Organic & Biomolecular Chemistry

Cite this: *Org. Biomol. Chem.*, 2012, **10**, 4243

www.rsc.org/obc

**PAPER**

# An efficient nickel-catalyzed alkenylation of functionalized benzylic halides with alkenylaluminum reagents†

**Deepak B. Biradar and Han-Mou Gau***

***Received 11th February 2012, Accepted 3rd April 2012***
**DOI: 10.1039/c2ob25303h**



Highly efficient and simple coupling reactions of benzylic bromides or chlorides with alkenylaluminum reagents catalyzed by $NiCl_2(PPh_3)_2$ are reported. The coupling reactions proceed effectively at room temperature employing low loading of catalyst, 0.5 mol% for benzylic bromides having either electron-donating or -withdrawing substituents on the aromatic ring, affording coupling products in excellent yields of up to 94% in short reaction times. The coupling reactions of benzylic chloride require 5 mol% of the catalyst and a longer reaction time of 2 h.

## Introduction

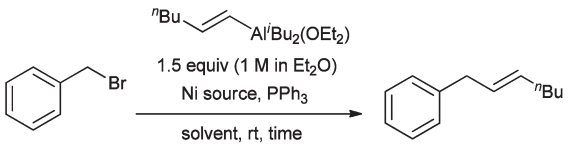
The development of efficient methods that allow the incorporation of double bonds with high regio- and stereoselectivity are of enormous importance. Transition metal-catalyzed cross-coupling reactions of organometallic compounds containing an alkenyl nucleophile with an organic electrophile are one of the most powerful methods for this purpose.[1] Due to their extraordinary diversity, many research groups have attracted much attention in identifying milder procedures and broader structural generalities for this transformation. A variety of organometallic reagents of Zn, Zr,[2] Mg,[3] B,[4] Sn,[5] Cu,[6] In,[7] as well as Li,[8] Si,[9] and Mn[10] have been used in palladium or nickel cross-coupling reactions, and the synthetic scope of this kind of reaction has been continuously expanded by the use of new organic electrophiles, catalysts, or organometallic reagents.

In the last few decades, the synthesis of alkenes by attaching a C–C single bond onto C=C moieties *via* cross-coupling have gained considerable importance due to their wide applicability and high selectivity in the preparation of biologically active compounds.[11] In the mid-1970s, Negishi's group discovered the first example of the Pd- or Ni-catalyzed reaction of alkenylalanes with aryl halides.[12] Since then, many groups reported cross-coupling protocols of Pd-catalyzed alkenylation involving organometals especially about alkenyl–alkenyl, alkenyl–aryl and alkenyl–alkyl couplings.[13] There are few reports of benzylic moieties involved in such kind of cross coupling reactions.[14] Benzyl cross coupling products can be achieved *via* coupling of either alkenyl metal and benzylic halide or benzylic metal and alkenyl halide. Although, there are a few reports about these kind of transformations, the reactions are catalyzed by expensive Pd metal either by using zinc reagent or using an additive to achieve higher reactivity or selectivity.[15] Also, some of the reactions need high temperatures or prolonged reaction time to complete. Moreover, the substrate scope is limited. Therefore, an efficient and practical synthetic method of alkenyl–benzylic cross coupling is of considerable importance.

Organoalanes are less studied in cross-coupling reactions although they have high reactivity and greater Lewis acidity of aluminum center. Recently, several groups[16] including us[17] have developed organoalane reagents and successfully used them in catalytic reactions. Furthermore, the organoalanes have been proven to be highly efficient coupling reagents with benzylic or aryl halides catalyzed by $NiCl_2(PPh_3)_2$ or $Pd(OAc)_2$ system.[18] To continue our efforts in developing the organoalane compounds and to extend their application in cross-coupling reactions, herein, we report the efficient, simple and inexpensive Ni catalyzed cross-coupling reactions of organic electrophiles with alkenylalanes in good to excellent yields.

## Results and discussion

The coupling reaction between benzyl bromide and the alkenylaluminum reagent prepared *via* hydroalumination[19] of 1-hexyne was chosen as the model system (Scheme 1), and results are summarized in Table 1. To find a good catalytic system,




**Scheme 1**

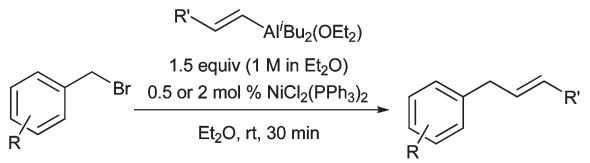
*Department of Chemistry, National Chung Hsing University, Taichung, 402, Taiwan. E-mail: hmgau@dragon.nchu.edu.tw; Fax: (+)886-4-22862547; Tel: (+)886-4-22878615*

†Electronic supplementary information (ESI) available: $^1H$ and $^{13}C$ NMR spectra of coupling products. See DOI: 10.1039/c2ob25303h

**Table 1** Optimization of coupling reactions of benzyl bromide with alkenylaluminum reagent[a]

| Entry | Ni source (mol%) | $PPh_3$ (mol%) | Solvent | Time (min) | Yield[b] (%) |
|---|---|---|---|---|---|
| 1 | — | — | DME | 60 | NR |
| 2 | $NiCl_2$ (1) | — | DME | 60 | NR |
| 3 | $NiCl_2$ (1) | 1 | DME | 60 | 87 |
| 4 | $Ni(acac)_2$ (1) | 1 | DME | 60 | 92 |
| 5 | $Ni(OAc)_2$ (1) | 1 | DME | 60 | 88 |
| 6 | $Ni(ClO_4)_2$ (1) | 1 | DME | 60 | 85 |
| 7 | $Ni(PPh_3)_2Cl_2$ (1) | — | DME | 60 | 92 |
| 8 | $Ni(PPh_3)_2Cl_2$ (1) | — | Toluene | 60 | 81 |
| 9 | $Ni(PPh_3)_2Cl_2$ (1) | — | $CH_2Cl_2$ | 60 | 66 |
| 10 | $Ni(PPh_3)_2Cl_2$ (1) | — | Hexane | 60 | 76 |
| 11 | $Ni(PPh_3)_2Cl_2$ (1) | — | THF | 60 | 62 |
| 12 | $Ni(PPh_3)_2Cl_2$ (1) | — | $Et_2O$ | 60 | 98 |
| 13 | $Ni(PPh_3)_2Cl_2$ (1) | — | $Et_2O$ | 30 | 98 |
| 14 | $Ni(PPh_3)_2Cl_2$ (0.5) | — | $Et_2O$ | 30 | 98 |
| 15 | $Ni(PPh_3)_2Cl_2$ (0.25) | — | $Et_2O$ | 30 | 45 |

[a] Benzyl bromide/Al reagent = 1/1.5 mmol; solvent = 3 mL. [b] Yields are based on $^1H$ NMR spectra.

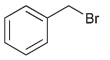
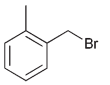
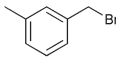
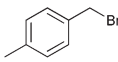
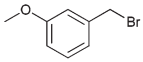
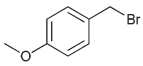
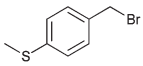
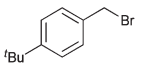
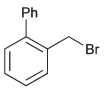
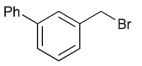
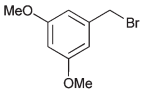
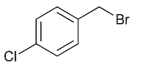
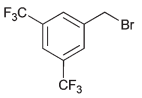
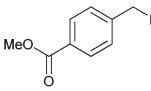
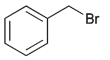
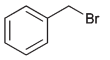
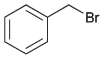



**Scheme 2**

preliminary experiments were performed in DME, and several Ni salts were surveyed. In the absence of both Ni/phosphine or phosphine, the reaction did not take place at all over 1 h (Table 1, entries 1 and 2). While employing 1 mol% each phosphine and different Ni salts such as $NiCl_2$, $Ni(acac)_2$, $Ni(OAc)_2$, and $Ni(ClO_4)_2$, the coupling product was furnished in ≥85% yields with ≥15% homocoupling product of dibenzyl (entries 2–6). However, the reaction in the presence of 1 mol% $NiCl_2(PPh_3)_2$ yielded 92% of coupling product with 8% homocoupling product in 1 h (entry 7). As it is known that solvent plays an important role in organoalane mediated reactions, which were then screened. Non-coordinating solvents like toluene, $CH_2Cl_2$, and hexane provide the coupling product in 88%, 66%, and 76% yields, respectively. Whereas the strong coordinating solvent THF made the reaction slow and lowered the yield to 62% in 1 h. The weaker coordinating diethyl ether turned out to be the best solvent for the reaction, which gave more than 98% of the desired product with less than 2% of dibenzyl as a by-product in 1 h (entry 12) as well as in 30 min (entry 13). When the amount of $NiCl_2(PPh_3)_2$ was reduced to 0.5 mol%, the reaction afforded **2a** in 98% yield (entry 14). A further decrease in catalyst loading furnished the coupling product in lower yield (entry 15).

To evaluate the scope and limitations of the reaction, a variety of functionalized benzylic bromides and alkenylaluminium reagents were subjected to coupling reactions (Scheme 2).

**Table 2** Coupling of substituted benzyl bromides and alkenylaluminum reagent[a]

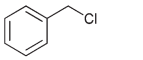
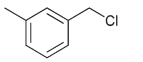
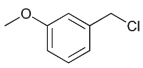
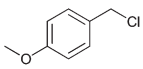
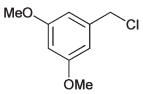
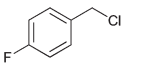
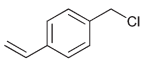
| Entry | Substrate | | R′ | Product | Yield[b] (%) |
|---|---|---|---|---|---|
| 1 |  | (**1a**) | $n$-$C_4H_9$ | **2a** | 92 |
| 2 |  | (**1b**) | $n$-$C_4H_9$ | **2b** | 85 |
| 3 |  | (**1c**) | $n$-$C_4H_9$ | **2c** | 91 |
| 4 |  | (**1d**) | $n$-$C_4H_9$ | **2d** | 92 |
| 5 |  | (**1e**) | $n$-$C_4H_9$ | **2e** | 93 |
| 6 |  | (**1f**) | $n$-$C_4H_9$ | **2f** | 91 |
| 7 |  | (**1g**) | $n$-$C_4H_9$ | **2g** | 90 |
| 8 |  | (**1h**) | $n$-$C_4H_9$ | **2h** | 91 |
| 9 |  | (**1i**) | $n$-$C_4H_9$ | **2i** | 70 |
| 10 |  | (**1j**) | $n$-$C_4H_9$ | **2j** | 92 |
| 11 |  | (**1k**) | $n$-$C_4H_9$ | **2k** | 91 |
| 12 |  | (**1l**) | $n$-$C_4H_9$ | **2l** | 94 |
| 13 |  | (**1m**) | $n$-$C_4H_9$ | **2m** | 85 |
| 14[c] |  | (**1n**) | $n$-$C_4H_9$ | **2n** | 90 |
| 15[c] |  | (**1o**) | $PhCH_2$ | **2o** | 82 |
| 16[c] |  | (**1p**) | Cyclohexyl | **2p** | 88 |
| 17[c] |  | (**1q**) | 3-Thienyl | **2q** | 87 |

[a] Benzyl bromide/Al reagent = 1/1.5 mmol; $Et_2O$ = 3 mL. [b] Isolated yields of products. [c] 2 mol% $NiCl_2(PPh_3)_2$ was used.

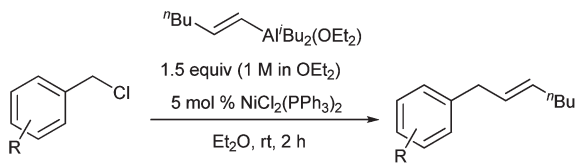
The catalytic system works effectively with low catalyst loading of $NiCl_2(PPh_3)_2$ to afford the products in good yield. The results are summarized in Table 2. For substituted benzyl bromides containing an electron-donating substituent on the aromatic ring (entries 1–11), low catalyst loadings of 0.5 mol% were effective enough to produce coupling products in excellent yields of ≥90% in 30 min except for 2-methylbenzyl bromide and 2-phenylbenzyl bromide, which afforded the product in 85%

**Table 3** Coupling of substituted benzyl bromides and alkenylaluminum reagent[a]

| Entry | Substrate | | Product | Yield[b] (%) |
|---|---|---|---|---|
| 1 |  | (**1a′**) | **2a** | 93 |
| 2 |  | (**1c′**) | **2c** | 92 |
| 3 |  | (**1e′**) | **2e** | 93 |
| 4 |  | (**1f′**) | **2f** | 92 |
| 5 |  | (**1k′**) | **2k** | 93 |
| 6 |  | (**1r′**) | **2r** | 91 |
| 7 |  | (**1s′**) | **2s** | 93 |

[a] Benzyl chloride/($^n$BuCH=CH)Al$^i$Bu$_2$(OEt$_2$) = 1/1.5 mmol; Et$_2$O = 3 mL. [b] Isolated yields of products.




**Scheme 3**

and 70% yields, respectively. The same catalyst loading of 0.5 mol% was good enough for the substituted benzyl bromides containing electron-withdrawing substituents on the aromatic ring such as 4-chlorobenzyl bromide or 3,5-bis(trifluoromethyl) benzyl bromide to afford the coupling product in 94% and 85% yields, respectively (entries 12 and 13). However, an ester substituted benzyl bromide required a higher catalyst loading of 2 mol % to afford a 90% yield of coupling product in 30 min (entry 14).

To extend the reaction scope, the coupling reaction of benzyl halides with functionalized alkenylaluminum reagents were then studied. A catalyst loading of 2 mol% was employed for the coupling reactions of benzyl bromide with the aluminum reagent prepared by using benzyl acetylene and cyclohexyl acetylene affording the products in 82% and 88% yields (entries 15 and 16), respectively, in 30 min. Moreover, the reagent having a heterocyclic moiety prepared by using 3-thienyl acetylene also gave the coupling product in 87% yield as well (entry 17).

To broaden the reaction scope, we subsequently examined coupling reactions of benzyl chlorides (Table 3, Scheme 3). The catalytic system with 5 mol% of catalyst loading in 2 h exhibits similar yields toward benzyl chlorides compared to benzyl bromides with 0.5 mol% in 30 min. For example, 5 mol% of catalyst was used for benzyl chloride to afford coupling product **2a** in a 93% yield (Table 3, entry 1) compared to the 0.5 mol% used for benzyl bromide in the 92% yield (Table 2, entry 1). Similarly, 5 mol% of the catalysts were used for 3-methyl, 3-methoxy, 4-methoxy, and 3,5-dimethoxy-substituted benzyl chlorides (Table 3, entries 2–5) relative to 0.5 mol% of the catalyst for the corresponding substituted benzyl bromides (Table 2, entries 3–5,11). For 4-fluorobenzyl chloride with an electron-withdrawing fluoro substituent, 5 mol% of the catalyst was used to afford coupling product **2r** in a 91% yield (Table 3, entry 6). We also examined 4-(vinyl)benzyl chloride (**1s′**), which also afforded the coupling product in 93% yield with the same amount of catalyst loading in 2 h (Table 3, entry 7).

## Conclusions

In summary, an extremely efficient, simple and inexpensive benzyl–alkenyl coupling reaction of benzylic bromides or chlorides with organoalanes is reported. In this study, a wide variety of benzyl bromides and chlorides are examined, and the coupling reactions of benzylic bromides containing either strong electron-withdrawing or electron-donating substituents on the aromatic ring proceed effectively at room temperature in short reaction times of 30 min while using a low catalyst loading of 0.5 mol% of $NiCl_2(PPh_3)_2$, achieving coupling products in excellent yields. In contrast, the coupling reaction of benzyl chlorides requires a higher catalyst loading of 5 mol% and a longer reaction time of 2 h to give corresponding products in similar yields.

## Experimental

### General

$^1$H NMR and $^{13}$C specta were obtained with a Varian Mercury-400 ($^1$H, 400 MHz; $^{13}$C, 100 MHz) spectrometer and chemical shifts were measured relative to tetramethylsilane (0.00 ppm) as the internal reference. Mass spectroscopy was performed using a Finnigan MAT 95 XL ThermoQuest Mass Spectrometer. DIBAL-H in hexane and alkynes were purchased from Strem chemicals and Acros, respectively. All solvents were dried by refluxing for at least 24 h over $P_2O_5$ (dichloromethane) or sodium–benzophenone and were freshly distilled prior to use. All synthesis and manipulations were carried out under a dry nitrogen atmosphere.

### General procedures for the synthesis of alkenyl aluminum reagent

Under a dry nitrogen atmosphere, DIBAL-H in hexane was charged into a reaction vessel. An alkyne was added *via* a gas-tight syringe at room temperature. The reaction mixture was allowed to react at 50 °C for 5 h. The resulted solution was cooled to room temperature followed by evaporation of hexane under reduced pressures to dryness. Then a dry ether was transferred into the reaction vessel to give an alkenylaluminum solution which was used in the coupling reaction.

**General procedures for the coupling reaction of benzylic bromide or chloride with alkenyl aluminum reagents catalyzed by $NiCl_2(PPh_3)_2$**

Under a dry nitrogen atmosphere, 0.5 mol% $NiCl_2(PPh_3)_2$ (0.0032 g, 0.0050 mmol) and aluminum reagent (1.5 mmol) were mixed in 3 mL dry diethyl ether at room temperature, and the mixture was stirred for 15 min followed by an addition of benzylic bromide (1.00 mmol). After stirring for 30 min at this temperature, the reaction mixture was quenched by aqueous hydrochloric acid (3 M, 2 mL). The organic layer was separated, and the aqueous layer was extracted with hexane or diethyl ether (3 × 15 mL). The combined organic phase was dried over $MgSO_4$, filtered, and concentrated. The residue was purified by column chromatography using hexane as an eluent to give the products. The coupling reaction of benzylic chloride uses 5 mol % $NiCl_2(PPh_3)_2$ (0.032 g, 0.050 mmol) with a reaction time of 2 h.

**(*E*)-Hept-2-enylbenzene (2a).** Colorless liquid, 0.16 g (92%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.31–7.24 (m, 2H), 7.21–7.15 (m, 3H), 5.61–5.46 (m, 2H), 3.33 (d, $J$ = 5.6 Hz, 2H), 2.02 (dt, $J$ = 6.0, 6.8 Hz, 2H), 1.40–1.26 (m, 4H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 141.1, 132.1, 128.7, 128.5, 128.3, 125.8, 39.1, 32.2, 31.7, 22.2, 13.9 ppm. HRMS calculated for $C_{13}H_{18}$ [$M^+$]: 174.1409, found 174.1401.

**(*E*)-1-(Hept-2-enyl)-2-methylbenzene (2b).** Colorless liquid, 0.16 g (85%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.15–7.08 (m, 4H), 5.57–5.49 (m, 1H), 5.46–5.37 (m, 1H), 3.30 (d, $J$ = 6.4 Hz, 2H), 2.28 (s, 3H), 2.01 (dt, $J$ = 6.4, 6.8 Hz, 2H), 1.38–1.24 (m, 4H), 0.88 (t, $J$ = 6.4 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 139.1, 136.2, 131.9, 130.0, 128.9, 127.8, 126.0, 125.9, 36.6, 32.2, 31.7, 22.2, 19.3, 13.9 ppm. HRMS calculated for $C_{14}H_{20}$ [$M^+$]: 188.1565, found 188.1557.

**(*E*)-1-(Hept-2-enyl)-3-methylbenzene (2c).** Colorless liquid, 0.171 g (91%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.20–7.14 (m, 1H), 7.01–6.97 (m, 3H), 5.60–5.46 (m, 2H), 3.29 (d, $J$ = 5.6 Hz, 2H), 2.32 (s, 3H), 2.02 (dt, $J$ = 6.4, 6.4 Hz, 2H), 1.40–1.26 (m, 4H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 141.1, 137.9, 132.0, 129.3, 128.8, 128.2, 126.6, 125.5, 39.0, 32.2, 31.7, 22.2, 21.4, 13.9 ppm. HRMS calculated for $C_{14}H_{20}$ [$M^+$]: 188.1565, found 188.1561.

**(*E*)-1-(Hept-2-enyl)-4-methylbenzene (2d).** Colorless liquid, 0.173 g (92%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.14–7.05 (m, 4H), 5.58–5.44 (m, 2H), 3.28 (d, $J$ = 5.6 Hz, 2H), 2.32 (s, 3H), 2.01 (dt, $J$ = 6.8, 6.8 Hz, 2H), 1.40–1.24 (m, 4H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 138.1, 135.3, 131.8, 129.01, 128.98, 128.3, 38.6, 32.2, 31.7, 22.2, 21.0, 13.9 ppm. HRMS calculated for $C_{14}H_{20}$ [$M^+$]: 188.1565, found 188.1558.

**(*E*)-1-(Hept-2-enyl)-3-methoxybenzene (2e).** Pale yellow liquid, 0.19 g (93%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.23–7.16 (m, 1H), 6.80–6.70 (m, 3H), 5.60–5.47 (m, 2H), 3.79 (s, 3H), 3.30 (d, $J$ = 5.2 Hz, 2H), 2.03 (dt, $J$ = 6.0, 6.8 Hz, 2H), 1.40–1.26 (m, 4H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 159.6, 142.7, 132.2, 129.2, 128.5, 120.8, 114.1, 111.2, 55.0, 39.0, 32.1, 31.6, 22.2, 13.9 ppm. HRMS calculated for $C_{14}H_{20}O$ [$M^+$]: 204.1514, found 204.1508.

**(*E*)-1-(Hept-2-enyl)-4-methoxybenzene (2f).** Pale yellow liquid, 0.186 g (91%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.12–7.06 (m, 2 H), 6.87–6.80 (m, 2H), 5.58–5.43 (m, 2H), 3.78 (s, 3H), 3.26 (d, $J$ = 6.0 Hz, 2H), 2.06–1.98 (m, 2H), 1.40–1.26 (m, 4H), 0.89 (t, $J$ = 6.8 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 157.8, 133.2, 131.7, 129.3, 129.1, 113.8, 55.2, 38.1, 32.2, 31.7, 22.2, 13.9 ppm. HRMS calculated for $C_{14}H_{20}O$ [$M^+$]: 204.1514, found 204.1512.

**(*E*)-(4-(Hept-2-enyl)phenyl)(methyl)sulfane (2g).** Colorless liquid, 0.198 g (90%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.22–7.17 (m, 2 H), 7.10 (d, $J$ = 8.0 Hz, 2H), 5.57–5.44 (m, 2H), 3.28 (d, $J$ = 5.2 Hz, 2H), 2.46 (s, 3H), 2.02 (dt, $J$ = 6.0, 6.4 Hz, 2H), 1.40–1.25 (m, 4H), 0.89 (t, $J$ = 6.8 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 138.3, 135.4, 132.2, 129.0, 128.5, 127.3, 38.5, 32.2, 31.6, 22.2, 16.4, 13.9 ppm. HRMS calculated for $C_{14}H_{20}S$ [$M^+$]: 220.1286, found 220.1280.

**(*E*)-1-*tert*-Butyl-4-(hept-2-enyl)benzene (2h).** Colorless liquid, 0.209 g (91%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.32–7.28 (m, 2H), 7.11 (d, $J$ = 8.0 Hz, 2H), 5.61–5.46 (m, 2H), 3.29 (d, $J$ = 6.0 Hz, 2H), 2.02 (dt, $J$ = 6.0, 6.8 Hz, 2H), 1.37–1.28 (m, 13H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 148.6, 138.1, 131.9, 128.8, 128.1, 125.2, 38.5, 34.3, 32.2, 31.7, 31.4, 22.3, 14.0 ppm. HRMS calculated for $C_{17}H_{26}$ [$M^+$]: 230.2035, found 230.2030.

**(*E*)-2-(Hept-2-enyl)biphenyl (2i).** Colorless liquid, 0.175 g (70%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.42–7.20 (m, 9H), 5.46 (dt, $J$ = 6.4, 15.2. Hz, 1H), 5.29 (dt, $J$ = 6.4, 15.2 Hz, 1H), 3.27 (d, $J$ = 6.4 Hz, 2H), 1.97 (dt, $J$ = 6.4, 6.8 Hz, 2H), 1.34–1.23 (m, 4H), 0.87 (t, $J$ = 6.8 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 141.9, 141.8, 138.3, 132.0, 130.0, 129.6, 129.3, 128.9, 127.9, 127.3, 126.8, 125.8, 36.3, 32.0, 31.6, 22.2, 13.9 ppm. HRMS calculated for $C_{19}H_{22}$ [$M^+$]: 250.1722, found 250.1716.

**(*E*)-3-(Hept-2-enyl)biphenyl (2j).** Colorless liquid, 0.230 g (92%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.62–7.57 (m, 2H), 7.46–7.40 (m, 4H), 7.39–7.31 (m, 2H), 7.20–7.16 (m, 1H), 5.66–5.51 (m, 2H), 3.40 (d, $J$ = 6.0 Hz, 2H), 2.05 (dt, $J$ = 6.0, 6.4 Hz, 2H), 1.42–1.28 (m, 4H), 0.91 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 141.6, 141.4, 141.3, 132.3, 128.71, 128.66, 128.60, 127.42, 127.38, 127.2, 127.1, 124.8, 39.1, 32.2, 31.6, 22.2, 13.9 ppm. HRMS calculated for $C_{19}H_{22}$ [$M^+$]: 250.1722, found 250.1713.

**(*E*)-1-(Hept-2-enyl)-3,5-dimethoxybenzene (2k).** Pale yellow liquid, 0.213 g (91%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 6.38–6.33 (m, 2H), 6.30 (t, $J$ = 2.4 Hz, 1H), 5.58–5.47 (m, 2H), 3.77 (s, 6H), 3.26 (d, $J$ = 4.8 Hz, 2H), 2.03 (dt, $J$ = 4.8, 6.8 Hz, 2H), 1.41–1.27 (m, 4H), 0.89 (t, $J$ = 6.8 Hz, 3H) ppm. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 160.8, 143.6, 132.4, 128.3, 106.5, 98.0, 55.2, 39.3, 32.1, 31.6, 22.2, 13.9 ppm. HRMS calculated for $C_{15}H_{22}O_2$ [$M^+$]: 234.1620, found 234.1613.

**(*E*)-1-Chloro-4-(hept-2-enyl)benzene (2l).** Colorless liquid, 0.196 g (94%). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.30–7.24 (m, 2H), 7.16–7.10 (m, 2H), 5.60–5.48 (m, 2H), 3.31 (d, $J$ = 4.8 Hz,

2H), 2.06 (dt, $J$ = 5.2, 6.4 Hz, 2H), 1.42–1.30 (m, 4H), 0.93 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 139.5, 132.6, 131.6, 129.8, 128.4, 128.1, 38.3, 32.1, 31.6, 22.2, 13.9 ppm. HRMS calculated for $C_{13}H_{17}Cl$ [$M^+$]: 208.1019, found 208.1010.

**(*E*)-1-(Hept-2-enyl)-3,5-bis(trifluoromethyl)benzene (2m).** Pale yellow liquid, 0.263 g (85%). $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$ 7.71 (s, 1H), 7.63 (s, 2H), 5.63–5.49 (m, 2H), 3.45 (d, $J$ = 6.0 Hz, 2H), 2.09–2.04 (m, 2H), 1.42–1.28 (m, 4H), 0.90 (t, $J$ = 6.8 Hz, 3H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 143.7, 134.4, 131.6 (q, $J$ = 32.8 Hz), 128.7, 126.6, 123.5 (q, $J$ = 270.3 Hz), 120.0 (q, $J$ = 3.6 Hz), 38.6, 32.2, 31.5, 22.2, 13.8 ppm. HRMS calculated for $C_{15}H_{16}F_6$ [$M^+$]: 310.1156, found 310.1165.

**(*E*)-Methyl 4-(hept-2-enyl)benzoate (2n).** Colorless liquid, 0.208 g (90%). $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$ 7.98–7.93 (m, 2H), 7.28–7.22 (m, 2H), 5.59–5.47 (m, 2H), 3.90 (s, 3H), 3.37 (d, $J$ = 4.8 Hz, 2H), 2.03 (dt, $J$ = 5.2, 6.8 Hz, 2H), 1.41–1.25 (m, 4H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 167.0, 146.5, 132.8, 129.6, 128.4, 127.8, 127.6, 51.8, 38.9, 32.1, 31.5, 22.1, 13.8 ppm. HRMS calculated for $C_{15}H_{20}O_2$ [$M^+$]: 232.1463, found 232.1457.

**(*E*)-1,4-Diphenylbut-2-ene (2o).** Colorless liquid, 0.170 g (82%). $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$ 7.32–7.17 (m, 10H), 5.68–5.66 (m, 2H), 3.37 (d, $J$ = 4.8 Hz, 4H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 140.7, 130.4, 128.5, 128.4, 126.0, 39.0 ppm.

**(*E*)-(3-Cyclohexylallyl)benzene (2p).** Colorless liquid, 0.176 g (88%). $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$ 7.30–7.25 (m, 2H), 7.20–7.14 (m, 3H), 5.56–5.43 (m, 2H), 3.31 (d, $J$ = 5.6 Hz, 2H), 1.99–1.89 (m, 1H), 1.78–1.60 (m, 5H), 1.32–1.02 (m, 5H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 141.2, 138.1, 128.4, 128.3, 126.1, 125.8, 40.6, 39.1, 33.1, 26.2, 26.1 ppm. HRMS calculated for $C_{15}H_{20}$ [$M^+$]: 200.1565, found 200.1563.

**(*E*)-3-(3-Phenylprop-1-enyl)thiophene (2q).** Pale yellow liquid, 0.174 g (87%). $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$ 7.34–7.29 (m, 2H), 7.27–7.22 (m, 4H), 7.21–7.17 (m, 1H), 7.10–7.07 (m, 1H), 6.46 (d, $J$ = 15.6 Hz, 1H), 6.21 (dt, $J$ = 6.8, 15.6 Hz, 1H), 3.51 (d, $J$ = 6.8 Hz, 2H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 140.1, 140.0, 129.2, 128.7, 128.5, 126.2, 125.8, 125.3, 125.0, 121.0, 39.2 ppm. HRMS calculated for $C_{13}H_{12}S$ [$M^+$]: 200.0660, found 200.0666.

**(*E*)-1-Fluoro-4-(hept-2-enyl)benzene (2r).** Colorless liquid, 0.174 g (91%). $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$ 7.15–7.09 (m, 2H), 6.99–6.92 (m, 2H), 5.57–5.44 (m, 2H), 3.28 (d, $J$ = 5.2 Hz, 2H), 2.02 (dt, $J$ = 6.4, 6.8 Hz, 2H), 1.40–1.25 (m, 4H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 161.4 (d, $J$ = 242 Hz), 136.7 (d, $J$ = 2.8 Hz), 132.3, 129.8 (d, $J$ = 8.2 Hz), 128.6, 115.0 (d, $J$ = 20.9 Hz), 38.2, 32.2, 31.7, 22.2, 13.9 ppm. HRMS calculated for $C_{13}H_{17}F$ [$M^+$]: 192.1314, found 192.1317.

**(*E*)-1-(Hept-2-enyl)-4-vinylbenzene (2s).** Colorless liquid, 0.186 g (93%). $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$ 7.33 (d, $J$ = 8.0 Hz, 2H), 7.14 (d, $J$ = 8.0 Hz, 2H), 6.69 (dd, $J$ = 10.8, 17.6 Hz, 1H), 5.70 (d, $J$ = 17.6 Hz, 1H), 5.58–5.46 (m, 2H), 5.18 (d, $J$ = 11.2 Hz, 1H), 3.31 (d, $J$ = 5.6 Hz, 2H), 2.02 (dt, $J$ = 6.0, 6.8 Hz, 2H), 1.39–1.26 (m, 4H), 0.89 (t, $J$ = 7.2 Hz, 3H) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): $\delta$ 140.9, 136.7, 135.4, 132.2, 128.6, 128.5, 126.2, 112.9, 38.8, 32.2, 31.7, 22.2, 13.9 ppm. HRMS calculated for $C_{15}H_{20}$ [$M^+$]: 200.1565, found 200.1572.

## Acknowledgements

Financial support from the National Science Council of Taiwan, ROC, under Grant No. NSC 99-2113-M-005-005-MY3 is appreciated.

## Notes and references

1 (*a*) *Metal-Catalyzed Cross-Coupling Reactions*, ed. F. Diederich and P. J. Stang, Wiley-VCH, Weinheim, 1998; (*b*) H. Geissler, in *Transition Metals for Organic Synthesis*, ed. M. Beller and C. Bolm, Wiley-VCH, Weinheim, 1998, Ch. 2.10, pp. 158–183; (*c*) J. Tsuji, *Transition Metal Reagents and Catalysts*, Wiley, Chichester, U.K., 2000, Ch. 3, pp. 27–108; (*d*) O. Reiser, *Angew. Chem., Int. Ed.*, 2006, **45**, 2838.
2 (*a*) *Handbook of Organopalladium Chemistry for Organic Synthesis*, ed. E. Negishi, Wiley-Interscience, New York, 2002, vol. 1, Part III; (*b*) *Metal-Catalyzed Cross-Coupling Reactions*, ed. A. de Meijere and F. Diederich, Wiley-VCH, Weinheim, 2004.
3 (*a*) K. Tamao, K. Sumitani and M. Kumada, *J. Am. Chem. Soc.*, 1972, **94**, 4374; (*b*) K. Tamao, K. Sumitani, Y. Kiso, M. Zembayashi, A. Fujioka, S. Kodama, I. Nakajima, A. Minato and M. Kumada, *Bull. Chem. Soc. Jpn.*, 1976, **49**, 1958.
4 (*a*) A. Suzuki, *J. Organomet. Chem.*, 1999, **576**, 147; (*b*) N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 2457; (*c*) G. A. Molander and B. Canturk, *Angew. Chem., Int. Ed.*, 2009, **48**, 9240; (*d*) G. A. Molander and D. L. Sandrock, *Org. Lett.*, 2009, **11**, 2369; (*e*) G. A. Molander and A. R. Brown, *J. Org. Chem.*, 2006, **71**, 7491.
5 (*a*) V. Farina, V. Krishnamurthy and W. J. Scott, *Org. React.*, 1997, **50**, 1; (*b*) J. K. Stille, *Pure Appl. Chem.*, 1985, **57**, 1771; (*c*) J. K. Stille, *Angew. Chem., Int. Ed. Engl.*, 1986, **25**, 508; (*d*) T. N. Mitchell, *Synthesis*, 1992, 803.
6 (*a*) N. Jabri, A. Alexakis and J. F. Normant, *Tetrahedron Lett.*, 1981, **22**, 959; (*b*) N. Jabri, A. Alexakis and J. F. Normant, *Tetrahedron Lett.*, 1981, **22**, 3851; (*c*) A. Alexakis, C. Chuit, M. Commercon-Bourgain, J. P. Foulon, N. Jabri, P. Mangeney and J. F. Normant, *Pure Appl. Chem.*, 1984, **56**, 91.
7 (*a*) I. Pèrez, J. P. Sestelo and L. A. Sarandeses, *Org. Lett.*, 1999, **1**, 1267; (*b*) I. Pèrez, J. P. Sestelo and L. A. Sarandeses, *J. Am. Chem. Soc.*, 2001, **123**, 4155.
8 S. I. Murahashi, *J. Organomet. Chem.*, 2002, **653**, 27.
9 S. E. Denmark and M. H. Ober, *Aldrichimica Acta*, 2003, **36**, 75.
10 E. Riguet, M. Alami and G. Cahiez, *Tetrahedron Lett.*, 1997, **38**, 4397.
11 (*a*) E. Negishi and Z. Owczarczyk, *Tetrahedron Lett.*, 1991, **32**, 6683; (*b*) M. Pour and E. Negishi, *Tetrahedron Lett.*, 1996, **37**, 4679; (*c*) M. Pour and E. Negishi, *Tetrahedron Lett.*, 1997, **38**, 525; (*d*) K. E. Drouet and E. A. Theodorakis, *J. Am. Chem. Soc.*, 1999, **121**, 456; (*e*) S. Ribe, R. K. Kondru, D. N. Beratan and P. Wipf, *J. Am. Chem. Soc.*, 2000, **122**, 4608; (*f*) E. Negishi, A. Alimardanov and C. Xu, *Org. Lett.*, 2000, **2**, 65; (*g*) F. Zeng and E. Negishi, *Org. Lett.*, 2001, **3**, 719; (*h*) T. W. Lee and E. J. Corey, *J. Am. Chem. Soc.*, 2001, **123**, 1872; (*i*) C. F. Thompson, T. F. Jamison and E. N. Jacobsen, *J. Am. Chem. Soc.*, 2001, **123**, 9974; (*j*) T. Hu and J. S. Panek, *J. Org. Chem.*, 1999, **64**, 3000; (*k*) H. Ghasemi, L. M. Antunes and M. G. Organ, *Org. Lett.*, 2004, **6**, 2913; (*l*) X. Zeng, F. Zeng and E. Negishi, *Org. Lett.*, 2004, **6**, 3245.
12 E. Negishi and S. Baba, *Chem. Commun.*, 1976, 597.
13 (*a*) A. Suzuki and H. C. Brown, *Suzuki Coupling; Organic Syntheses via Boranes Series*, Aldrich Chemical Co., Milwaukee, 2003, vol. 3; (*b*) N. Jabri, A. Alexakis and J. F. Normant, *Tetrahedron Lett.*, 1982, **23**, 1589; (*c*) K. Takami, H. Yorimitsu and K. Oshima, *Org. Lett.*, 2002, **4**, 2993; (*d*) E. Negishi, D. E. van Horn and T. Yoshida, *J. Am. Chem. Soc.*, 1985, **107**, 6639; (*e*) S. Gagneur, J. L. Montchamp and E. Negishi, *Organometallics*, 2000, **19**, 2417; (*f*) J. F. Normant and A. Alexakis, *Synthesis*, 1981, 841; (*g*) A. Satoh and A. Suzuki, *Tetrahedron Lett.*, 1988,

**29**, 1811; (*h*) E. Negishi, M. Ay, Y. V. Gulevich and Y. Noda, *Tetrahedron Lett.*, 1993, **34**, 1437; (*i*) A. López-Pérez, J. Adrio and J. C. Carretero, *Org. Lett.*, 2009, **11**, 5514.

14 (*a*) H. Avedissian, L. Bérillon, G. Cahiez and P. Knochel, *Tetrahedron Lett.*, 1998, **39**, 6163; (*b*) B. H. Lipshutz, T. Butler and A. Lower, *J. Am. Chem. Soc.*, 2006, **128**, 15396; (*c*) S. L. Wiskur, A. Korte and G. C. Fu, *J. Am. Chem. Soc.*, 2004, **126**, 82; (*d*) Y. M. A. Yamada, K. Takeda, H. Takahashi and S. Ikegami, *J. Org. Chem.*, 2003, **68**, 7733; (*e*) B. H. Lipshutz, G. Bülow, R. F. Lowe and K. L. Stevens, *Tetrahedron*, 1996, **52**, 7265; (*f*) B. H. Lipshutz, S. Kim, P. Mollard and K. L. Stevens, *Tetrahedron*, 1998, **54**, 1241; (*g*) B. Liégault, J.-L. Renaud and C. Bruneau, *Chem. Soc. Rev.*, 2008, **37**, 290.

15 E. Negishi, A. O. King and N. Okukado, *J. Org. Chem.*, 1977, **42**, 1821.

16 (*a*) T. L. May, J. A. Dabrowski and A. H. Hoveyda, *J. Am. Chem. Soc.*, 2011, **133**, 736; (*b*) F. Gao, K. P. McGrath, Y. Lee, K. Mandai and A. H. Hoveyda, *J. Am. Chem. Soc.*, 2010, **132**, 14315; (*c*) Y. Lee, K. Akiyama, D. Gillingham, M. K. Brown and A. H. Hoveyda, *J. Am. Chem. Soc.*, 2008, **130**, 446; (*d*) C. Hawner, D. Müller, L. Gremaud, A. Felouat, S. Woodward and A. Alexakis, *Angew. Chem., Int. Ed.*, 2010, **49**, 7769; (*e*) M. Tissot, D. Müller, S. Belot and A. Alexakis, *Org. Lett.*, 2010, **12**, 2770; (*f*) C. Hawner, K. Li, V. Cirriez and A. Alexakis, *Angew. Chem., Int. Ed.*, 2008, **47**, 8211.

17 (*a*) D. B. Biradar and H.-M. Gau, *Org. Lett.*, 2009, **11**, 3386; (*b*) C.-A. Chen, K.-H. Wu and H.-M. Gau, *Adv. Synth. Catal.*, 2008, **350**, 1626; (*c*) K.-H. Wu, C.-A. Chen and H.-M. Gau, *Angew. Chem., Int. Ed.*, 2007, **46**, 5373; (*d*) K.-H. Wu and H.-M. Gau, *J. Am. Chem. Soc.*, 2006, **128**, 14808; (*e*) K.-H. Wu, D.-W. Chuang, C.-A. Chen and H.-M. Gau, *Chem. Commun.*, 2008, 2343.

18 (*a*) D. B. Biradar and H.-M. Gau, *Chem. Commun.*, 2011, **47**, 10467; (*b*) S.-L. Ku, X.-P. Hui, C.-A. Chen and H.-M. Gau, *Chem. Commun.*, 2007, 3847.

19 D. B. Biradar and H.-M. Gau, *Org. Lett.*, 2009, **11**, 499.

