Tetrahedron 67 (2011) 318–325

Contents lists available at ScienceDirect

Tetrahedron

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

Silica supported palladium-phosphine complex: recyclable catalyst for Suzuki–Miyaura cross-coupling reactions at ambient temperature

Wei Chen [a], Pinhua Li [a,*], Lei Wang [a,b,*]

[a] Department of Chemistry, Huaibei Normal University, Huaibei, Anhui 235000, PR China
[b] State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, Shanghai 200032, PR China

ARTICLE INFO

Article history:
Received 12 July 2010
Received in revised form 1 November 2010
Accepted 9 November 2010
Available online 12 November 2010

Keywords:
Immobilized catalyst
Palladium-phosphine complex
Suzuki–Miyaura reactions
Recyclability

ABSTRACT

A new silica immobilized palladium-phosphine complex has been developed. It was found to be an efficient catalyst for Suzuki–Miyaura cross-coupling reactions under mild conditions. It is important to note that the supported catalyst could be reused at least 10 times without a significant loss of catalytic activity.

1. Introduction

The Suzuki–Miyaura reaction,[1] palladium-catalyzed cross-coupling of aryl halides with arylboronic acids, is one of the most valuable synthetic methods for the preparing symmetric and nonsymmetric biaryls, which are important skeletons in the structures of biologically active compounds,[2] agrochemicals, pharmaceuticals,[3] ligands,[4] and functional materials.[5] Over the past few decades, significant progresses in this area have been achieved with a variety of homogeneous catalysts.[6] Although homogeneous catalysts have many advantages, and homogeneous catalysts were difficult to be recovered and reused, and the residual Pd metal along with the products could induce serious problems in the synthesis of bioactive and functional substrates, and it could not be used in large-scale syntheses particular on environmental and economic concerns. To overcome these problems, the application of reusable and recoverable heterogeneous catalysts has recently attracted much attention due to the increasing worldwide momentum for the development of environmentally friendly reactions in terms of green chemistry.[7] In this context, a lot of efforts have been made to design and synthesize recoverable catalysts. Various inorganic and organic supports have been explored, such as mesoporous silica,[8] ionic liquids,[9] and polymers.[10] The grafting of such supports with homogeneous catalysts often provides good catalytic activity together with possible recovery of the catalyst system by simple conduction. More recently, new smart supports, such as magnetic nanoparticles (MNPs) have emerged and have great potential for catalyst recovery.[11]

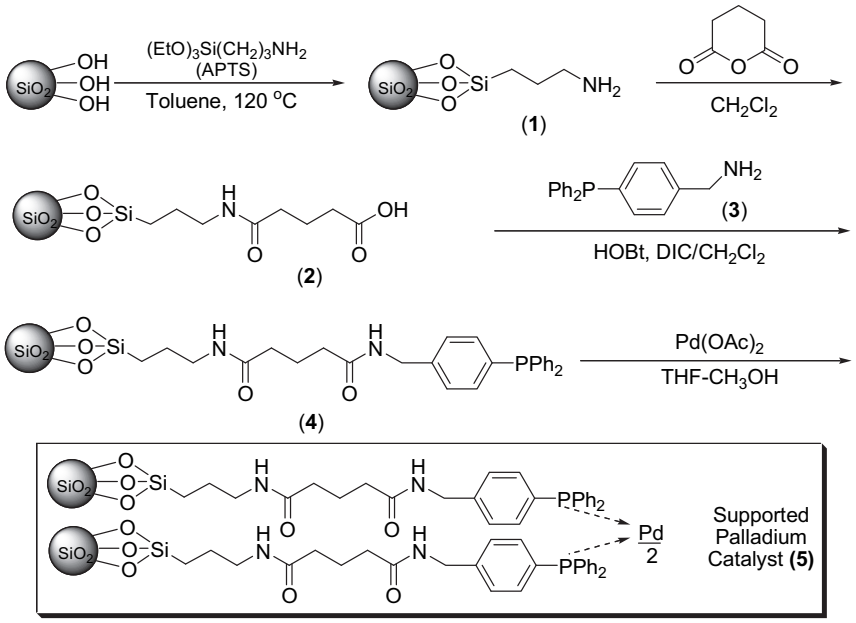
Thiel et al. have reported supported palladium-phosphine complex catalyzed Suzuki–Miyaura cross-coupling reaction, but the results were not representing the best of advance in this area.[12] In continuing our efforts to develop greener synthetic methodology for the organic transformations,[13] we here report the synthesis of a new, recoverable, and highly active silica anchored palladium-phosphine catalyst and its application for the Suzuki–Miyaura cross-coupling reactions in aqueous medium under aerobic condition (Scheme 1). The catalyst shows a high catalytic activity in the coupling reactions of various aryl halides and organoboronic acids. Easy catalyst recovery and excellent recycling efficiency of the catalyst make it as an ideal catalytic system for the coupling reactions in aqueous phase. It is important to note that the grafted catalyst could be recovered and reused at least 10 times without significant loss of its reactivity.

2. Results and discussion

The silica gel immobilized palladium catalyst was prepared according to the four-step procedure summarized in Scheme 1. The aminopropyl functionalized silica gel (**1**) was prepared through the reaction of a commercially available silica gel with 3-aminopropyltriethyoxylsilane (APTS) in refluxing toluene for 20 h, then it was isolated and washed subsequently with toluene, methanol, and

* Corresponding authors. Tel.: +86 561 3802 069; fax: +86 561 3090 518; e-mail address: leiwang@chnu.edu.cn (L. Wang).

0040-4020/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2010.11.042



Scheme 1.

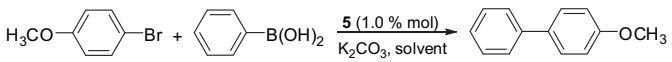
dichloromethane, and dried at 80 °C for 10 h under reduced pressure. The above aminopropyl functionalized silica gel (**1**) was subsequently reacted with glutaric anhydride in dichloromethane at room temperature with shaking for 24 h.

After the organics were filtered, the silica was washed with toluene, water, and methanol and dried in vacuum, carboxylic acid-functionalized silica gel (**2**) was obtained, and then the silica gel (**2**) reacted with phosphine (**3**) to generate the phosphine-functionalized silica gel (**4**). The obtained **4** then reacted with palladium(II) acetate in THF/CH_3OH at room temperature for 5 h to generate the silica supported palladium-phosphine complex, so called supported palladium catalyst (**5**).

Our initial investigation was directed toward exploring the reaction conditions for the model cross-coupling of phenylboronic acid with 4-bromoanisole in the presence of catalyst **5**. At first, the solvent effect was examined, and a significant solvent effect was observed (Table 1). The use of non-aqueous alcoholic solvents, such as MeOH, EtOH, and *i*-PrOH, resulted in excellent yields of the products (Table 1, entries 1–3). When the reactions were conducted in water, good yield of the product was obtained (Table 1, entry 4). While the reactions were carried out in aprotic polar solvents, such as THF, DMF, DMSO, CH_3CN, and 1,4-dioxane, moderate yields of the products were isolated (Table 1, entries 6–10).

Unfortunately, in nonpolar solvents, such as toluene and hexane, poor results were obtained (Table 1, entries 11 and 12). It was worth noting that the best result was observed when the reaction was performed in MeOH/H_2O (1:1, v/v) (Table 1, entry 5). Hence, the aqueous MeOH was finally selected as the solvent for the reaction because it is highly efficient, less expensive, and readily available. Our next studies focused on the effect of base. With regard to other reaction conditions, K_2CO_3 was found to act as an excellent base

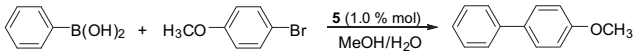
Table 1
Effect of the solvent on Suzuki–Miyaura reaction[a]



Entry	Solvent	Yield[b] [%]
1	MeOH	92
2	EtOH	89
3	*i*-PrOH	87
4	H_2O	80
5	MeOH/H_2O (1:1)	94
6	DMF	71
7	DMSO	68
8	CH_3CN	70
9	Dioxane	41
10	THF	47
11	Toluene	31
12	Hexane	19

[a] Reaction conditions: 4-bromoanisole (94 mg, 0.5 mmol), phenylboronic acid (72 mg, 0.6 mmol), supported palladium catalyst **5** (42.4 mg, containing Pd 0.005 mmol), K_2CO_3 (138 mg, 1.0 mmol) in solvent (2.0 mL) at room temperature for 4 h.
[b] Isolated yields.

Table 2
Effect of the base on Suzuki–Miyaura reaction[a]



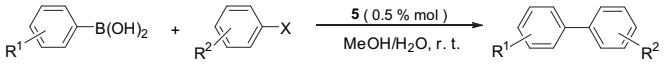
Entry	Bases	Yield[b] [%]
1	K_2CO_3	94
2	Na_2CO_3	89
3	Cs_2CO_3	88
4	K_3PO_4	93
5	KOAc	86
6	KF	81
7	TBAA	43
8	Et_3N	69
9	DBU	0
10[c]	K_2CO_3	95
11[d]	K_2CO_3	94
12[e]	K_2CO_3	72

[a] Reaction conditions: 4-bromoanisole (94 mg, 0.5 mmol), phenylboronic acid (72 mg, 0.6 mmol), supported palladium catalyst **5** (42.4 mg, containing Pd 0.005 mmol), base (1.0 mmol) in MeOH/H_2O (1:1, v/v, 2.0 mL) at room temperature for 4 h.
[b] Isolated yields.
[c] Supported palladium catalyst **5** (84.8 mg, containing Pd 0.01 mmol) was used.
[d] Supported palladium catalyst **5** (21.2 mg, containing Pd 0.0025 mmol) was used.
[e] Supported palladium catalyst **5** (10.6 mg, containing Pd 0.0005 mmol) was used, 12 h.

(Table 2, entry 1). Na_2CO_3, Cs_2CO_3, K_3PO_4, KOAc, and KF were also effective (Table 2, entries 2–6). Other bases, such as triethylamine and TBAA (tetra-*n*-butylammonium acetate) were substantially less effective (Table 2, entries 7 and 8). To our surprise, the reaction did not work when DBU (1,8-diazabicyclo [5.4.0] undec-7-ene) was used as base (Table 2, entry 9). We also have screened the amount of supported palladium catalyst, and 0.5 mol % loading of palladium was found to be optimal (Table 2, entries 10–12).

Having established a standard set of reaction conditions (0.5 mol % of supported palladium catalyst **5**, K_2CO_3, MeOH/H_2O (1:1, v/v), room temperature), several representative coupling reactions involving a variety of arylboronic acids and aryl halides were investigated, the results were illustrated in Table 3. A wide array of electronically diverse aryl iodides, bromides, and chlorides with phenylboronic acid were examined. As can be seen from Table 3, aryl iodides and bromides bearing electron-withdrawing and electron-donating groups coupled efficiently with phenylboronic acid, and generated the corresponding products in good to excellent yields within 4 h (Table 3, entries 1–5 and 9–17). 2-Bromopyridine and 3-bromopyridine were able to undergo the coupling reactions smoothly and generate the cross-coupling products in good yields (Table 3, entries 18 and 19). Unfortunately, the coupling reactions of aryl chlorides, such as 4-nitrocholorobenzene, 4-chloroacetophenone, and 4-choloroanisole with phenylboronic acid gave the poor results (Table 3, entries 21–23). On the other hand, arylboronic acids bearing electron-withdrawing and electron-donating groups also coupled efficiently with 4-bromoanisole within 4 h and good to excellent yields of the products were isolated (Table 3, entries 24–29). However, when thiophene-2-boronic acid was used as coupling partner, no desired product was obtained (Table 3, entry 32), because of poisoning of palladium catalyst on the sulfur atom.[14] The supported palladium-catalyzed cross-coupling could tolerate *ortho*-substituted aryl halides, as well as arylboronic acid (Table 3, entries 5, 6–7, 10, 25, 29–31). When the reactions of 2,4-dimethoxybenzeneboronic acid with iodobenzene, 2,4-dichlorobenzeneboronic acid with iodobenzene, 2-bromoanisole with phenylboronic acid, 2-methoxybenzeneboronic acid with 4-bromoanisole, and 2,4-dimethoxybenzeneboronic acid with bromobenzene were carried out under the present reaction conditions, the products were obtained in high yields (Table

Table 3
Suzuki–Miyaura coupling reaction of aryl halide with arylboronic acid[a]



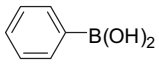
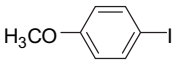
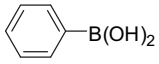
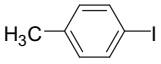
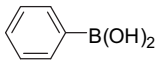
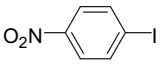
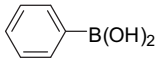
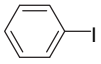
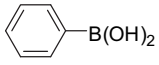
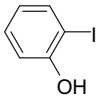
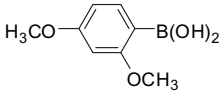
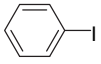
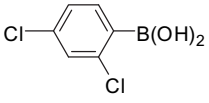
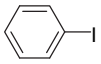
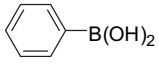
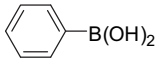
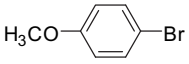
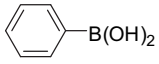
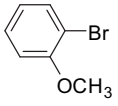
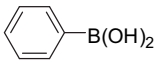
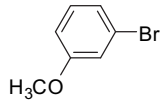
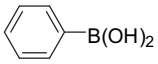
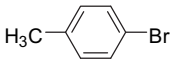
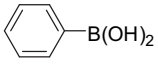
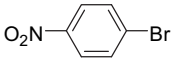
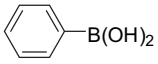
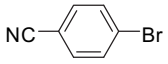
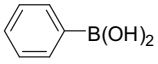
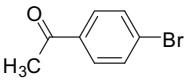
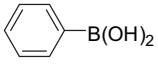
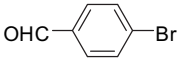
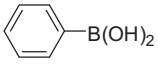
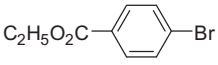
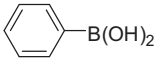
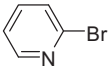
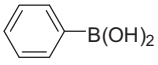
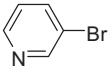
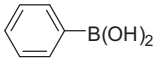
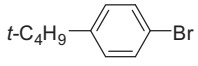
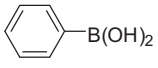
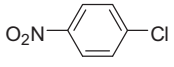
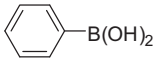
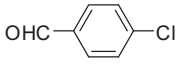
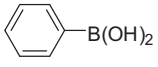
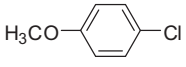
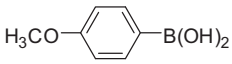
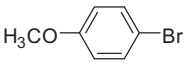
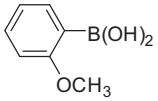
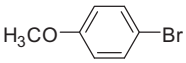
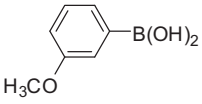
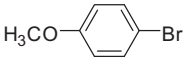
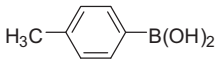
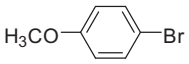
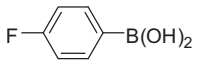
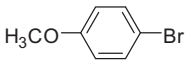
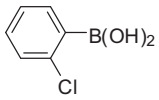
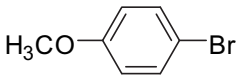
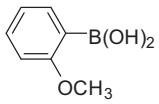
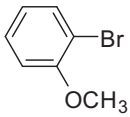
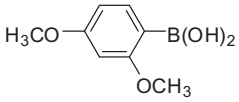
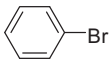
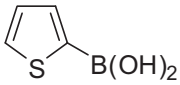
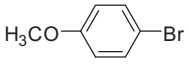
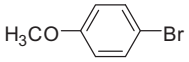
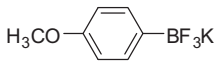
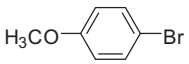
Entry	Arylboronic acid	Aryl halide	Product	Yield[b] [%]
1			**3a**	92
2			**3b**	91
3			**3c**	89
4			**3d**	93
5			**3e**	83
6			**3f**	94
7			**3g**	80
8			**3h**	77
9			**3a**	94
10			**3i**	86

Table 3 (*continued*)

Entry	Arylboronic acid	Aryl halide	Product	Yield[b] [%]
11			**3j**	88
12			**3b**	89
13			**3c**	84
14			**3k**	90
15			**3l**	87
16			**3m**	89
17			**3n**	86
18			**3o**	93
19			**3p**	89
20			**3q**	80
21[c]			**3c**	42
22[c]			**3m**	37
23[c]			**3a**	Trace
24			**3r**	87
25			**3s**	82
26			**3t**	84

(*continued on next page*)

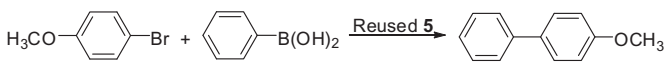
Table 3 (*continued*)

Entry	Arylboronic acid	Aryl halide	Product	Yield[b] [%]
27			**3u**	85
28			**3v**	91
29			**3w**	82
30			**3x**	79
31			**3f**	80
32			**3y**	0
33	Ph_4BNa		**3a**	86
34			**3r**	89

[a] Reaction conditions: aryl halide (0.5 mmol), organoboron compound (0.6 mmol), supported palladium catalyst **5** (25 mg, containing Pd 0.0025 mmol), K_2CO_3 (1.0 mmol) in MeOH/H_2O (1:1, v/v, 2.0 mL) at room temperature for 4 h.
[b] Isolated yields.

3, entries 6–7, 10, 25, and 31). Fortunately, the coupling reaction of 2-bromoanisole with 2-methoxyphenylboronic acid also provided the product in 79% yield (Table 3, entry 30). When 2,4-diiodobenzene reacted with phenylboronic acid (2 equiv), the corresponding product terphenyl was isolated in 77% yield (Table 3, entry 8). However, on further increasing the steric hindrance of the substrate, the catalytic activity decreased. 2,2′,6-Biphenyl derivatives and 2,2′,6,6′-biphenyl derivatives could not be obtained from the corresponding substrates under the present coupling reaction conditions. It was noteworthy that the present protocol is applicable even to sodium tetraphenylborate and potassium aryltrifluoroborate, they could also couple efficiently with 4-

Table 4
Successive trials by using recoverable catalyst **5**[a]



Entry	Yield[b] [%]	Entry	Yield[b] [%]
1	94	6	92
2	92	7	90
3	93	8	89
4	90	9	88
5	90	10	86

[a] Reaction conditions: 4-bromoanisole (94 mg, 0.5 mmol), phenylboronic acid (72 mg, 0.6 mmol), reused supported palladium catalyst **5** (42.4 mg, containing Pd 0.005 mmol), K_2CO_3 (138 mg, 1.0 mmol) in MeOH/H_2O (1:1, v/v, 2.0 mL) at room temperature for 4 h.
[b] Isolated yields.

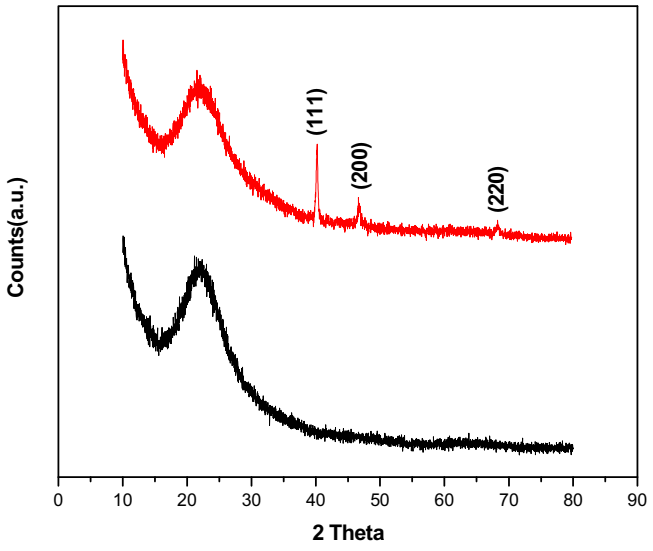


Fig. 1. Black line, XRD pattern of phosphine-functionalized silica gel **4**; red line, XRD pattern of silica supported Pd catalyst **5**.

bromoanisole and generate the cross-coupling products in good to excellent yields (Table 3, entries 33 and 34). When phenyl tosylate was used as one of the substrate, there was no desired product was observed.

The recyclability of supported palladium catalyst **5** was also surveyed. After carrying out the reaction, the reaction solution was vacuum-filtered using a sintered-glass funnel and washed with Et_2O (5.0 mL), water (5.0 mL), C_2H_5OH (5.0 mL), and Et_2O (5.0 mL). After being dried, the supported catalyst could be reused directly without further purification, and it could be recovered, recycled and used for 10 consecutive trials without loss of its catalytic activity (Table 4). Moreover, palladium leaching in catalyst **5** was also determined and ICP analysis of the clear filtrates indicated that Pd content is $<$0.30 ppm.

3. Conclusions

In summary, we have successfully developed a silica supported Pd–phosphine complex **5**, which was used as an efficient heterogeneous catalyst for Suzuki–Miyaura cross-coupling reaction in aqueous medium at ambient temperature. The catalyst shows not only high catalytic activity, but also offers many practical advantages, such as oxygen insensitivity, thermal stability, and recyclability. The catalyst could be reused for 10 consecutive cycles without a significant loss of its catalytic activity. These advantages make the process highly valuable from the synthetic and environmental points of view. Further investigation on the application of this kind of catalyst is in progress in our laboratory.

4. Experimental

4.1. General methods

Unless otherwise stated, all the reactions were carried out under an air atmosphere, and commercially obtained materials were used without further purification. Products were purified by flash chromatography on 230–400 mesh silica gel, SiO_2. All ^{1}H NMR, ^{13}C NMR spectra were measured on a Bruker Avance NMR spectrometer (400 MHz or 100 MHz, respectively) with $CDCl_3$ as solvent and recorded in parts per million relative to tetramethylsilane as internal standard. The CHN analysis was performed on a Vario El III elementar. The Pd content was determined by a Jarrell-Ash 1100 ICP analysis. The preparation of aminopropyl functionalized silica gel **1**, and carboxylic acid-functionalized silica gel **2** has been previously described,[15] and phosphine **3** was prepared according to the literature.[16]

4.2. Preparation of phosphine-functionalized silica gel 4

To a suspension of the carboxylic acid-functionalized silica gel **2** (2.0 g, the loading was 0.72 mmol/g) in dichloromethane (20 mL) were added *N*,*N*-diisopropylcarbodiimide (4.5 mmol), 1-hydroxybenzotriazole (4.5 mmol), triethylamine (4.5 mmol), and phosphine **3** (2.0 mmol). The mixture was shaken for 18 h at room temperature and filtered. The residue was washed with dichloromethane, THF, methanol and dried to constant weight in vacuum. Then 2.32 g of **4** was obtained. The loading of **4** was quantified via CHN microanalysis and was found to be 0.52 mmol/g based on the nitrogen content determination.

4.3. Preparation of supported palladium catalyst (5)

To a round-bottomed flask, palladium acetate (33.6 mg, 0.15 mmol) and THF/CH_3OH (v/v, 4/1, 10 mL) were added. The solution was stirred at room temperature under an inert atmosphere for 30 min, and then 1.0 g of the above phosphine-functionalized silica gel **4** was added. The mixture was stirred at room temperature for 5 h, then the organics were filtered, the solid was washed thoroughly with THF, and dried under vacuum at 60 °C for 3 h. A silica supported Pd catalyst **5** powder (1.11 g) was obtained with a loading of 0.118 mmol of palladium per gram determined via inductively coupled plasma atomic emission spectrometry (ICP-AES). IR (KBr): ν Si–O 1083 cm^{-1}, ν C=O 1673 cm^{-1}, ν C–H 2938 cm^{-1}, ν N–H 3329 cm^{-1}. XRD measurements of supported palladium catalyst (**5**) exhibit diffraction peaks corresponding to the typical structure of palladium particles formed and seem consistent with that of metallic palladium (Fig. 1).

4.4. General procedure for catalytic Suzuki–Miyaura reactions

Under air atmosphere, a round-bottomed flask was charged with the silica supported Pd catalyst **5** (21.2 mg, contain palladium 0.0025 mmol), K_2CO_3 (138 mg, 1.0 mmol), aryl halide (0.5 mmol), organoboron compound (0.6 mmol), and MeOH/H_2O (1:1, v/v, 2.0 mL). The reaction mixture was stirred at room temperature for 4 h, then the reaction solution was vacuum-filtered using a sintered-glass funnel and washed with Et_2O (5.0 mL), the combined organic layers were dried over Na_2SO_4, filtered, concentrated, and the residue was purified by flash chromatography on silica gel to obtain the desired cross-coupling product.

4.5. Analytical data for the Suzuki–Miyaura coupling products

*4.5.1. 4-Methoxybiphenyl (**3a**)*[17]. A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.56–7.52 (4H, m), 7.43–7.39 (2H, m), 7.32–7.28 (1H, m), 7.00–6.96 (2H, m), 3.85 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.1, 140.8, 133.7, 128.7, 128.1, 126.7, 114.2, 55.3.

*4.5.2. 4-Methylbiphenyl (**3b**)*[18]. A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.57 (2H, d, J=7.3 Hz), 7.49 (2H, d, J=8.0 Hz), 7.42 (2H, t, J=7.8 Hz), 7.36–7.30 (1H, m), 7.25–7.21 (2H, m), 2.39 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.1, 138.3, 137.0, 129.5, 128.7, 127.0, 126.9, 21.1.

*4.5.3. 4-Nitrobiphenyl (**3c**)*[18]. A pale yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.26–8.24 (2H, m), 7.70–7.67 (2H, m), 7.59–7.57 (2H, m), 7.47–7.38 (3H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.6, 147.0, 138.7, 129.1, 128.9, 127.8, 127.4, 124.1.

*4.5.4. 1,1′-Biphenyl (**3d**)*[18]. A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.65–7.62 (4H, m), 7.48 (4H, t, J=7.6 Hz), 7.38 (2H, t, J=7.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.5, 128.9, 127.5, 127.4.

*4.5.5. 2-Hydroxybiphenyl (**3e**)*[19]. A white solid. ^{1}H NMR (400MHz, $CDCl_3$): δ 7.47–7.43 (4H, m), 7.38–7.33 (1H, m), 7.25–7.21 (2H, m), 6.99–6.94 (2H, m), 5.28 (1H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.3, 137.0, 130.2, 129.1, 129.0, 128.1, 127.8, 120.8, 115.8.

*4.5.6. 2,4-Dimethoxybiphenyl (**3f**)*[20]. A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.48 (2H, d, J=7.6 Hz), 7.35 (2H, t, J=7.6 Hz), 7.27–7.20 (2H, m), 6.53–6.51 (2H, m), 3.78 (3H, s), 3.73 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 160.2, 157.3, 138.3, 131.1, 129.3, 127.9, 126.4, 123.5, 104.5, 98.9, 55.3, 55.2.

*4.5.7. 2,4-Dichlorobiphenyl (**3g**)*[21]. A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47–7.45 (1H, m), 7.40–7.35 (5H, m),

7.24–7.22 (2H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.0, 138.2, 133.6, 133.2, 132.0, 129.6, 129.3, 128.1, 127.8, 127.1.

*4.5.8. Terphenyl (**3h**)[22].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.67 (4H, s), 7.65–7.63 (4H, m), 7.47–7.44 (4H, m), 7.38–7.34 (2H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.7, 140.1, 128.8, 127.5, 127.3, 127.0.

*4.5.9. 2-Methoxybiphenyl (**3i**)[23].* A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54–7.52 (2H, m), 7.41–7.39 (2H, m), 7.34–7.30 (3H, m), 7.05–6.97 (2H, m), 3.80 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 156.4, 138.5, 130.9, 130.6, 129.5, 128.6, 127.9, 126.9, 120.8, 111.1, 55.5.

*4.5.10. 3-Methoxybiphenyl (**3j**)[23].* A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.59 (2H, d, *J*=8.0 Hz), 7.43 (2H, t, *J*=7.6 Hz), 7.37–7.33 (2H, m), 7.18 (1H, d, *J*=7.7 Hz), 7.13 (1H, s), 6.91–6.88 (1H, m), 3.86 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.9, 142.7, 141.1, 129.7, 128.7, 127.4, 127.2, 119.7, 112.9, 112.6, 55.3.

*4.5.11. 1,1′-Biphenyl-4-carbonitrile (**3k**)[23].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.65 (4H, dd, *J*=8.4, 8.8 Hz), 7.55–7.53 (2H, m), 7.46–7.36 (3H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 145.6, 139.1, 132.5, 129.0, 128.6, 127.6, 127.1, 118.9, 110.8.

*4.5.12. 1-(4-Biphenylyl)ethanone (**3l**)[17].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.05–8.02 (2H, m), 7.70–7.67 (2H, m), 7.64–7.62 (2H, m), 7.49–7.45 (2H, m), 7.42–7.38 (1H, m), 2.64 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.8, 145.7, 139.8, 135.8, 128.9, 128.2, 127.2, 26.7.

*4.5.13. 1,1′-Biphenyl-4-carboxaldehyde (**3m**)[18].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.05 (1H, s), 7.95 (2H, d, *J*=8.4 Hz), 7.75 (2H, d, *J*=8.4 Hz), 7.65–7.63 (2H, m); 7.50–7.46 (2H, m), 7.44–7.42 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 191.9, 147.1, 139.7, 135.1, 130.2, 129.0, 128.4, 127.6, 127.3.

*4.5.14. 4-(Ethoxycarbonyl)-1,1′-biphenyl (**3n**)[18].* A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.14 (2H, d, *J*=8.4 Hz), 7.68–7.63 (4H, m), 7.49 (2H, t, *J*=7.6 Hz), 7.40 (1H, t, *J*=7.3 Hz), 4.45–4.38 (2H, m), 1.44 (3H, t, *J*=7.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 166.7, 145.6, 140.3, 130.1,129.5, 129.1, 128.2, 127.5, 127.2, 61.1, 14.5.

*4.5.15. 2-Phenylpyridine(**3o**)[23].* A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.69 (1H, d, *J*=4.8 Hz), 8.00–7.98 (2H, m), 7.74–7.72 (2H, m), 7.50–7.46 (2H, m), 7.43–7.41 (1H, m), 7.24–7.20 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.4, 149.6, 139.3, 136.7, 128.9, 128.7, 126.8, 122.0, 120.5.

*4.5.16. 3-Phenylpyridine (**3p**)[23].* A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.86 (1H, s), 8.59 (1H, d, *J*=4.4 Hz), 7.89–7.86 (1H, m), 7.60–7.57 (2H, m), 7.50–7.47 (2H, m), 7.43–7.35 (2H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.4, 148.3, 137.8, 134.3, 129.0, 128.1, 127.1, 123.5.

*4.5.17. 1-tert-Butyl-4-phenyl benzene (**3q**)[17].* A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.59–7.56 (2H, m), 7.54–7.51 (2H, m), 7.47–7.44 (2H, m), 7.43–7.39 (2H, m), 7.32–7.28 (1H, m), 1.35 (9H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 150.2, 141.0, 138.3, 128.7, 127.0, 126.8, 125.7, 34.5, 31.4.

*4.5.18. 4,4′-Dimethoxy-1,1′-biphenyl (**3r**)[19].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (4H, d, *J*=8.8 Hz), 6.95 (4H, d, *J*=8.8 Hz), 3.84 (6H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.6, 133.4, 127.7, 114.1, 55.3.

*4.5.19. 2,4′-Dimethoxybiphenyl (**3s**)[24].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (2H, d, *J*=8.4 Hz), 7.31–7.27 (2H, m), 7.03–6.93 (4H, m), 3.84 (3H, s), 3.81 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.6, 156.4, 130.8, 130.6, 130.2, 128.1, 120.8, 113.4, 111.1, 55.5, 55.2.

*4.5.20. 3,4′-Dimethoxy-1,1′-biphenyl (**3t**)[19].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52 (2H, d, *J*=6.8 Hz), 7.33 (1H, t, *J*=8.0 Hz), 7.14 (1H, d, *J*=7.6 Hz), 7.09 (1H, t, *J*=2.0 Hz), 6.97 (2H, d, *J*=5.2 Hz), 6.85 (1H, dd, *J*=1.6, 5.6 Hz), 3.86 (3H, s), 3.84 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.9, 159.2, 142.3, 133.6, 129.7, 128.2, 119.2, 114.1, 112.5, 112.0, 55.3, 55.2.

*4.5.21. 4-Methoxy-4′-methylbiphenyl (**3u**)[25].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.51 (2H, d, *J*=8.8 Hz), 7. 45 (2H, d, *J*=8.0 Hz), 7.22 (2H, d, *J*=8.0 Hz), 6.95 (2H, d, *J*=8.8 Hz), 3.81 (3H, s), 2.36 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.9, 137.8, 136.4, 133.7, 129.5, 127.8, 126.4, 114.1, 55.3, 21.0.

*4.5.22. 4-Fluoro-4′-methoxybiphenyl (**3v**)[18].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.51–7.45 (4H, m), 7.12–7.06 (2H, m), 6.98–6.95 (2H, m), 3.84 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 162.1 (d, *J*=244 Hz), 160.8, 159.1, 136.9 (d, *J*=3.2 Hz), 132.8, 128.1 (d, *J*=22.4 Hz), 115.5 (d, *J*=21.2 Hz), 114.2, 55.3.

*4.5.23. 2-Chloro-4′-methoxybiphenyl (**3w**)[26].* A white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.72 (1H, dd, *J*=1.6, 7.6 Hz), 7.44 (2H, d, *J*=8.8 Hz), 7.39–7.28 (3H, m), 7.02 (2H, d, *J*=8.8 Hz), 3.89 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.3, 140.1, 132.7, 131.9, 131.3, 130.8, 130.0, 128.1, 126.7, 113.6, 55.3.

*4.5.24. 2,2′-Bis(methoxy)-1,1′-biphenyl (**3x**)[27].* A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38 (2H, dt, *J*=1.2, 7.8 Hz), 7.29 (2H, dd, *J*=1.6, 7.6 Hz), 7.06 (2H, dt, *J*=1.2, 7.6 Hz), 7.03 (2H, d, *J*=8.0 Hz), 3.81 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.2, 131.7, 128.7, 127.7, 120.5, 111.3, 55.6.

Acknowledgements

Financial supports from the National Natural Science Foundation of China (No. 20972057, 21002039), the Natural Science Foundation of Anhui (No. 090416223), the Key Project of Science and Technology of the Department of Education, Anhui Province (No. ZD2010-9) are gratefully acknowledged.

References and notes

1. For reviews, see: (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457–2483; (b) Hassan, J.; Sevignon, M.; Gozzi, C.; Schulz, E.; Lemaire, M. *Chem. Rev.* **2002**, *102*, 1359–1470; (c) Corbet, J. P.; Mignani, G. *Chem. Rev.* **2006**, *106*, 2651–2710; (d) Phan, N. T. S.; Van Der Sluys, M.; Jones, C. W. *Adv. Synth. Catal.* **2006**, *348*, 609–679; (e) Yin, L.; Liebscher, J. *Chem. Rev.* **2007**, *107*, 133–173; (f) Molander, G. A.; Ellis, N. *Acc. Chem. Res.* **2007**, *40*, 275–286; (g) Martin, R.; Buchwald, S. L. *Acc. Chem. Res.* **2008**, *41*, 1461–1473; (h) Alonso, F.; Beletskaya, I. P.; Yus, M. *Tetrahedron* **2008**, *64*, 3047–3101.
2. (a) Markham, A.; Goa, K. L. *Drugs* **1997**, *54*, 299–311; (b) Boren, J.; Cascante, M.; Marin, S.; Comin-Anduix, B.; Centelles, J. J.; Lim, S.; Bassilian, S.; Ahmed, S.; Lee, W. N.; Boros, L. G. *J. Biol. Chem.* **2001**, *276*, 37747–37753; (c) Capdeville, R.; Buchdunger, E.; Zimmermann, J.; Matter, A. *Nat. Rev. Drug Discov.* **2002**, *1*, 493–502.
3. (a) Gangjee, A.; Vasudevan, A.; Queener, S. F. *J. Med. Chem.* **1997**, *40*, 3032–3039; (b) Gangjee, A.; Devraj, R.; Queener, S. F. *J. Med. Chem.* **1997**, *40*, 470–478; (c) McPhail, K. L.; Rivett, D. E. A.; Lack, D. E.; Davies-Coleman, M. T. *Tetrahedron* **2000**, *56*, 9391–9396; (d) Juteau, H.; Gareau, Y.; Labelle, M.; Sturino, C. F.; Sawyer, N.; Tremblay, N.; Lamontagne, S.; Carriere, M. C.; Denis, D.; Metters, K. M. *Bioorg. Med. Chem.* **2001**, *9*, 1977–1984; (e) Rosowsky, A.; Chen, H.; Fu, H.; Queener, S. F. *Bioorg. Med. Chem.* **2003**, *11*, 59–67; (f) Long, Y. Q.; Jiang, X. H.; Dayam, R.; Sachez, T.; Shoemaker, R.; Sei, S.; Neamati, N. *J. Med. Chem.* **2004**, *47*, 2561–2573; (g) Forsch, R. A.; Queener, S. F.; Rosowsky, A. *Bioorg. Med. Chem. Lett.* **2004**, *14*, 1811–1815.
4. Tomori, H.; Fox, J. M.; Buchwald, S. L. *J. Org. Chem.* **2000**, *65*, 5334–5341.
5. (a) Kertesz, M.; Choi, C. H.; Yang, S. *Chem. Rev.* **2005**, *105*, 3448–3481; (b) Lightowler, S.; Hird, M. *Chem. Mater.* **2005**, *17*, 5538–5549.

6. (a) Old, D. W.; Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 9722–9723; (b) Fu, G. C.; Littke, A. F. *Angew. Chem., Int. Ed.* **1998**, *37*, 3387–3388; (c) Wolfe, J. P.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **1999**, *38*, 2413–2416; (d) Fujihara, T.; Yoshida, S.; Ohta, H.; Tsuji, Y. *Angew. Chem., Int. Ed.* **2008**, *47*, 8310–8314; (e) Fujihara, T.; Yoshida, S.; Terao, J.; Tsuji, Y. *Org. Lett.* **2009**, *11*, 2121–2124.
7. For reviews, see: (a) Sheldon, R. A.; Arends, I.; Hanefeld, U. *Green Chemistry and Catalysis*; Wiley-VCH: Weinheim, 2007; (b) Song, C. E.; Lee, S. G. *Chem. Rev.* **2002**, *102*, 3495–3524; (c) Lu, Z. L.; Lindner, E.; Mayer, H. A. *Chem. Rev.* **2002**, *102*, 3543–3578; (d) Lamblin, M.; Nassar-Hardy, L.; Hierso, J. C.; Fouquet, E.; Felpin, F. X. *Adv. Synth. Catal.* **2010**, *352*, 33–79; (e) Kitamura, Y.; Sako, S.; Tsutsui, A.; Monguchi, Y.; Maegaw, T.; Kitade, Y.; Sajikia, H. *Adv. Synth. Catal.* **2010**, *352*, 718–730.
8. (a) Li, C. *Catal. Rev.* **2004**, *46*, 419–492; (b) Karimi, B.; Abedi, S.; Clark, J. H.; Budarin, V. *Angew. Chem., Int. Ed.* **2006**, *45*, 4776–4779; (c) Sayah, R.; Glegoła, K.; Framery, E.; Dufaud, V. *Adv. Synth. Catal.* **2007**, *349*, 373–381; (d) Huang, J.; Zhu, F.; He, W.; Zhang, F.; Wang, W.; Li, H. *J. Am. Chem. Soc.* **2010**, *132*, 1494–1495; (e) Shi, S.; Zhang, Y. *Green Chem.* **2008**, *10*, 868–872.
9. (a) Audic, N.; Clavier, H.; Mauduit, M.; Guillemin, J. C. *J. Am. Chem. Soc.* **2003**, *125*, 9248–9249; (b) Yao, Q. W.; Zhang, Y. L. *Angew. Chem., Int. Ed.* **2003**, *42*, 3395–3398; (c) Lee, S. G.; Zhang, Y. J.; Piao, J. Y.; Yoon, H.; Song, C. E.; Choi, J. H.; Hong, J. *Chem. Commun.* **2003**, 2624–2625; (d) Kawasaki, I.; Tsunoda, K.; Tsuji, T.; Yamaguchi, T.; Shibuta, H.; Uchida, N.; Yamashita, M.; Ohta, S. *Chem. Commun.* **2005**, 2134–2136; (e) Miao, T.; Wang, L.; Li, P. H.; Yan, J. C. *Synthesis* **2008**, 3828–3834.
10. (a) Fan, Q. H.; Ren, C. Y.; Yeung, C. H.; Hu, W. H.; Chan, A. S. C. *J. Am. Chem. Soc.* **1999**, *121*, 7407–7408; (b) Ohkuma, T.; Takeno, H.; Honda, Y.; Noyori, R. *Adv. Synth. Catal.* **2001**, *343*, 369–375; (c) Yan, J. C.; Wang, L. *Synthesis* **2008**, 2065–2072; (d) Miao, T.; Wang, L. *Tetrahedron Lett.* **2008**, *49*, 2173–2176; (e) Li, P. H.; Wang, L.; Wang, M.; Zhang, Y. C. *Eur. J. Org. Chem.* **2008**, 1157–1160; (f) Schweizer, S. P.; Becht, J. M.; Drian, C. L. *Tetrahedron* **2010**, *66*, 765–772; (g) Luo, C. C.; Zhang, Y. H.; Wang, Y. G. *J. Mol. Catal., A: Chem.* **2005**, *229*, 7–12.
11. For recent examples of superparamagnetic nanoparticles (MNPs) supported catalysts, see: (a) Rosario-Amorin, D.; Wang, X.; Gaboyard, M.; Clerac, R.; Nlate, S.; Heuz, K. *Chem.—Eur. J.* **2009**, *15*, 12636–12643; (b) Hu, A.; Yee, G. T.; Lin, W. *J. Am. Chem. Soc.* **2005**, *127*, 12486–12487; (c) Schatz, A.; Grass, R. N.; Stark, W. J.; Reiser, O. *Chem.—Eur. J.* **2008**, *14*, 8262–8266; (d) Shokouhimehr, M.; Piao, Y. Z.; Kim, J.; Jang, Y. J.; Hyeon, T. *Angew. Chem., Int. Ed.* **2007**, *46*, 7039–7043; (e) Che, C.; Li, Z.; Lin, S. Y.; Chen, J. W.; Zheng, J.; Wu, J. C.; Zheng, Q. X.; Zhang, G. Q.; Yang, Z.; Jiang, B. W. *Chem. Commun.* **2009**, 5990–5992; (f) Gleeson, O.; Tekoriute, R.; Gunko, Y. K.; Connon, S. J. *Chem.—Eur. J.* **2009**, *15*, 5669–5673; (g) Dalaigh, C. O.; Corr, S. A.; Gunko, Y.; Connon, S. J. *Angew. Chem., Int. Ed.* **2007**, *46*, 4329–4332; (h) Wittmann, S.; Schatz, A.; Grass, R. N.; Stark, W. J.; Reiser, O. *Angew. Chem., Int. Ed.* **2010**, *49*, 1867–1870; (i) Jin, M. J.; Lee, D. H. *Angew. Chem., Int. Ed.* **2010**, *49*, 1119–1122.
12. (a) Wang, L.; Reis, A.; Seifert, A.; Philippi, T.; Ernst, S,; Jia, M.; Thiel, W. R. *Dalton Trans.* **2009**, 3315–3320; (b) Shylesh, S.; Wang, L.; Thiel, W. R. *Adv. Synth. Catal.* **2010**, *352*, 425–432.
13. (a) Wang, M.; Li, P. H.; Wang, L. *Eur. J. Org. Chem.* **2008**, 2255–2261; (b) Wu, Q.; Wang, L. *Synthesis* **2008**, 2007–2012; (c) Li, P. H.; Wang, L.; Zhang, Y. C. *Tetrahedron* **2008**, *64*, 10825–10830; (d) Li, P. H.; Wang, L.; Zhang, Y. C.; Wang, G. W. *Tetrahedron* **2008**, *64*, 7633–7638; (e) Li, P. H.; Wang, L.; Zhang, Y. C.; Wang, M. *Tetrahedron Lett.* **2008**, *49*, 6650–6654; (f) Li, P. H.; Wang, L. *Tetrahedron* **2007**, *63*, 5455–5459; (g) Li, P. H.; Wang, L. *Adv. Synth. Catal.* **2006**, *348*, 681–685.
14. (a) Phan, N. T. S.; Khan, J.; Styring, P. *Tetrahedron* **2005**, *61*, 12065–12073; (b) Guram, A. S.; King, A. O.; Allen, J. G.; Wang, X.; Schenkel, L. B.; Chan, J.; Bunel, E. E.; Faul, M. M.; Larsen, R. D.; Martinelli, M. J.; Reider, P. J. *Org. Lett.* **2006**, *8*, 1787–1789.
15. Yan, J. C.; Wang, L. *Chirality* **2009**, *21*, 413–420.
16. (a) Wang, Y. C.; Lai, C. W.; Kwong, F. Y.; Jia, W.; Chan, K. S. *Tetrahedron* **2004**, *60*, 9433–9439; (b) Ueda, M.; Nishimura, M.; Miyaura, N. *Synlett* **2000**, 856–858.
17. Nishio, R.; Sugiura, M.; Kobayashi, S. *Org. Lett.* **2005**, *7*, 4831–4834.
18. Zhang, L.; Meng, T. H.; Wu, J. *J. Org. Chem.* **2007**, *72*, 9346–9349.
19. Scheuermann, G. M.; Rumi, L.; Steurer, P.; Bannwarth, W.; Mulhaupt, R. *J. Am. Chem. Soc.* **2009**, *131*, 8262–8270.
20. Cho, J. K.; Najman, R.; Dean, T. W.; Ichihara, O.; Muller, C.; Bradley, M. *J. Am. Chem. Soc.* **2006**, *128*, 6276–6277.
21. Kylmälä, T.; Kuuloja, N.; Xu, Y. J.; Rissanen, K.; Franzén, R. *Eur. J. Org. Chem.* **2008**, 4019–4024.
22. Xu, L.; Li, B.-J.; Wu, Z.-H.; Lu, X.-Y.; Guan, B.-T.; Wang, B.-Q.; Zhao, K.-Q.; Shi, Z.-J. *Org. Lett.* **2010**, *12*, 884–887.
23. Bolliger, J. L.; Frech, C. M. *Chem.—Eur. J.* **2010**, *16*, 4075–4081.
24. Liu, Q.; Lan, Y.; Liu, J.; Li, G.; Wu, Y. D.; Lei, A. *J. Am. Chem. Soc.* **2009**, *131*, 10201–10210.
25. Yin, Z.; Zhang, Z.; Wang, Y. *Tetrahedron* **2006**, *62*, 9359–9364.
26. Antelo Miguez, J. M.; Adrio, L. A.; Sousa-Pedrares, A.; Vila, J. M.; Hii, K. K. *J. Org. Chem.* **2007**, *72*, 7771–7774.
27. Moncomble, A.; Floch, P. L.; Gosmini, C. *Chem.—Eur. J.* **2009**, *15*, 4770–4774.