Tetrahedron 69 (2013) 5178–5184

Contents lists available at SciVerse ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Sonogashira/hydroarylation sequential reactions: catalyzed by NHC–Pd complexes

Longguang Yang [a], Yunfei Li [a], Qian Chen [a], Yufeng Du [a], Changsheng Cao [a,*], Yanhui Shi [a,b,*], Guangsheng Pang [c]

[a] College of Chemistry and Chemical Engineering and Jiangsu Key Laboratory of Green Synthetic Chemistry for Functional Materials, Jiangsu Normal University, Xuzhou 221116, PR China
[b] State Key Laboratory of Coordination Chemistry, Nanjing University, Nanjing 210093, PR China
[c] State Key Laboratory of Inorganic Synthesis and Preparative Chemistry, Jilin University, Changchun 130012, PR China

ARTICLE INFO

Article history:
Received 26 January 2013
Received in revised form 2 April 2013
Accepted 15 April 2013
Available online 18 April 2013

Keywords:
Sonogashira reaction
Hydroarylation
Carbenes
Palladium complexes

ABSTRACT

It was found that an air-stable NHC–palladium complex of Pd[(s)-3-C_3H_5-4-($C_5H_5CH_2$)-1-(2,6-$^iPr_2C_6H_3$)-$C_3H_3N_2$](C_5H_5N)Br_2 derived from L-phenylalanine is an effective pre-catalyst for copper-free and phosphine-free Sonogashira reaction of alkynes under aerobic conditions in short reaction time. Moreover, the palladium compound would be reused to catalyze the hydroarylation of alkyne prepared from Sonogashira reaction, which makes firstly Sonogashira/Hydroarylation sequential reactions successful. The arylation of alkynes underwent with a high regio- and stereoselectivity and only trans-arylation of alkyne was observed. No *Z*/*E* isomerization of the olefin was observed in the system.

1. Introduction

Palladium catalyzed copper-free Sonogashira coupling reaction[1] and the hydroarylation of alkynes[2] are extremely powerful tools for constructing compounds with unsaturated carbon–carbon bonds, which are often encountered in nature products, biologically important molecules, agrochemicals as well as fine chemicals.[3] Although the *N*-heterocyclic carbenes (NHCs) have been used widely in organometallic chemistry and catalysis,[4] comparison to reports of phosphine based Pd catalyst for Sonogashira reaction, considerably fewer studies have appeared using NHC based Pd catalyst. However, unlike their phosphine analogs, inexpensive Pd–NHC complexes are very user friendly due to their significant air and moisture stability, and less toxicity. Consequently, the development of air-stable, robust, and well-defined NHC–Pd complexes for a copper-free Sonogashira reaction is an important objective in this effort.[5] As alkyne is the starting material of the hydroarylation and commercially available alkynes are limited, it is interesting and necessary to develop a practical procedure of Sonogashira/hydroarylation sequential reactions, realizing the reuse of Pd catalyst. Although various of hydroarylation of alkynes have been reported so far,[6] to the best of our knowledge, no Sonogashira/hydroarylation sequential reactions of alkynes have been studied. The possible reason for this is that these two reactions require very different conditions. Excessive base should be used in Sonogashira reaction, whereas, the hydroarylation of alkynes is promoted by Lewis acid,[6d,7] and even carried out in strong protonic acid some times.[2b] Therefore, most catalysts would lose activity in these two conflicting conditions.

On the extension of our work in exploring efficient catalysts for copper-free phosphine-free Sonogashira coupling reaction under aerobic conditions, a new efficient NHC–palladium catalyst was reported herein. Furthermore, we would like to report for the first time palladium catalyzed Sonogashira/hydroarylation sequential reactions.

2. Results and discussion

In our previous study, palladium–NHC complexes derived from L-phenylanaline have been successfully applied to copper-free phosphine-free Sonogashira reaction.[8] Benzyl Pd complex (**1**) (Fig. 1) showed the best catalytic activity in all catalysts studied, and we suggest the possible reason is the weak π donation properties of benzene, which stabilizes the highly reactive low-valent catalytic intermediate. Because the allyl group is a good π or σ donor, it is

* Corresponding authors. Tel./fax: +86 516 8350 0349; e-mail address: yhshi@jsnu.edu.cn (Y. Shi).

0040-4020/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tet.2013.04.061

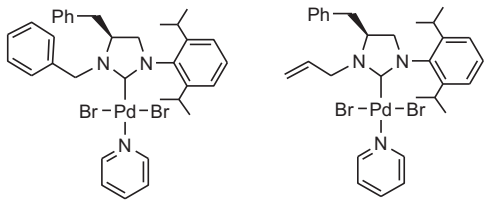
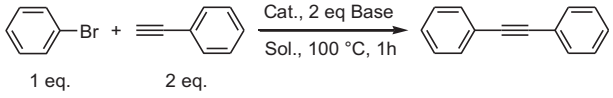


Fig. 1. Pd–NHC catalyst.

interesting to synthesize allyl complex (**2**) and investigate its catalytic performance in the Sonogashira reaction.[9]

To prove our hypothesis that **2** would be a better pre-catalyst for the Sonogashira reaction, we compared the catalytic activity of complex **1** and **2** in the reaction of bromobenzene with phenylacetylene. The reactions were conducted with 1 mol % **1** or **2** in DMSO and K_2CO_3 as base under aerobic conditions, which were the optimized conditions for **1** catalyzed Sonogashira reaction according to our previous study.[8] The results were presented in Table 1. To our delight, complex **2** gave the higher yield of desired product than complex **1** did (entry 1 vs 2). The common Pd salts, such as $Pd(OAc)_2$ and $PdCl_2$ didn't work at all at the tested conditions (entries 3 and 4).

Table 1
Sonogashira coupling reactions under different conditions



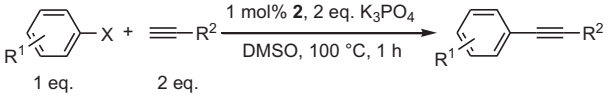
Entry	Cat. (mol %)	Base	Solvent	Yield[a] (%)
1	**1** (1)	K_2CO_3	DMSO	31
2	**2** (1)	K_2CO_3	DMSO	43
3	$PdCl_2$(1)	K_2CO_3	DMSO	0
4	$Pd(OAc)_2$(1)	K_2CO_3	DMSO	0
5	**2** (1)	K_2CO_3	DMF	25
6	**2** (1)	K_2CO_3	DMSO:H_2O=3:1	34
7	**2** (1)	K_2CO_3	DMF:H_2O=3:1	30
8	**2** (1)	K_2CO_3	THF	0
9	**2** (1)	K_2CO_3	Toluene	0
10	**2** (1)	K_2CO_3	Dioxane	0
11	**2** (1)	Cs_2CO_3	DMSO	60
12	**2** (1)	KOH	DMSO	38
13	**2** (1)	$K_3PO_4 \cdot 3H_2O$	DMSO	62
14	**2** (1)	Et_3N	DMSO	32
15	**2** (1)	K_3PO_4	DMSO	80
16	**2** (0.5)	K_3PO_4	DMSO	48
17	**1** (1)	K_3PO_4	DMSO	42

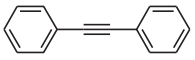
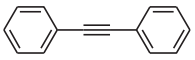
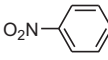
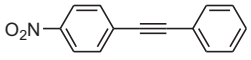
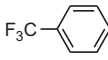
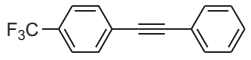
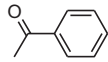
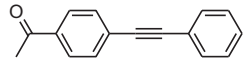
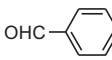
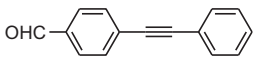
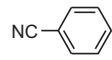
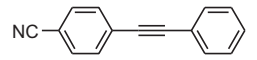
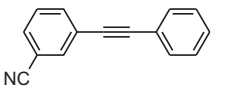
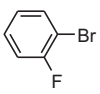
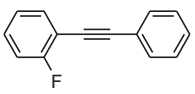
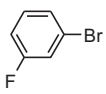
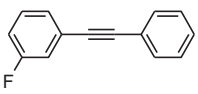
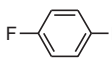
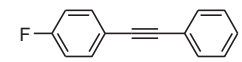
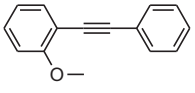
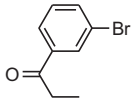
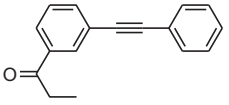
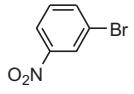
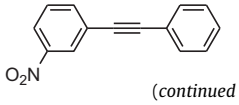
[a] Determined by GC–MS with 1,2,3,4-tetrahydronaphthalene as an internal standard.

As the solvent normally is a very important parameter determining cross-coupling efficiency, we tested the reaction catalyzed by **2** in different solvents (entries 1 and 5–10). The results showed that DMSO is the best solvent tested, and relatively low yield was observed in DMF or a mixed solvent of DMF with water (3:1). No product was even observed in THF, toluene or dioxane as solvent at all. Furthermore, the same model systems were used to evaluate the influence base on the reaction (entries 1 and 11–15). The results show that among the bases employed, anhydrous K_3PO_4 is the most suitable base. Stronger bases, such as KOH and Cs_2CO_3 lead to lower yields even compared to $K_3PO_4 \cdot 3H_2O$. Low yield was observed with organic base, Et_3N as well. Reducing the amount of catalyst to 0.5 mol % would decrease the yield to 48% (entry 16). Therefore, the optimum reaction conditions for the copper-free Sonogashira coupling reaction catalyzed by **2** were conducted with 1 mol % of **2** in DMSO and K_3PO_4 as base under aerobic conditions. Under this optimized conditions, the result of reaction catalyzed by **1** further proved that the complex **2** is more efficient catalyst than complex **1** (entry 15 vs 17).

To probe the substrate scope of the reaction, many aryl iodides and bromides were chosen to react with different terminal alkynes under the optimized conditions. The results were presented in Table 2. The results showed that the Pd–NHC can not only catalyze the reaction with more reactive aryl iodides, but also can catalyze

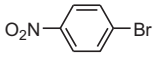
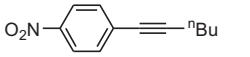
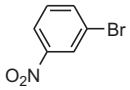
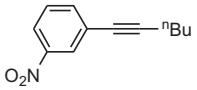
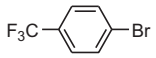
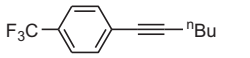
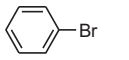
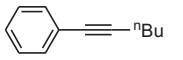
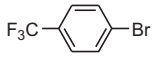
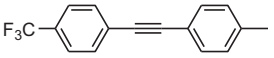
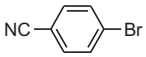
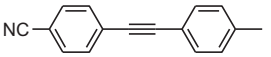
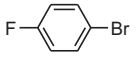
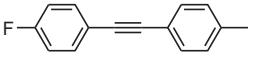
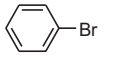
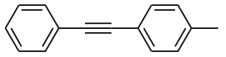
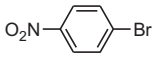
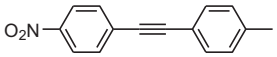
Table 2
Probe the substrate scope of the Sonogashira reaction catalyzed by **2**



Entry[a]	Aryl halide	R^2	Product	**3** Yield (%)[b]
1		Ph		73 (**3a**)
2		Ph		81 (**3a**)
3		Ph		96 (**3b**)
4		Ph		93 (**3c**)
5		Ph		94 (**3d**)
6		Ph		95 (**3e**)
7		Ph		94 (**3f**)
8		Ph		96 (**3g**)
9		Ph		82 (**3h**)
10		Ph		84 (**3i**)
11		Ph		86 (**3j**)
12		Ph		78 (**3k**)
13		Ph		90 (**3l**)
14		Ph		91 (**3m**)

(*continued on next page*)

Table 2 (*continued*)

Entry[a]	Aryl halide	R^2	Product	**3** Yield (%)[b]
15		^{n}Bu		99 (**3n**)
16		^{n}Bu		99 (**3o**)
17		^{n}Bu		99 (**3p**)
18		^{n}Bu		82 (**3q**)
19		*p*-Tol		97 (**3r**)
20		*p*-Tol		95 (**3s**)
21		*p*-Tol		88 (**3t**)
22		*p*-Tol		77 (**3u**)
23		*p*-Tol		98 (**3v**)

[a] Reaction conducted with 0.01 mmol of **2**, 1 mmol of aryl halides, 2 mmol of alkyne and 2 mmol of K_3PO_4 in 2 mL of DMSO.
[b] Isolated yield on average of two runs.

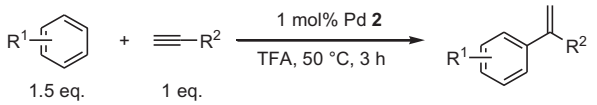
the reaction in good to excellent yield (73%–99%) with less reactive aryl bromides in the absence of copper co-catalysis. The higher yield was obtained for aryl bromides with strong electron-withdrawing group compared to that with weaker electron-withdrawing group (like entry 3 vs entry 11).

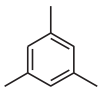
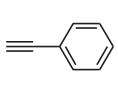
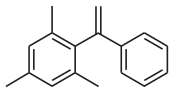
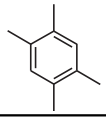
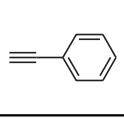
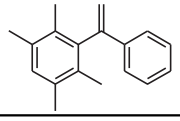
The reaction of aryl bromides with aliphatic alkynes, like 1-hexyne led better results, compared to that with aromatic alkynes (entries 1 and 22 vs entry 18, and entries 4 and 19 vs entry 17). All the reactions tested were very fast, and they can be completed within 1 h. Unfortunately, the tested reactions of phenylacetylene with phenyl chloride could not proceed under this conditions.

To develop a practical Sonogashira/hydroarylation reaction, we tested the catalytic activity of **2** in the hydroarylation of phenylacetylene with mesitylene and 1,2,4,5-tetramethylbenzene in the first stage of our work.[2b,10] The reaction was carried out with 1 mol % of **2** in 2 mL of trifluoroacetic acid (TFA) as solvent at 50 °C under aerobic atmosphere. To our delight, the reactions occurred with a highly regioselectivity and completed within 3 h. The steric hindered Markovnikov product was the only product to be isolated in high yield, as shown in Table 3.

It is interesting to see if Sonogashira/Hydroarylation of alkyne can be performed in a two-step one-pot process. After the completion of the coupling reaction of phenyl iodine with phenylacetylene under optimized conditions, mesitylene and TFA were added directly to the cooled reaction mixture. Unfortunately, when the mixture was heated at 50 °C for 3 h, no addition product of arene to internal alkyne was detected. Firstly we thought the Pd catalyst may lose the activity, so another 1 mol % of **3a** was added with mesitylene and TFA into the reaction vessel. However, still no

Table 3
Hydroarylation of phenylacetylene with arene



Entry[a]	Ar–H	Alkyne	Product	**4** Yield (%)[b]
1				91 (**4a**)
2				84 (**4b**)

[a] Reaction conducted with 1 mmol of phenylacetylene, 1.5 mmol of arene and 0.01 mmol of catalyst **2** in 2 mL of TFA.
[b] Isolated yield on average of two runs.

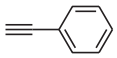
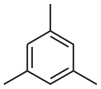
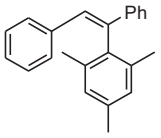
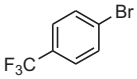
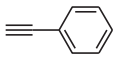
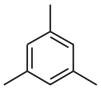
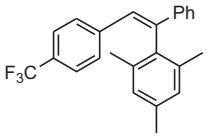
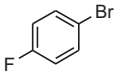
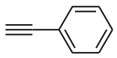
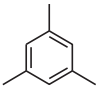
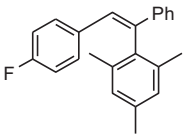
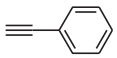
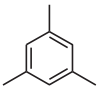
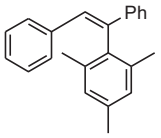
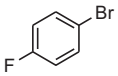
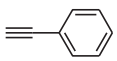
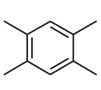
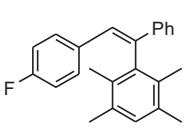
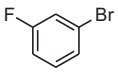
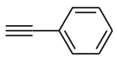
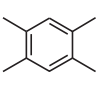
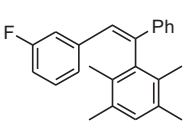
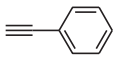
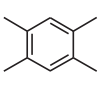
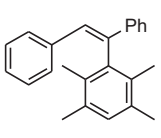
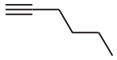
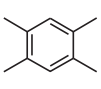
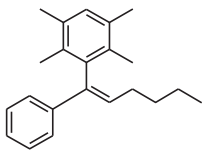
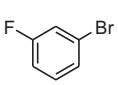
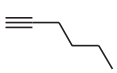
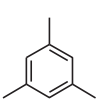
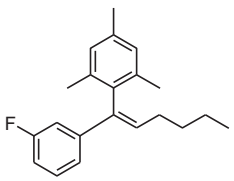
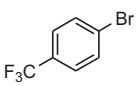
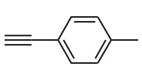
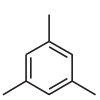
arylation was taken place. Then, we guessed probably the left base and DMSO would hinder the arylation reaction. Therefore, we tried the reaction in a two-step one catalyst process. After the completion of coupling reaction of phenyl iodine with phenylacetylene, mesitylene and TFA were added into the reaction mixture in which inorganic salts and DMSO were washed away with saturated brine. Remarkably, the trans-addition *Z*-isomer as the only product was isolated in 89% yield after the mixture was heated at 50 °C for 3 h (Table 4, entry 1). Therefore, the Pd complex could survive under two different conditions and successively catalyze the two reactions.

The scope and generality of this reaction also have been explored by the reaction of various aryl halides, alkynes, with several arenes (Table 4). If the aryl halides have substitute, such as CN, NO_2, CHO, and COMe, the Sonogashira reaction went well, whereas, the alkyne arylation could not occur. A reasonable explanation is that the unsaturated bond in these groups deactivated cationic Pd(II) catalytic species. The reaction is quite general with respect to the internal alkyne, both arylalkyne and alkylalkyne worked well. It was reported that the yield increased with increasing number of electron rich substituents on arenes.[6c,d,11] It is not so obvious in our catalytic system and even benzene gave good yields too. Interestingly, the reaction underwent with a high regio- and stereoselectivity and yielded the trans-hydroarylation product in high yields; whilst, either *Z* or *E* isomer was isolated in good selectivity. No *Z*/*E* isomerization of the olefin was observed in this protocol and no other stereo- or regioisomers were isolated from the reaction mixture. The regio- and stereochemistry of the products were established on the basis of chemical shifts in ^{1}H NMR compared with those of known compounds. The structures (shown in Fig. 2) of (*Z*)-3-(2-(3-fluorophenyl)-1-phenylvinyl)-1,2,4,5-tetramethylbenzene (**5e**) were further confirmed to be in the *Z*-configuration by X-ray crystal structure analysis. The regiochemistry of the products is dominated by electronic effects of the substituents in alkyne, aryl group is added to the alkynyl carbon substituted electron rich phenyl group.

3. Conclusion

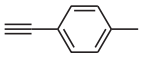
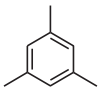
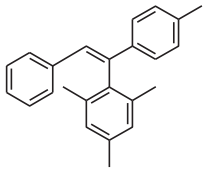
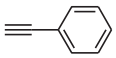
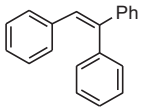
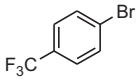
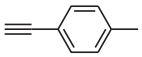
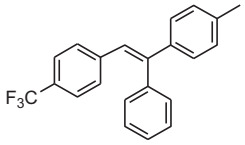
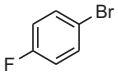
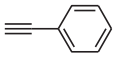
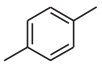
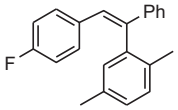
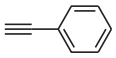
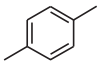
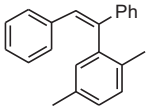
Complex **2** showed good catalytic activity in Cu-free Sonogashira coupling reaction and Sonogashira/hydroarylation of alkynes sequential reaction. All reactions were very fast, the Sonogashira reaction can be completed within 1 h under aerobic conditions, and alkyne hydroarylation was only required 3 h. The arylation underwent with a high regio- and stereoselectivity and yielded trans-hydroarylation product as a sole isomer in high yields.

Table 4
Sonogashira/hydroarylation sequential reaction of alkyne with arene

Entry	Aryl halide	Alkyne	Ar–H	Product	**5** Yield (%)[a]
1					89 (**5a**)
2					83 (**5b**)
3					77 (**5c**)
4					65 (**5a**)
5					73 (**5d**)
6					69 (**5e**)
7					95 (**5f**)
8					73 (**5g**)
9					76 (**5h**)
10					87 (**5i**)

(*continued on next page*)

Table 4 (*continued*)

Entry	Aryl halide	Alkyne	Ar–H	Product	**5** Yield (%)[a]
11					70 (**5j**)
12					61 (**5k**)
13					75 (**5l**)
14					73 (**5m**)
15					62 (**5n**)

[a] Isolated yield on average of two runs.

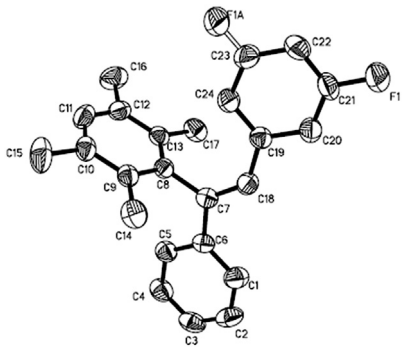


Fig. 2. ORTEP structure of complex **5e** showing 30% probability ellipsoids; hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and bond angles (°): C(6)–C(7) 1.495(3), C(7)–C(8) 1.505(3), C(7)–C(18) 1.334(4), C(18)–C(19) 1.480(3), C(6)–C(7)–C(8) 116.9(2), C(6)–C(7)–C(18) 121.0(2), C(8)–C(7)–C(18) 122.1(2), C(7)–C(18)–C(19) 130.5(2).

4. Experimental

4.1. General

The NHC–palladium complex **2** was prepared according to our previous reports.[8,9] All other reagents were commercially sourced and were used without further purification. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker DPX 400 MHz spectrometer at room temperature and referenced to the residual signals of the solvent. Elemental analyses were performed on a EuroVektor Euro EA-300 elemental analyzer. X-ray crystallography was conducted on a Rigaku Mercury CCD device with graphite-monochromated Mo Kα radiation (λ=0.71073 Å). Absorption correction was performed using the SADABS program. The structure was solved by directed methods using the SHELXS-97 program and refined by full-matrix least squares techniques on F^2.

4.2. Catalysis-general procedure

4.2.1. Sonogashira reactions. In a typical run, a 4 mL vial equipped with a magnetic stirrer bar was charged with a mixture of aryl halide (1 mmol), alkyne (2 mmol), Pd catalyst (0.01 mmol), K_3PO_4 (2 mmol), and 2 mL of DMSO in air. The mixture was stirred at 100 °C for 1 h, then cooled to room temperature and brine was added into it. The resulting mixture was extracted with ethyl acetate three times, and the crude product was obtained by removing the volatiles. The product was purified by flash column chromatography on silica gel.

4.2.2. Hydroarylation reactions. After the Sonogashira reaction was completed, brine was added to cool the reaction mixture. The resulting solution was extracted with ethyl acetate three times, and the organic phase was combined. Arene (1 mmol) and TFA (2 mL) was added to the residue after the volatiles were removed, and the mixture was stirred at 50 °C for 3 h. After the pH of the resulting mixture was adjusted by aqueous NaOH solution until pH reached 11–12, the mixture was extracted with ethyl acetate three times. The crude product was obtained by removing the

volatiles and the product was purified by flash column chromatography on silica gel.

*4.2.3. 1,2-Diphenylethyne (**3a**).*[1d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.53–7.55 (m, 4H), 7.34–7.36 (m, 6H).

*4.2.4. 1-Nitro-4-(phenylethynyl)benzene (**3b**).*[1d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.22 (d, *J*=8.0 Hz, 2H), 7.67 (d, *J*=4.0 Hz, 2H), 7.55–7.57 (m, 2H), 7.39–7.40 (m, 3H).

*4.2.5. 1-(Phenylethynyl)-4-(trifluoromethyl)benzene (**3c**).*[11a] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.59–7.64 (m, 4H), 7.54–7.59 (m, 2H), 7.36–7.38 (m, 3H).

*4.2.6. 1-(4-(Phenylethynyl)phenyl)ethanone (**3d**).*[11a] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.94 (d, *J*=8.0 Hz, 2H), 7.61 (d, *J*=8.0 Hz, 2H), 7.54–7.56 (m, 2H), 7.36–7.38 (m, 3H), 2.62 (s, 3H).

*4.2.7. 4-(Phenylethynyl)benzaldehyde (**3e**).*[1d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 10.02 (s, 1H), 7.87 (d, *J*=8.0 Hz, 2H), 7.68 (d, *J*=8.0 Hz, 2H), 7.55–7.57 (m, 2H), 7.37–7.38 (m, 3H).

*4.2.8. 4-(Phenylethynyl)benzonitrile (**3f**).*[1d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.59–7.65 (m, 4H), 7.53–7.55 (m, 2H), 7.37–7.39 (m, 3H).

*4.2.9. 3-(Phenylethynyl)benzonitrile (**3g**).*[11a] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.81 (s, 1H), 7.74 (d, *J*=4.0 Hz, 1H), 7.60 (d, *J*=8.0 Hz, 1H), 7.53–7.55 (m, 2H), 7.46 (t, *J*=8.0 Hz, 1H), 7.37–7.38 (m, 3H).

*4.2.10. 1-Fluoro-2-(phenylethynyl)benzene (**3h**).*[11b] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.51–7.52 (m, 2H), 7.29–7.34 (m, 5H), 7.21 (d, *J*=8.0 Hz, 1H), 7.02 (br, 1H).

*4.2.11. 1-Fluoro-3-(phenylethynyl)benzene (**3i**).*[11c] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.48–7.54 (m, 3H), 7.26–7.32 (m, 4H), 7.06–7.12 (m, 2H).

*4.2.12. 1-Fluoro-4-(phenylethynyl)benzene (**3j**).*[11c] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.50–7.53 (m, 4H), 7.34–7.35 (m, 3H), 7.05 (t, *J*=8.0 Hz, 2H).

*4.2.13. 1-Methoxy-2-(phenylethynyl)benzene (**3k**).*[11d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.48–7.51 (m, 3H), 7.40–7.43 (m, 3H), 7.04 (t, *J*=8.0 Hz, 1H), 6.84–6.94 (m, 2H), 3.88 (s, 3H).

*4.2.14. 1-(3-(Phenylethynyl)phenyl)propan-1-one (**3l**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.12 (s, 1H), 7.92 (d, *J*=8.0 Hz, 1H), 7.70 (d, *J*=8.0 Hz, 1H), 7.55 (dd, *J*=8.0 Hz, *J*=4.0 Hz, 2H), 7.45 (t, *J*=8.0 Hz, 1H), 7.38–7.35 (m, 3H), 3.05–2.99 (m, 2H), 1.24 (t, *J*=8.0 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): 154.3, 151.8, 141.6, 138.8, 127.2, 126.4, 125.6, 125.1, 56.1, 49.2, 34.1, 32.1.

*4.2.15. 1-Nitro-3-(phenylethynyl)benzene (**3m**).*[11a] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.38 (s, 1H), 8.18 (d, *J*=8.0 Hz, 1H), 7.82 (d, *J*=8.0 Hz, 1H), 7.56–7.51 (m, 3H), 7.39–7.33 (t, *J*=4.0 Hz, 3H).

*4.2.16. 1-(Hex-1-ynyl)-4-nitrobenzene (**3n**).*[11e] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.14 (d, *J*=8.0 Hz, 2H), 7.51 (d, *J*=8.0 Hz, 2H), 2.45 (t, *J*=8.0 Hz, 2H), 1.64-1.57 (m, 2H), 1.52-1.43 (m, 2H), 0.95 (t, *J*=8.0 Hz, 3H).

*4.2.17. 1-(Hex-1-ynyl)-3-nitrobenzene (**3o**).*[11f] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.22 (s, 1H), 8.10 (d, *J*=8.0 Hz, 1H), 7.67 (d, *J*=8.0 Hz, 1H), 7.44 (t, *J*=8.0 Hz, 1H), 2.42 (t, *J*=4.0 Hz, 2H), 1.63–1.56 (m, 2H), 1.51–1.45 (m, 2H), 0.95 (t, *J*=8.0 Hz, 3H).

*4.2.18. 1-(Hex-1-ynyl)-4-(trifluoromethyl)benzene (**3p**).*[11g] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.53 (d, *J*=8.0 Hz, 2H), 7.47 (d, *J*=8.0 Hz, 2H), 2.42 (t, *J*=8.0 Hz, 2H), 1.62–1.56 (m, 2H), 1.50–1.45 (m, 2H), 0.95 (t, *J*=8.0 Hz, 3H).

*4.2.19. Hex-1-ynylbenzene (**3q**).*[11e] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.39 (d, *J*=8.0 Hz, 2H), 7.29–7.26 (m, 3H), 2.41 (t, *J*=8.0 Hz, 2H), 1.62–1.55 (m, 2H), 1.50–1.45 (m, 2H), 0.95 (t, *J*=8.0 Hz, 3H).

*4.2.20. 1-Methyl-4-((4-(trifluoromethyl)phenyl)ethynyl)benzene (**3r**).*[11d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.60 (d, *J*=4.0 Hz, 4H), 7.44 (d, *J*=8.0 Hz, 2H), 7.18 (d, *J*=8.0 Hz, 2H), 2.38 (s, 3H).

*4.2.21. 4-(p-Tolylethynyl)benzonitrile (**3s**).*[11h] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.63–7.57 (m, 4H), 7.43 (d, *J*=8.0 Hz, 2H), 7.18 (d, *J*=8.0 Hz, 2H), 2.38 (s, 3H).

*4.2.22. 1-Fluoro-4-(p-tolylethynyl)benzene (**3t**).*[11i] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.52–7.48 (m, 2H), 7.41 (d, *J*=8.0 Hz, 2H), 7.16 (d, *J*=8.0 Hz, 2H), 7.04 (t, *J*=8.0 Hz, 2H), 2.37 (s, 3H).

*4.2.23. 1-Methyl-4-(phenylethynyl)benzene (**3u**).*[11d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.53 (d, *J*=8.0 Hz, 2H), 7.43 (d, *J*=8.0 Hz, 2H), 7.34 (d, *J*=8.0 Hz, 3H), 7.16 (d, *J*=8.0 Hz, 2H), 2.37 (s, 3H).

*4.2.24. 1-Methyl-4-((4-nitrophenyl)ethynyl)benzene (**3v**).*[11j] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.21 (d, *J*=8.0 Hz, 2H), 7.65 (d, *J*=8.0 Hz, 2H), 7.45 (d, *J*=8.0 Hz, 2H), 7.19 (d, *J*=8.0 Hz, 2H), 2.39 (s, 3H).

*4.2.25. 1,3,5-Trimethyl-2-(1-phenylvinyl)benzene (**4a**).*[6a] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.26 (d, *J*=4.0 Hz, 4H), 7.24-7.22 (m, 1H), 6.90 (s, 2H), 5.94 (s, 1H), 5.08 (s, 1H), 2.31 (s, 3H), 2.10 (s, 6H).

*4.2.26. 1,2,4,5-Tetramethyl-3-(1-phenylvinyl)benzene (**4b**).*[6a] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.26 (d, *J*=4.0 Hz, 4H), 7.23 (t, *J*=4.0 Hz, 1H), 6.96 (s, 1H), 5.96 (s, 1H), 5.05 (s, 1H), 2.23 (s, 6H), 2.03 (s, 6H).

*4.2.27. (Z)-2-(1,2-Diphenylvinyl)-1,3,5-trimethylbenzene (**5a**).*[2b] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.34–7.25 (m, 5H), 7.14 (d, *J*=4.0 Hz, 4H), 6.97–6.91 (m, 4H), 2.35 (s, 3H), 2.00 (s, 6H).

*4.2.28. (Z)-1,3,5-Trimethyl-2-(1-phenyl-2-(4-(trifluoromethyl)phenyl)vinyl)benzene (**5b**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.39–7.28 (m, 7H), 7.15 (s, 1H), 7.23 (d, *J*=8.0 Hz, 2H), 6.94 (s, 2H), 2.36 (s, 3H), 1.99 (s, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): 142.6, 140.9, 137.4, 135.9, 135.4, 129.0, 128.7, 128.5, 128.0, 126.5, 126.2, 125.3, 125.2, 21.3, 19.8. Anal. Calcd for $C_{24}H_{21}F_3$ (366.42 g/mol): C, 78.67; H, 5.78. Found: C, 78.24; H, 5.69.

*4.2.29. (Z)-2-(2-(4-Fluorophenyl)-1-phenylvinyl)-1,3,5-trimethylbenzene (**5c**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.32–7.28 (m, 3H), 7.15–7.08 (m, 3H), 7.01–6.94 (m, 6H), 2.36 (s, 3H), 2.00 (s, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): 138.8, 137.4, 137.1, 136.0, 135.8, 129.8, 129.5, 129.3, 127.7, 127.6, 127.1, 126.0, 115.5, 115.3, 21.3, 19.8. Anal. Calcd for $C_{23}H_{21}F$ (316.41 g/mol): C, 87.31; H, 6.69. Found: C, 86.95; H, 6.48.

*4.2.30. (Z)-3-(2-(4-Fluorophenyl)-1-phenylvinyl)-1,2,4,5-tetramethylbenzene (**5d**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.32–7.27 (m, 3H), 7.11 (t, *J*=8.0 Hz, 3H), 6.98 (t, *J*=8.0 Hz, 2H), 6.91–6.78 (m, 3H), 2.24 (s, 6H), 1.94 (s, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): 140.0, 138.7, 137.4, 134.2, 131.7, 130.9, 128.6, 128.3, 127.8, 127.7, 127.0, 126.1, 115.4, 115.2, 20.3, 16.2. Anal. Calcd for $C_{24}H_{23}F$ (330.44 g/mol): C, 87.23; H, 7.02. Found: C, 86.94; H, 7.11.

*4.2.31. (Z)-3-(2-(3-Fluorophenyl)-1-phenylvinyl)-1,2,4,5-tetramethylbenzene (**5e**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.33–7.24 (m, 5H), 7.10–7.05 (m, 2H), 7.01 (s, 1H), 6.80–6.72 (m, 2H), 6.51 (d, *J*=8.0 Hz, 1H), 2.23 (s, 6H), 1.93 (s, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): 142.6, 141.4, 139.8, 139.7, 138.4, 134.3, 131.1, 129.5, 128.6, 127.6, 126.6,

126.3, 124.7, 114.9, 113.9, 20.3, 16.2. Anal. Calcd for $C_{24}H_{23}F$ (330.44 g/mol): C, 87.23; H, 7.02. Found: C, 87.01; H, 7.12.

*4.2.32. (Z)-3-(1,2-Diphenylvinyl)-1,2,4,5-tetramethylbenzene (**5f**).*[2b] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.34–7.24 (m, 5H), 7.15 (s, 1H), 7.11 (d, J=8.0 Hz, 3H), 7.00 (s, 1H), 6.91 (d, J=8.0 Hz, 2H), 2.23 (s, 6H), 1.94 (s, 6H).

*4.2.33. (Z)-1,2,4,5-Tetramethyl-3-(1-phenylhex-1-enyl)benzene (**5g**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.23–7.16 (m, 5H), 6.94 (s, 1H), 6.28 (t, J=4.0 Hz, 1H), 2.24 (s, 6H), 1.98 (s, 6H), 1.84–1.79 (m, 2H), 1.40–1.35 (m, 2H), 1.30–1.29 (m, 2H), 0.86–0.82 (m, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): 141.0, 139.9, 133.5, 132.1, 130.2, 129.5, 128.3, 126.6, 125.9, 31.5, 29.8, 29.4, 22.6, 20.3, 16.4, 14.1. Anal. Calcd for $C_{22}H_{28}$ (292.46 g/mol): C, 90.35; H, 9.65. Found: C, 90.03; H, 9.74.

*4.2.34. (Z)-2-(1-(3-Fluorophenyl)hex-1-enyl)-1,3,5-trimethylbenzene (**5h**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.21–7.15 (m, 1H), 6.96 (d, J=8.0 Hz, 1H), 6.91–6.84 (m, 4H), 6.29 (t, J=8.0 Hz, 1H), 2.32 (s, 3H), 2.04 (s, 6H), 1.89–1.83 (m, 2H), 1.42–1.35 (m, 2H), 1.31–1.26 (m, 2H), 0.85 (t, J=8.0 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): 143.2, 143.1, 137.8, 136.5, 136.2, 135.4, 130.9, 129.7, 129.6, 128.3, 121.3, 113.5, 112.6, 31.5, 29.8, 29.4, 22.7, 21.2, 19.9, 14.1. Anal. Calcd for $C_{21}H_{25}F$ (296.42 g/mol): C, 85.09; H, 8.50. Found: C, 84.78; H, 8.61.

*4.2.35. (Z)-1,3,5-Trimethyl-2-(1-p-tolyl-2-(4-(trifluoromethyl)phenyl)vinyl)benzene (**5i**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.37 (d, J=8.0 Hz, 2H), 7.24 (s, J=8.0 Hz, 2H), 7.13 (d, J=4.0 Hz, 3H), 7.02 (d, J=8.0 Hz, 2H), 6.94 (s, 2H), 2.36 (s, 6H), 1.99 (s, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): 142.5, 141.1, 138.0, 137.9, 137.3, 135.9, 135.5, 129.4, 129.0, 128.5, 126.1, 125.6, 125.2, 21.3, 21.2, 19.8. Anal. Calcd for $C_{25}H_{23}F_3$ (380.45 g/mol): C, 78.93; H, 6.09. Found: C, 78.76; H, 6.15.

*4.2.36. (Z)-1,3,5-Trimethyl-2-(2-phenyl-1-p-tolylvinyl)benzene (**5j**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.22 (d, J=8.0 Hz, 2H), 7.10 (s, 6H), 6.93 (d, J=8.0 Hz, 4H), 2.34 (s, 6H), 1.99 (s, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): 139.8, 138.7, 137.7, 137.2, 136.9, 136.1, 129.3, 128.8, 128.5, 128.3, 127.2, 126.9, 126.0, 21.3, 21.2, 19.9. Anal. Calcd for $C_{24}H_{24}$ (312.45 g/mol): C, 92.26; H, 7.74. Found: C, 91.97; H, 7.83.

*4.2.37. Ethene-1,1,2-triyltribenzene (**5k**).*[6d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.29 (s, 8H), 7.18 (s, 2H), 7.08 (s, 3H), 7.00 (d, J=4.0 Hz, 2H), 6.93 (s, 1H).

*4.2.38. (E)-1-Methyl-4-(1-phenyl-2-(4-(trifluoromethyl)phenyl)vinyl)benzene (**5l**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.39–7.32 (m, 6H), 7.23 (d, J=8.0 Hz, 1H), 7.18–7.13 (m, 4H), 7.07 (t, J=8.0 Hz, 2H), 6.94 (d, J=4.0 Hz, 1H), 2.38 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): 145.1, 143.2, 141.2, 140.1, 138.1, 136.7, 130.3, 129.7, 129.1, 128.3, 128.0, 127.9, 126.4, 125.8, 124.9, 21.4. Anal. Calcd for $C_{22}H_{17}F_3$ (338.37 g/mol): C, 78.09; H, 5.06. Found: C, 77.86; H, 5.15.

*4.2.39. (Z)-2-(2-(4-Fluorophenyl)-1-phenylvinyl)-1,4-dimethylbenzene (**5m**).* ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.30–7.23 (m, 3H), 7.14–7.07 (m, 4H), 6.99–6.91 (m, 6H), 2.27 (s, 3H), 1.97 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): 140.4, 139.3, 137.3, 136.0, 133.3, 130.6, 129.0, 128.6, 128.4, 128.2, 127.9, 127.5, 127.0, 126.6, 115.4, 115.1, 21.1, 19.2. Anal. Calcd for $C_{22}H_{19}F$ (302.38 g/mol): C, 87.38; H, 6.33. Found: C, 87.16; H, 6.40.

*4.2.40. (Z)-2-(1,2-Diphenylvinyl)-1,4-dimethylbenzene (**5n**).*[6d] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.33–7.22 (m, 5H), 7.13–7.04 (m, 6H), 6.95 (d, J=8.0 Hz, 3H), 2.26 (s, 3H), 1.98 (s, 3H).

Acknowledgements

We are grateful to the foundation of the National Natural Science Foundation of China (Grants 21071121 and 21172188), Scientific Research Foundation (SRF) for the Returned Overseas Chinese Scholars (ROCS), State Education Ministry (SEM), the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), 333 Project for the Cultivation of High-level Talents (33GC10002), and Graduate Foundation of Jiangsu Education Committee (CXLX11_0909) for financial support of this work.

Supplementary data

CCDC 900073 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html, or from the Cambridge Crystallographic Data Center, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44)1223-336-33; or e-mail: deposit@ccdc.cam.ac.uk.

References and notes

1. (a) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, *50*, 4467; (b) Hundermark, T.; Littke, A. F.; Buchwald, S. L.; Fu, G. C. *Org. Lett.* **2000**, *2*, 1729; (c) Bakherad, M.; Amin, A. H.; Keivanloo, A.; Bahramian, B.; Raeissi, M. *Tetrahedron Lett.* **2010**, *51*, 5653; (d) Samantaray, M. K.; Shaikh, M. M.; Ghosh, P. *J. Organomet. Chem.* **2009**, *694*, 3477; (e) Dash, C.; Shaikh, M. M.; Ghosh, P. *Eur. J. Inorg. Chem.* **2009**, *12*, 1608; (f) Roy, S.; Plenio, H. *Adv. Synth. Catal.* **2010**, *352*, 1014.
2. (a) Gonell, S.; Poyatos, M.; Mata, J. A.; Peris, E. *Organometallics* **2011**, *30*, 5985; (b) Viciu, M. S.; Stevens, E. D.; Petersen, J. L.; Nolan, S. P. *Organometallics* **2004**, *23*, 3752.
3. (a) Ren, T. *Chem. Rev.* **2008**, *108*, 4185; (b) Negishi, E. I.; Anastasia, L. *Chem. Rev.* **2003**, *103*, 1979; (c) Zapf, A.; Beller, M. *Top. Catal.* **2002**, *19*, 101; (d) Chinchilla, R.; Nájera, C. *Chem. Rev.* **2007**, *107*, 874; (e) Sonogashira, K. *J. Organomet. Chem.* **2002**, *653*, 46.
4. (a) Fortman, G. C.; Nolan, S. P. *Chem. Soc. Rev.* **2011**, *40*, 5151; (b) Diez-Gonzalez, S.; Marion, N.; Nolan, S. P. *Chem. Rev.* **2009**, *109*, 3612; (c) Arnold, P. L.; Casely, I. J. *Chem. Rev.* **2009**, *109*, 3599; (d) Enders, D.; Niemeier, O.; Henseler, A. *Chem. Rev.* **2007**, *107*, 5606; (e) Dröge, T.; Glorius, F. *Angew. Chem., Int. Ed.* **2010**, *49*, 6940; (f) Bugaut, X.; Glorius, F. *Chem. Soc. Rev.* **2012**, *41*, 3511; (g) Moore, J. L.; Rovis, T. *Top. Curr. Chem.* **2010**, *291*, 77.
5. (a) Gu, S.; Chen, W. *Organometallics* **2009**, *28*, 909; (b) Inés, B.; SanMartin, R.; Churruca, F.; Dominguez, E.; Urtiaga, M. K.; Arriortua, M. I. *Organometallics* **2008**, *27*, 2833; (c) Soheili, A.; Albanzeze-Walker, J.; Murry, J. A.; Dormer, P. G.; Hughes, D. L. *Org. Lett.* **2003**, *5*, 4191.
6. (a) Hashimoto, T.; Kutubi, S.; Izumi, T.; Rahman, A.; Kitamura, T. *J. Organomet. Chem.* **2010**, *696*, 99; (b) Choi, D. S.; Kim, J. H.; Shin, U. S.; Deshmukh, R. R.; Song, C. E. *Chem. Commun.* **2007**, 3482; (c) Yoon, M. Y.; Kim, J. H.; Choi, D. S.; Shin, U. S.; Lee, J. Y.; Song, C. E. *Adv. Synth. Catal.* **2007**, *349*, 1725; (d) Li, R.; Wang, S. R.; Lu, W. *Org. Lett.* **2007**, *9*, 2219; (e) Ritleng, V.; Sirlin, C.; Pfeffer, M. *Chem. Rev.* **2002**, *102*, 1731; (f) Merlic, C. A.; Pauly, M. E. *J. Am. Chem. Soc.* **1996**, *118*, 11319.
7. (a) Tsuchimoto, T.; Maeda, T.; Shirakawa, E.; Kawakami, Y. *Chem. Commun.* **2000**, 1573; (b) Song, C. E.; Jung, D.; Choung, S. Y.; Roh, E. J.; Lee, S. *Angew. Chem., Int. Ed.* **2004**, *43*, 6183.
8. Yang, L.; Guan, P.; He, P.; Chen, Q.; Cao, C.; Peng, Y.; Shi, Z.; Pang, G.; Shi, Y. *Dalton Trans.* **2012**, *41*, 5020.
9. Yang, L.; Li, Y.; Chen, Q.; Zhao, J.; Cao, C.; Shi, Y.; Pang, G. *Trans. Metal Chem.* **2013**, *38*, 367.
10. (a) Glorius, F. *Top. Organomet. Chem.* **2007**, *21*, 1; (b) Christmann, U.; Vilar, R. *Angew. Chem., Int. Ed.* **2005**, *44*, 366; (c) Fernandez-Rodriguez, M. A.; Hartwig, J. F. *J. Org. Chem.* **2009**, *74*, 1663; (d) Fernandez-Rodriguez, M. A.; Shen, Q.; Hartwig, J. F. *Chem.—Eur. J.* **2006**, *12*, 7782; (e) Fernandez-Rodriguez, M. A.; Shen, Q.; Hartwig, J. F. *J. Am. Chem. Soc.* **2006**, *128*, 2180.
11. (a) Guan, J. T.; Weng, T. Q.; Yu, G. A.; Liu, S. H. *Tetrahedron Lett.* **2007**, *48*, 7129; (b) Komáromi, A.; Tolnai, G. L.; Novák, Z. *Tetrahedron Lett.* **2008**, *49*, 7294; (c) Bandini, M.; Luque, R.; Budarin, V.; Macquarrie, D. J. *Tetrahedron* **2005**, *61*, 9860; (d) Thakur, K. G.; Jaseer, E. A.; Naidu, A. B.; Sekar, G. *Tetrahedron Lett.* **2009**, *50*, 2865; (e) Bakherad, M.; Keivanloo, A.; Bahramian, B.; Hashemi, M. *Tetrahedron Lett.* **2009**, *50*, 1557; (f) Sedelmeier, J.; Ley, S. V.; Lange, H.; Baxendale, I. R. *Eur. J. Org. Chem.* **2009**, 4412; (g) Shimada, T.; Yamamoto, Y. *J. Am. Chem. Soc.* **2002**, *124*, 12670; (h) Rao, M. L. N.; Jadhav, D. N.; Dasgupta, P. *Org. Lett.* **2010**, *12*, 2048; (i) Mino, T.; Shirae, Y.; Saito, T.; Sakamoto, M.; Fujita, T. *J. Org. Chem.* **2006**, *71*, 9499; (j) Gholap, A. R.; Venkatesan, K.; Pasricha, R.; Daniel, T.; Lahoti, R. J.; Srinivasan, K. V. *J. Org. Chem.* **2005**, *70*, 4869.