.4; IR (KBr) 2938, 2866, 2188, 1752, 1471, 1390, 1255, 1160, 767, 650 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{10}H_{12}Br_2$ 289.9306, found 289.9308.

*6-Bromo-2,7-dimethylocta-2,6-dien-4-yn-3-yl acetate (**8**):* light yellow oil (117 mg, 87%); ^1H NMR (400 MHz, $CDCl_3$) δ 2.18 (s, 3H), 2.00 (s, 3H), 1.95 (d, *J* = 6.0 Hz, 6H), 1.72 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.5, 145.0, 133.9, 125.3, 95.9, 90.0, 86.0, 24.1, 23.4, 20.6, 17.7; IR (KBr) 2966, 2856, 1765, 1622, 1462, 1375, 1269, 1113, 802, 681 cm^{-1}; HRMS (ESI/[M + Na]$^+$) calcd for $C_{12}H_{15}O_2BrNa$ 293.0148, found 293.0152.

*(2,7-Dimethylocta-2,6-dien-4-yne-3,6-diyl)dibenzene (**9**):* pale yellow solid (117 mg, 82%), mp 95−96 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.30 (m, 6H), 7.25 (m, 4H), 2.09 (s, 6H), 1.81 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.4, 139.8, 129.2, 127.9, 126.5, 119.7, 93.4, 24.1, 21.5; IR (KBr) 2914, 2139, 1730, 1643, 1462, 1375, 1266, 1123, 874, 746, 545 cm^{-1}; HRMS (EI/[M]$^+$) calcd for $C_{22}H_{22}$ 286.1722, found 286.1726.

*2,7-Dimethyl-6-phenylocta-2,6-dien-4-yn-3-yl acetate (**10**):* light yellow solid (114 mg, 85%), mp 88−89 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.30 (m, 4H), 7.23 (m, 1H), 2.12 (d, *J* = 8.3 Hz, 6H), 1.91 (s, 3H), 1.81 (s, 3H), 1.68 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 143.6, 139.0, 131.2, 129.2, 128.0, 126.8, 126.2, 118.8, 93.6, 85.8, 24.1, 21.6, 20.6, 17.6; IR (KBr) 2915, 2197, 1769, 1490, 1447, 1372,

dx.doi.org/10.1021/jo400276e | J. Org. Chem. 2013, 78, 4580−4586

1299, 1207, 1115, 958, 878, 756, 693 cm^{-1}; HRMS (ESI/$[M + Na]^+$) calcd for $C_{18}H_{20}O_2Na$ 291.1356, found 291.1355.

2,7-Dimethyl-6-(phenylethynyl)octa-2,6-dien-4-yn-3-yl acetate (11): light yellow solid (128 mg, 88%), mp 101−102 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.45 (m, 2H), 7.31 (m, 3H), 2.19 (s, 3H), 2.12 (s, 3H), 2.08 (s, 3H), 1.99 (s, 3H), 1.72 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.7, 154.7, 132.5, 131.4, 128.2, 128.1, 125. 8, 123.4, 101.1, 91.3, 89.6, 86.0, 84.6, 22.9, 20.6, 17.6; IR (KBr) 2925, 2346, 2192, 1767, 1465, 1370, 1201, 1123, 1089, 802, 743, 665 cm^{-1}; HRMS (ESI/$[M + Na]^+$) calcd for $C_{20}H_{20}O_2Na$ 315.1356, found 315.1358.

■ ASSOCIATED CONTENT

Supporting Information

Text and figures giving ^1H and ^{13}C NMR spectra for compounds **1b,e−m**, **2a−i**, **3a−j**, **4a−i**, **5a−e**, **6a−e**, and **7−11** and additional characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*H.J.: e-mail, jianghf@scut.edu.cn; fax and tel, (+86) 20-87112906.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (21202046 and 20932002), the National Basic Research Program of China (973 Program) (2011CB808600), the Changjiang Scholars and Innovation Team Project of Ministry of Education, the Guangdong Natural Science Foundation (S2012040007088), the China Postdoctoral Science Foundation (2012T50673 and 2011M501318), and the Fundamental Research Funds for the Central Universities (2012ZP0003 and 2012ZB0011).

■ REFERENCES

(1) Nicolaou, K. C.; Edmonds, D. J.; Bulger, P. G. *Angew. Chem., Int. Ed.* **2006**, *45*, 7134−7186.

(2) (a) *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E.-i., Ed.; Wiley Interscience: New York, 2002. For selected examples, see: (b) Wang, Z.; Lu, X. *J. Org. Chem.* **1996**, *61*, 2254−2255. (c) Wang, Z.; Zhang, Z.; Lu, X. *Organometallics* **2000**, *19*, 775−780. (d) Liu, G.; Lu, X. *Org. Lett.* **2001**, *3*, 3879−3882. (e) Tong, X.; Beller, M.; Tse, M. K. *J. Am. Chem. Soc.* **2007**, *129*, 4906−4907. (f) Feng, C.; Loh, T.-P. *J. Am. Chem. Soc.* **2010**, *132*, 17710−17712. (g) Zhou, F.; Han, X.; Lu, X. *J. Org. Chem.* **2011**, *76*, 1491−1494.

(3) (a) Nielsen, M. B.; Diederich, F. *Chem. Rev.* **2005**, *105*, 1837−1868. (b) Martin, R. E.; Diederich, F. *Angew. Chem., Int. Ed.* **1999**, *38*, 1350−1377. (c) Salaneck, W. R.; Lundström, I.; Rånby, B. *Conjugated Polymers and Related Materials*; Oxford University Press: Oxford, U.K., 1993. (d) Skotheim, T. A.; Elsenbaumer, R. L.; Reynolds, J. R. *Handbook of Conducting Polymers*, 2nd ed.; Marcel Dekker: New York, 1997.

(4) (a) Xi, Z.; Goldberg, I. H. In *Comprehensive Natural Product Chemistry*; Barton, D. H., Nakanishi, R. K., Eds.; Pergamon: Oxford, U.K., 1999; Vol. 7, p 553. (b) Grissom, J. W.; Gunawardena, G. U.; Klingberg, D.; Huang, D. *Tetrahedron* **1996**, *52*, 6453−6518. (c) Dai, W.-M.; Nicolaou, K. C. *Angew. Chem., Int. Ed.* **1991**, *30*, 1387−1416.

(5) For selected examples, see: (a) Kido, Y.; Yamaguchi, M. *J. Org. Chem.* **1998**, *63*, 8086−8087. (b) Martin, R. E.; Gubler, U.; Cornil, J.; Balakina, M.; Boudon, M.; Bosshard, C.; Gisselbrecht, J.; Diederich, F.; Günter, P.; Gross, M.; Brédas, J. *Chem. Eur. J.* **2000**, *6*, 3622−3635. (c) Camacho, D. H.; Saito, S.; Yamamoto, Y. *J. Am. Chem. Soc.* **2002**, *124*, 924−925. (d) Takayama, Y.; Delas, C.; Muraoka, K.; Uemura, M.; Sato, F. *J. Am. Chem. Soc.* **2003**, *125*, 14163−14167. (e) Nakano, Y.; Ishizuka, K.; Muraoka, K.; Ohtani, H.; Takayama, H.; Sato, F. *Org. Lett.* **2004**, *6*, 2373−2376.

(6) For selected examples, see: (a) Wu, W.; Jiang, H. *Acc. Chem. Res.* **2012**, *45*, 1736−1748. (b) Zhou, P.; Huang, L.; Jiang, H.; Wang, A.; Li, X. *J. Org. Chem.* **2010**, *75*, 8279−8282. (c) Zhou, P.; Zheng, M.; Jiang, H.; Li, X.; Qi, C. *J. Org. Chem.* **2011**, *76*, 4759−4763. (d) Wu, W.; Jiang, H.; Gao, Y.; Huang, H.; Zeng, W.; Cao, D. *Chem. Commun.* **2012**, *48*, 10340−10342.

(7) (a) Katz, T. J.; Yang, G. X.; Rickman, B. H.; Iwashita, T. *J. Am. Chem. Soc.* **1993**, *115*, 2038−2039. (b) Trost, B. M.; Kottirsch, G. *J. Am. Chem. Soc.* **1990**, *112*, 2816−2818. (c) Zhao, Y.; Tykwinski, R. R. *J. Am. Chem. Soc.* **1999**, *121*, 458−459. (d) Kim, M.; Miller, R. L.; Lee, D. *J. Am. Chem. Soc.* **2005**, *127*, 12818−12819. (e) Hoshi, M.; Nakayama, H.; Shirakawa, K. *Synthesis* **2005**, 1991−2007. (f) Cho, E. J.; Kim, M.; Lee, D. *Eur. J. Org. Chem.* **2006**, 3074−3078. (g) Ohe, K.; Fujita, M.; Matsumoto, M.; Tai, Y.; Miki, K. *J. Am. Chem. Soc.* **2006**, *128*, 9270−9271. (h) Wang, E.; Fu, X.; Xie, X.; Chen, J.; Gao, H.; Liu, Y. *Tetrahedron Lett.* **2011**, *52*, 1968−1972. (i) Huang, G.; Xie, K.; Lee, D.; Xia, Y. *Org. Lett.* **2012**, *14*, 3850−3853.

(8) See the Supporting Information for details.

(9) (a) Jiang, H.; Liu, X.; Zhou, L. *Chem. Eur. J.* **2008**, *14*, 11305−11309. (b) Jiang, H.; Qiao, C.; Liu, W. *Chem. Eur. J.* **2010**, *16*, 10968−10970. (c) Jiang, H.; Gao, Y.; Wu, W.; Huang, Y. *Org. Lett.* **2013**, *15*, 238−241.

(10) (a) Takahashi, Y.; Tsutsumi, K.; Nakagai, Y.; Morimoto, T.; Kakiuchi, K.; Ogoshi, S.; Kurosawa, H. *Organometallics* **2008**, *27*, 276−280. (b) Lee, D.; Kim, M. *Org. Biomol. Chem.* **2007**, *5*, 3418−3427.

(11) (a) Rautenstrauch, V. *J. Org. Chem.* **1984**, *49*, 950−952. (b) Caruana, P. A.; Frontier, A. J. *Tetrahedron* **2007**, *63*, 10646−10656.

(12) (a) Nakamura, I.; Bajracharya, G. B.; Mizushima, Y.; Yamamoto, Y. *Angew. Chem., Int. Ed.* **2002**, *41*, 4328−4331. (b) Jiang, H.; Pan, X.; Huang, L.; Zhao, J.; Shi, D. *Chem. Commun.* **2012**, *48*, 4698−4700.