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# Nickel-Catalyzed Coupling Reaction of Sterically Congested cis Bromides and Lithium Alkenylborates

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**Abstract:** Lithium alkenyl borates of general structure 5 ( $R_T$  = alkenyl) couple with *cis* bromides 1 at room temperature overnight in the presence of NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> as a catalyst to furnish dienes of general structure 3 with retention of the olefin geometries present in both coupling partners. By using this reaction, *cis*, *trans* dienes 3 (R = TBDMS, TES, TBDPS; R<sup>1</sup> = n-C<sub>5</sub>H<sub>11</sub>, c-C<sub>6</sub>H<sub>11</sub>; R<sup>2</sup> = H; R<sup>3</sup> = n-C<sub>5</sub>H<sub>11</sub>, Ph) and *cis*, *cis* diene 3 (R = TBDMS; R<sup>1</sup> =  $R^2$  = n-C<sub>5</sub>H<sub>11</sub>; R<sup>3</sup> = H) are synthesized in good yields. © 1998 Elsevier Science Ltd. All rights reserved.

#### **INTRODUCTION**

The *cis*, *trans* conjugated olefin systems with the 1'-hydroxyalkyl (or 1'-alkoxyalkyl) group attached to the *cis* olefin end is frequently seen in biologically important compounds and synthetic intermediates such as leukotriene  $B_4$ ,<sup>1</sup> the leukotriene  $B_4$  metabolites,<sup>1</sup> fostriecin,<sup>2</sup> himbacine,<sup>3</sup> etc. For construction of this unit, one possible method is the coupling reaction of the *cis* bromides 1 with alkenyl organometallics 2 in the presence of a transition metal catalyst (eq 1).<sup>4</sup> The advantage of this approach is the ready availability of the *cis* bromides 1 with high stereoselectivity and high optical purity.<sup>4c,5</sup> However, *cis* bromides of type 1 are generally less reactive substrates in the coupling reaction because of the steric congestion. To circumvent such a difficulty, improved conditions and other methods have been developed.<sup>3,6</sup>



Recently, we have reported the highly reactive reagents 4 for the coupling reactions. The borates 4 deliver the aryl and alkenyl group  $R_T$  efficiently to secondary allylic carbonates<sup>7</sup> and aryl mesylates<sup>8</sup> even at



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#### Scheme 1

room temperature, while the borates are compatible with ester groups present in the substrates. Since these substrates were among the less reactive partners in the coupling reaction with the classical organometallics,<sup>9</sup> the success with the borates 4 prompted us to investigate the possibility of the borates of type 4 for the coupling with the *cis* bromides 1. Although the borate 4 ( $R_T = (E)$ -1-heptenyl) indeed coupled with 1 ( $R^1 = n - C_5 H_{11}$ , R = TBDMS) under the nickel catalyst, somewhat higher temperature (40-45 °C) was required. This result indicates the low reactivity of 1 in the coupling reaction. Nevertheless, to realize efficient coupling with the less reactive 1, investigation has been continued and the borates of general structure 5 were elucidated, with which the coupling reaction went to completion at room temperature. Herein we report the results of these studies.

## **RESULTS AND DISCUSSION**

Four *cis* bromides **1a-d**, chosen for the study, were prepared from *trans* allylic alcohols **6a,b** stereoselectively (>98% *trans*) and in high yields according to the literature procedure<sup>5</sup> as delineated in Scheme 1. On the other hand, the boronate esters **9a-g**, which are precursors of the lithium borates **10a-g**,



Scheme 2. Preparation of the Borates 10a-g.



Scheme 3. Preparation of the Borate 12.



Scheme 4. Preparation of the Borate 14.

respectively, were synthesized efficiently through hydroboration using  $HBBr_2$  followed by esterification with the corresponding diols according to the procedure of  $Brown^{10}$  (Scheme 2). Furthermore, to examine the potency of the most efficient diol-ligand (2,2-dimethyl-1,3-propanediol ligand) (*vide infra*), boronate esters 11 and 13 were prepared by the literature procedures<sup>11,12</sup> in good yields and transferred into the borates 12 and 14 with MeLi as shown in Scheme 3 and 4, respectively.

First, the coupling reaction was examined by using 1a and the borate 10a. Thus, boronate ester 9a (1.5 equiv.) was converted into the borate 10a with MeLi (1.5 equiv.) at 0-5 °C for 30 min and 10a without isolation was submitted to the coupling with 1a (1 equiv.) in the presence of 10 mol% of NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> in THF. Unfortunately, several reactions at room temperature were capricious. However, slightly elevated temperature of ca 40-45 °C reproducibly led the reaction to completion, furnishing the *cis*, *trans* diene 15a in 76% yield (Table 1, entry 1). Fortunately, the *cis*, *trans* conjugated diene system, which is in general somewhat unstable, was retained under the conditions examined. A related borate with a Bu ligand, which are pivotal in the coupling with aryl mesylates,<sup>8</sup> did not provide better results in this case.

The required temperature (40-45 °C) might be unacceptable in certain cases when applied the reaction to more complicated compounds. We then turned our attention to the possibility of changing the ligand on the borates because the reactivity of the borates in the nickel-catalyzed coupling reaction with the allylic carbonates is highly dependent on the diol-ligand.<sup>7</sup> We selected boronate esters 9b-g and converted them into the borates 10b-g, respectively (Scheme 2). Coupling reaction with 1a was carried out at room temperature for 12 h in the presence of NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (10 mol%) and conversion of 1a and the geometric purity of the product 15a were analyzed by <sup>1</sup>H NMR spectroscopy. The results are also summarized in Table 1 (entries 2-7). The reaction was highly dependent on the diol-ligand and the order of reactivity was not at all parallel to that observed in the coupling with allylic carbonates: the best result was obtained with the borate 10g to afford 15a in 90% yield (entry 7), while with sterically less demanding borates 10b, d and homologue of 10a (ie., 10e) resulted in unsatisfactory conversions. In every entry, the cis stereochemistry is maintained in the product 15a (>95% purity). Attempted reaction of 1a and 10g with PdCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> as a catalyst was marginal (data not shown).

**O**R

|       | 1 <b>a</b> -c | + 10 <b>a</b> -g    | NiCl <sub>2</sub> (PI | ₽ħ <sub>3</sub> ) <sub>2</sub> | C <sub>5</sub> H <sub>11</sub> | 15a-c                |                  |
|-------|---------------|---------------------|-----------------------|--------------------------------|--------------------------------|----------------------|------------------|
|       |               |                     |                       | product <sup>a</sup>           |                                |                      |                  |
| entry | bromide       | borate <sup>b</sup> | temp. (°C)            | No.                            | R                              | yield,% <sup>c</sup> | purity,%         |
| 1     | la            | 10a                 | 40-45                 | 15a                            | TBDMS                          | 76                   | >95 <sup>d</sup> |
| 2     | 1 <b>a</b>    | 10b                 | rt                    | 15a                            | TBDMS                          | (56)                 | >95 <sup>d</sup> |
| 3     | 1a            | 10c                 | rt                    | 15a                            | TBDMS                          | (0)                  |                  |
| 4     | la            | 10d                 | rt                    | 15a                            | TBDMS                          | (68)                 | >95 <sup>d</sup> |
| 5     | la            | 10e                 | rt                    | 15a                            | TBDMS                          | (79)                 | >95 <sup>d</sup> |
| 6     | 1a            | 10f                 | rt                    | 15a                            | TBDMS                          | (0)                  |                  |
| 7     | 1a            | 10g                 | rt                    | 15a                            | TBDMS                          | 90 (100)             | 99°              |
| 8     | 1b            | 10g                 | rt                    | 15b                            | TES                            | 80                   | 97 <sup>e</sup>  |
| 9     | 1c            | 10g                 | rt                    | 15c                            | TBDPS                          | 84                   | 93 <sup>e</sup>  |

Table 1. Coupling of cis Bromides 1a-c and Borates 10a-g with NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (10 mol%).<sup>a</sup>

<sup>a</sup> Reactions were carried out with NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (10 mol%) for 10-16 h at the specified temperature in THF. <sup>b</sup> Borates were prepared from the corresponding 9 and MeLi at 0-5 °C for 15-30 min before use. <sup>c</sup> Numberes in the parentheses refer to conversion of the bromide 1a. <sup>d</sup> NMR determination of the crude product. <sup>e</sup> NMR determination of the purified product.

Then the power borate 10g was applied to the coupling with other *cis* bromides 1b,c possessing different hydroxyl protecting groups. The reactions proceeded smoothly and the corresponding products 15b,c were obtained in high yields with retention of the olefin stereochemistries (entries 8 and 9 of Table 1). The high reactivity realized with the 2,2-dimethyl-1,3-propanediol-ligand was not obstructed by the steric hindrance near the reaction site.

To check the generality of the 2,2-dimethyl-1,3-propanediol-ligand for the borates, other entries of coupling reactions producing the following dienes 16-18 were carried out. As expected, these products were obtained in all cases without difficulty in high yields. The following comments are worth mentioning: (1) the sterically more crowded *cis* bromide 1d could participate in the reaction; (2) although the dienes 17 and 18 are chemically more unstable than 15a due to the additional *cis* double bond or conjugation with phenyl group, they were obtained with retention of the olefin geometries of the coupling partners.



## CONCLUSION

We have presented new alkenyl borates of general structure 5 ( $R_T$  = alkenyl) for coupling of the *cis* bromides 1 with steric congestion. The reaction proceeded efficiently at room temperature with a slight excess of 5, which was prepared *in situ* from 1.5 equiv. of the boronate esters and 1.5 equiv. of MeLi. Moreover, the reaction proceeded with retention of the olefin geometries. Since boronate esters are air and moisture stable, and they can be synthesized by various methods using acetylenes, vinyl halides, and aldehydes, these synthetic advantages coupled with the powerful reactivity mentioned above should open new strategies for synthesis of the sterically hindered dienes. Synthesis of the LTB<sub>4</sub> metabolites using the present reaction is now under investigation.

#### **EXPERIMENTAL**

**General:** Infrared (IR) spectra are reported in wave numbers (cm<sup>-1</sup>). <sup>1</sup>H NMR (300 MHz) and <sup>13</sup>C NMR (75 MHz) spectra were measured in CDCl<sub>3</sub> using SiMe<sub>4</sub> ( $\delta = 0$  ppm) and the center line of CDCl<sub>3</sub> triplet ( $\delta = 77.1$  ppm) as internal standards, respectively. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl. (*E*)-1-Trimethylsilyl-1-octen-3-ol (**6a**) and (*E*)-1-cyclohexyl-3-trimethylsilyl-2-propen-1-ol (**6b**) were prepared according to the literatures, <sup>5b,c</sup> and NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> according to the literature method. <sup>13</sup>All of the reactions were carried out under nitrogen atmosphere.

(Z)-1-Bromo-1-octenyl-3-ol (7a). To a solution of the alcohol 6a (5.02 g, 25.1 mmol) in  $CH_2Cl_2$  (50 mL) was added  $Br_2$  (1.42 mL, 27.6 mmol) dropwise at -70 °C. After 10 min at -70 °C, the solution was poured into a mixture of  $Na_2S_2O_7$  aq. solution and hexane with vigorous stirring. After separation of the layers, the aqueous layer was extracted with hexane. The combined hexane solutions were dried over MgSO<sub>4</sub> and concentrated to give the bromine adduct quantitatively.

To the above adduct dissolved in THF (25 mL) was added *n*-Bu<sub>4</sub>NF (27.5 mL, 1 M in THF, 27.5 mmol) dropwise at -70 °C. After 15 min at -70 °C, the solution was poured into brine and the product was extracted with Et<sub>2</sub>O repeatedly. The combined extracts were dried over MgSO<sub>4</sub> and concentrated in vacuo to leave an oil, which was distilled under reduced pressure to give *cis* bromide **7a** (4.52 g, 87%): bp ca 110 °C/ 2 mmHg; <sup>1</sup>H NMR  $\delta$  0.88 (t, *J* = 7 Hz, 3 H), 1.24-1.68 (m, 8 H), 2.05 (br s, 1 H), 4.58 (q, *J* = 7 Hz, 1 H), 6.13 (t, *J* = 7 Hz, 1 H), 6.23 (d, *J* = 7 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  137.8, 108.4, 70.0, 36.0, 31.6, 24.6, 22.5, 14.0; IR (neat) 3338, 3080, 1624 cm<sup>-1</sup>.

(Z)-1-Bromo-3-((*tert*-butyldimethylsilyl)oxy)-1-octene (1a). To a solution of the alcohol 7a (1.80 g, 8.70 mmol) and imidazole (0.90 g, 13 mmol) in DMF (20 mL) was added TBDMSCl (1.60 g, 10.6 mmol). The solution was stirred overnight at room temperature and poured into a mixture of hexane and sat. NaHCO<sub>3</sub> aq. solution with vigorous stirring. The resulting layers were separated and aqueous layer was extracted with hexane twice. The combined extracts were dried over MgSO<sub>4</sub> and concentrated in vacuo to leave an oil, which was purified by chromatography on silica gel to afford the TBDMS ether 1a (2.75 g, 98%): bp 120 °C/2 mmHg; <sup>1</sup>H NMR  $\delta$  0.04 (s, 3 H), 0.08 (s, 3 H), 0.86-0.91 (m, 12 H), 1.22-1.57 (m, 8 H), 4.54 (q, J = 7 Hz, 1 H), 6.08 (t, J = 7 Hz, 1 H), 6.11 (d, J = 7 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  139.2, 106.0, 71.0, 37.0,

31.7, 25.8, 24.6, 22.6, 18.1, 14.0, -4.5, -5.0; IR (neat) 3080, 1622 cm<sup>-1</sup>.

(Z)-1-Bromo-3-((triethylsilyl)oxy)-1-octene (1b). A mixture of the alcohol 7a (1.00 g, 4.83 mmol), imidazole (0.66 g, 9.7 mmol), and TESCI (0.99 mL, 5.8 mmol) in DMF (10 mL) was stirred overnight to give the TES ether 1b, which was isolated as described above (1.40 g, 91%): bp 150 °C/ 2 mmHg; <sup>1</sup>H NMR  $\delta$  0.60 (q, J = 8 Hz, 6 H), 0.88 (t, J = 7 Hz, 3 H), 0.95 (t, J = 8 Hz, 9 H), 1.22-1.60 (m, 8 H), 4.54 (q, J = 7 Hz, 1 H), 6.09 (t, J = 7 Hz, 1 H), 6.12 (d, J = 7 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  139.0, 106.1, 70.7, 37.2, 31.8, 24.6, 22.6, 14.0, 6.7, 4.7; IR (neat) 3080, 1622 cm<sup>-1</sup>.

(Z)-1-Bromo-3-((*tert*-butyldiphenylsilyl)oxy)-1-octene (1c). A mixture of the alcohol 7a (1.00 g, 4.83 mmol), imidazole (0.50 g, 7.2 mmol), and TBDPSCl (1.5 mL, 5.8 mmol) in DMF (10 mL) was stirred overnight to give the TBDPS ether 1c, which was isolated as described above (2.04 g, 95%): <sup>1</sup>H NMR  $\delta$  0.82 (t, J = 7 Hz, 3 H), 1.05 (s, 9 H), 1.09-1.62 (m, 8 H), 4.57-4.66 (m, 1 H), 5.98 (dd, J = 1.2, 7 Hz, 1 H), 6.14 (t, J = 7 Hz, 1 H), 7.30-7.46 (m, 6 H), 7.60-7.71 (m, 4 H); <sup>13</sup>C NMR  $\delta$  138.3, 136.10, 136.08, 134.3, 129.74, 129.68, 127.7, 127.6, 106.5, 71.8, 37.1, 31.7, 27.0, 24.1, 22.5, 19.3, 14.0; IR (neat) 3070, 3043, 1622, 1093 cm<sup>-1</sup>.

(Z)-3-Bromo-1-cyclohexyl-2-propen-1-ol (7b). According to the procedure for the preparation of the *cis* bromide 7a, the alcohol 6b (2.75 g, 13 mmol) was converted first with  $Br_2$  (0.74 mL, 14 mmol) in  $CH_2Cl_2$  (15 mL) to the bromine adduct, which was then treated with *n*-Bu<sub>4</sub>NF (14.3 mL, 1 M in THF, 14.3 mmol) in THF (15 mL) to furnish the title compound 7b (2.52 g, 89%): bp 100-130 °C/ 2 mmHg; <sup>1</sup>H NMR  $\delta$  0.94-1.30 (m, 5 H), 1.39-1.55 (m, 1 H), 1.58-1.81 (m, 4 H), 1.84-1.95 (m, 1 H), 2.26 (br peak, 1 H), 4.33 (t, *J* = 7 Hz, 1 H), 6.12 (t, *J* = 7 Hz, 1 H), 6.27 (d, *J* = 7 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  136.3, 109.2, 73.9, 43.2, 28.4, 28.2, 26.4, 26.0, 25.8; IR (neat) 3342, 3078, 1622 cm<sup>-1</sup>.

(Z)-1-Bromo-3-((*tert*-butyldimethylsilyl)oxy)-3-cyclohexyl-1-propene (1d). A mixture of the alcohol 7b (150 mg, 0.68 mmol), imidazole (70 mg, 1.0 mmol), and TBDMSCl (123 mg, 0.82 mmol) in DMF (1.5 mL) was stirred overnight to give the silyl ether 1d, which was isolated as described above (220 mg, 97%): bp 140 °C/2 mmHg; <sup>1</sup>H NMR  $\delta$  0.03 (s, 3 H), 0.07 (s, 3 H), 0.88 (s, 9 H), 0.96-1.28 (m, 5 H), 1.34-1.47 (m, 1 H), 1.58-1.79 (m, 4 H), 1.80-1.91 (m, 1 H), 4.26-4.31 (m, 1 H), 6.06 (dd, J = 7, 8 Hz, 1 H), 6.18 (dd, J = 1, 7 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  137.8, 107.0, 74.8, 44.2, 28.5, 28.4, 26.6, 26.2, 26.1, 25.8, 18.1, -4.4, -5.0; IR (neat) 3080, 1622 cm<sup>-1</sup>.

(E)-Heptenylboronic Acid (8). 1-Heptyne (6.60 mL, 4.84 g, 50 mmol) was placed in a flask and a  $CH_2Cl_2$  solution of HBBr<sub>2</sub> (50 mL, 1.0 M, 50 mmol) was added to it over 30 min, during which time the flask was occasionally immersed to an ice-water bath to prevent a temperature rise. The solution was stirred at room temperature for 6 h and then cold water (10 mL) and  $Et_2O$  (25 mL) were added slowly to it with vigorous stirring. After 15 min, the organic layer was separated, washed with brine, dried over MgSO<sub>4</sub>, and concentrated in vacuo to give the boronic acid 8 (6.41 g, 90%): <sup>1</sup>H NMR (selected peaks)  $\delta$  5.40 and 5.52 (2d, J = 18 and 18 Hz, 0.3 H and 0.7 H), 6.51 and 6.96 (2dt, J = 18, 6 and 18, 6 Hz, 0.3 H and 0.7 H); IR (nujol) 3211, 1633, 1163, 997 cm<sup>-1</sup>.

(E)-2-(1-Heptenyl)-4,5-dimethyl-1,3,2-dioxaborolane (9a): A mixture of the boronic acid 8 (500 mg, 3.52 mmol), 2,3-butanediol (0.33 mL, 3.6 mmol), and granular  $MgSO_4$  (1.5 g) in benzene (15 mL) was stirred at room temperature overnight and filtered through a pad of Celite. The remaining white solid on the Celite was washed with benzene. The filtrates were concentrated in vacuo to give an oil, which was

purified by chromatography on silica gel to give the boronate ester 9a (610 mg, 88%) as a diastereometric mixture of *meso* : dl = 72 : 28, which was distilled under reduced pressure for the coupling reaction before use: bp 80-90 °C/1 mmHg; <sup>1</sup>H NMR  $\delta$  0.87 (t, J = 7 Hz, 3 H), 1.17-1.35 (m, 10 H), 1.35-1.47 (m, 2 H), 2.15 (dq, J = 1.5, 7 Hz, 2 H), 3.96-4.06 and 4.48-4.58 (2m, total 2 H), 5.43 (d, J = 18 Hz, 1 H), 6.65 (dt, J = 18, 7 Hz, 1 H); IR (neat) 1639, 1074, 999, 920 cm<sup>-1</sup>. Anal. calcd for C<sub>11</sub>H<sub>21</sub>BO<sub>2</sub>: C, 67.38; H, 10.79. Found: C, 67.00; H, 10.92.

(*E*)-2-(1-Heptenyl)-1,3,2-dioxaborolane (9b). According to the procedure for 9a, boronic acid 8 (500 mg, 3.52 mmol) was transformed into the title compound 9b (420 mg, 71%) with ethylene glycol (0.20 mL, 3.6 mmol) and granular MgSO<sub>4</sub> (1.5 g) in benzene (1.5 mL): bp ca 70 °C/ 1 mmHg; <sup>1</sup>H NMR  $\delta$  0.87 (t, *J* = 7 Hz, 3 H), 1.22-1.35 (m, 4H), 1.35-1.47 (m, 2 H), 2.16 (dq, *J* = 1.5, 7 Hz, 2 H), 4.22 (s, 4 H), 5.46 (dt, *J* = 18, 1.5 Hz, 1 H), 6.66 (dt, *J* = 18, 7 Hz, 1 H); IR (neat) 1637, 1028, 1001, 947 cm<sup>-1</sup>. Anal. calcd for C<sub>9</sub>H<sub>17</sub>BO<sub>2</sub>: C, 64.33; H, 10.20. Found: C, 63.46; H, 10.05.

(*E*)-2-(1-Heptenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (9c). According to the procedure for 9a, boronic acid 8 (500 mg, 3.52 mmol) was transformed into the title compound 9c (650 mg, 82%) with pinacol (0.43 g, 3.6 mmol) and granular MgSO<sub>4</sub> (1.5 g) in benzene (15 mL): bp 100-140 °C/ 2 mmHg; <sup>1</sup>H NMR  $\delta$  0.87 (t, *J* = 7 Hz, 3 H), 1.22-1.34 (m, 16 H), 1.35-1.47 (m, 2 H), 2.14 (dq, *J* = 7 Hz, 2 H), 5.42 (dt, *J* = 18, 1.5 Hz, 1 H), 6.63 (dt, *J* = 18, 7 Hz, 1 H); IR (neat) 1637, 1147, 999 cm<sup>-1</sup>. Anal. calcd for C<sub>13</sub>H<sub>25</sub>BO<sub>2</sub>: C, 69.66; H, 11.24. Found: C, 69.96; H, 11.25.

(*E*)-2-(1-Heptenyl)-1,3,2-dioxaborinane (9d). According to the procedure for 9a, boronic acid 8 (500 mg, 3.52 mmol) was transformed into the title compound 9d (540 mg, 84%) with 1,3-propanediol (0.26 mL, 3.6 mmol) and granular MgSO<sub>4</sub> (1.5 g) in benzene (15 mL): bp 80 °C/1 mmHg; <sup>1</sup>H NMR  $\delta$  0.86 (t, J = 7 Hz, 3 H), 1.21-1.33 (m, 4 H), 1.33-1.44 (m, 2 H), 1.91-1.99 (m, 2 H), 2.10 (dq, J = 1.5, 7 Hz, 2 H), 4.02 (t, J = 5.5 Hz, 4 H), 5.30 (dt, J = 18, 1.5 Hz, 1 H), 6.50 (dt, J = 18, 7 Hz, 1 H); IR (neat) 1639, 1101, 999 cm<sup>-1</sup>. Anal. calcd for C<sub>10</sub>H<sub>19</sub>BO<sub>2</sub>: C, 65.97; H, 10.52. Found: C, 65.95; H, 10.52.

(*E*)-2-(1-Heptenyl)-4,6-dimethyl-1,3,2-dioxaborinane (9e). According to the procedure for .9a, boronic acid 8 (1.0 g, 7.0 mmol) was transformed into the title compound 9e (1.38 g, 94%) as a diastereomeric mixture of *meso* : dl = 41 : 59 with 2,4-pentanediol (0.77 mL, 7.0 mmol) and granular MgSO<sub>4</sub> (3.0 g) in benzene (30 mL): bp ca 100 °C/1 mmHg; <sup>1</sup>H NMR  $\delta$  0.86 (t, J = 7 Hz, 3 H), 1.22-1.34 (m, 10 H), 1.33-1.45 (m, 2 H), 1.73 and 1.88 (t, J = 5 Hz and dt, J = 14, 3 Hz, total 2 H), 2.10 (m, 2 H), 4.06-4.17 and 4.21-4.31 (2m, total 2 H), 5.29-5.37 (m, 1 H), 6.46-6.59 (m, 1 H); IR (neat) 1637, 1128, 999, 904 cm<sup>-1</sup>. Anal. calcd for C<sub>12</sub>H<sub>23</sub>BO<sub>2</sub>: C, 68.59; H, 11.03. Found: C, 68.63; H, 11.01.

(*E*)-2-(1-Heptenyl)-4,4,6-trimethyl-1,3,2-dioxaborinane (9f). According to the procedure for 9a, boronic acid 8 (1.0 g, 7.0 mmol) was transformed into the title compound 9f (1.20 g, 77%) with 2-methyl-2,4-pentanediol (0.72 mL, 5.64 mmol) and granular MgSO<sub>4</sub> (3.0 g) in benzene (30 mL): bp ca 110 °C/ 1 mmHg; <sup>1</sup>H NMR  $\delta$  0.87 (t, *J* = 7 Hz, 3 H), 1.23-1.32 (m, 13 H), 1.34-1.43 (m, 2 H), 1.49 (dd, *J* = 11, 14 Hz, 1 H), 1.76 (dd, *J* = 3, 14 Hz, 1 H), 2.10 (dq, *J* = 1.5, 7 Hz, 2 H), 4.15-4.26 (m, 1 H), 5.33 (dt, *J* = 18, 1.5 Hz, 1 H), 6.53 (t, *J* = 18, 7 Hz, 1 H); IR (neat) 1637, 1165, 999 cm<sup>-1</sup>. Anal. calcd for C<sub>13</sub>H<sub>25</sub>BO<sub>2</sub>: C, 69.66; H, 11.24. Found: C, 69.64; H, 11.20.

(E)-2-(1-Heptenyl)-5,5-dimethyl-1,3,2-dioxaborinane (9g). According to the procedure for 9a, boronic acid 8 (1.0 g, 7.0 mmol) was transformed into the title compound 9g (1.30 g, 88%) with 2,2-

dimethyl-1,3-propanediol (0.73 g, 7.0 mmol) and granular MgSO<sub>4</sub> (3.0 g) in benzene (30 mL): bp 120-130 °C/2 mmHg; <sup>1</sup>H NMR  $\delta$  0.86 (t, J = 7 Hz, 3 H), 0.96 (s, 6 H), 1.22-1.34 (m, 4 H), 1.34-1.45 (m, 2 H), 2.11 (dq, J = 1.5, 7 Hz, 2 H), 3.62 (s, 4 H), 5.33 (dt, J = 18, 1.5 Hz, 1 H), 6.53 (dt, J = 18, 7 Hz, 1 H); IR (neat) 1637, 1092, 999 cm<sup>-1</sup>. Anal. calcd for C<sub>12</sub>H<sub>23</sub>BO<sub>2</sub>: C, 68.59; H, 11.03. Found: C, 68.43; H, 11.17.

(Z)-2-(1-Heptenyl)-5,5-dimethyl-1,3,2-dioxaborinane (11). To a solution of (Z)-1iodoheptene (1.0 g, 45 mmol) in  $Et_2O$  (5 mL) was added *t*-BuLi (6.1 mL, 1.64 M in pentane, 10 mmol) slowly at -78 °C. The solution was stirred for 1 h at -78 °C and B(O-*i*-Pr)<sub>3</sub> (1.2 mL, 5.0 mmol) was added dropwise to it. After the addition, the solution was allowed to warm to room temperature over 3 h and poured into brine. To the mixture was added aqueous 1 N HCl and the product was extracted with AcOEt three times. The combined extracts were dried over MgSO<sub>4</sub> and the volatile materials were removed by evaporation to furnish the corresponding boronic acid, which was used for the next reaction without further purification.

To the above boronic acid dissolved in  $Et_2O$  (20 mL) was added 2,2-dimethyl-1,3-propanediol (0.52 g, 5.0 mmol) and MgSO<sub>4</sub> (2.0 g). The resulting mixture was stirred at room temperature overnight and filtered through a pad of Celite with  $Et_2O$ . The remaining solid was washed with  $Et_2O$  twice. The combined filtrates were concentrated in vacuo and the residual oil thus obtained was purified by silica gel chromatography to afford the title boronate ester 11 (0.76 g, 80%), which was distilled under reduced pressure for the coupling reaction before use: bp 80 °C/1 mmHg; <sup>1</sup>H NMR  $\delta$  0.88 (t, J = 7 Hz, 3 H), 0.97 (s, 6 H), 1.24-1.43 (m, 6 H) 2.36 (dq, J = 1.5, 7 Hz, 2 H), 3.64 (s, 4 H), 5.23 (dt, J = 14, 1.5 Hz, 1 H), 6.32 (dt, J = 14, 7 Hz, 1 H); IR (neat) 1626, 1080 cm<sup>-1</sup>. Anal. calcd for  $C_{12}H_{23}BO_2$ : C, 68.59; H, 11.03. Found: C, 68.34; H, 11.00.

(E)-2-(2-Phenyl-1-ethenyl)-5,5-dimethyl-1,3,2-dioxaborinane (13). To an ice-cold solution of  $BH_3 \cdot SMe_2$  (1.0 mL, 10 mmol) in THF (5 mL) was added (-)- $\alpha$ -pinene (3.5 mL, 22 mmol). The solution was stirred for 1 h at 0 °C and then 2 h at room temperature and cooled down to -35 °C. Phenylacetylene (1.0 mL, 9.1 mmol) was added to it and stirring was continued for 1 h at -35 °C and then 3 h at room temperature. Acetaldehyde (7.7 mL, 140 mmol) was added to the solution and the solution was refluxed for 12 h. Evaporation of low-boiling materials afforded the corresponding ethyl boronate ester.

To a solution of the above product dissolved in THF (10 mL) was added 2,2-dimethyl-1,3-propanediol (0.94 g, 9.1 mmol). After 3 h at room temperature, the solution was concentrated in vacuo and the residue was purified by chromatography on silica gel to afford the title compound **13** (1.53 g, 78%) as the white solid, which was distilled under reduced pressure for the coupling reaction: bp 150 °C/1 mmHg; <sup>1</sup>H NMR  $\delta$  1.01 (s, 6 H), 3.71 (s, 4 H), 6.11 (d, J = 18 Hz, 1 H), 7.27-7.52 (m, 6 H); IR (nujol) 3088, 3026, 1624, 1080, 997 cm<sup>-1</sup>. Anal. calcd for C<sub>13</sub>H<sub>17</sub>BO<sub>2</sub>: C, 72.26; H, 7.93. Found: C, 72.43; H, 8.12.

(7Z, 9E)-6-((tert-Butyldimethylsilyl)oxy)-7,9-pentadecadiene (15a). To an ice-cold suspension of the boronate ester 9g (100 mg, 0.48 mmol) and NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (20 mg, 0.031 mmol) in THF (1 mL) was added a ethereal solution of MeLi (0.20 mL, 2.35 M, 0.47 mmol) to generate 10g. After 30 min at 0 °C, *cis* bromide 1a (100 mg, 0.311 mmol) was added to the solution and the cooling bath was removed. The solution was stirred overnight at room temperature and then sat. NH<sub>4</sub>Cl aq. solution was added to it. The mixture was extracted with hexane three times. The combined extracts were dried over MgSO<sub>4</sub> and concentrated in vacuo to leave an oil, which was purified by chromatography on silica gel to give the diene 15a (94 mg, 90%): <sup>1</sup>H NMR  $\delta$  0.02 (s, 3 H), 0.05 (s, 3 H), 0.85-0.91 (m, 15 H), 1.20-1.60 (m, 14 H), 2.10 (q,

J = 7 Hz, 2 H), 4.47-4.55 (m, 1 H), 5.24 (t, J = 11 Hz, 1 H), 5.67 (dt, J = 15, 7 Hz, 1 H), 5.89 (t, J = 11 Hz 1 H), 6.23 (ddd, J = 1, 11, 15 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  136.3, 133.5, 127.9, 125.7, 69.1, 38.5, 32.8, 31.8, 31.4, 28.9, 25.9, 25.0, 22.7, 22.5, 18.2, 14.0, -4.3, -4.8; IR (neat) 3025, 1254, 835, 775 cm<sup>-1</sup>. Anal. calcd for C<sub>21</sub>H<sub>42</sub>OSi: C, 74.48; H, 12.50. Found: C, 74.41; H, 12.42.

(7Z, 9E)-6-((Triethylsilyl)oxy)-7,9-pentadecadiene (15b). According to the procedure for 15a, coupling of bromide 1b (100 mg, 0.31 mmol) and borate 10g, prepared from the boronate ester 9g (95 mg, 0.45 mmol) and MeLi (0.25 mL, 1.80 M in Et<sub>2</sub>O, 0.45 mmol) in THF (1.2 mL), using NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound 15b (84 mg, 80%): <sup>1</sup>H NMR  $\delta$  0.58 (q, J = 8 Hz, 6 H), 0.83-0.99 (m, 15 H), 1.18-1.60 (m, 14 H), 2.10 (q, J = 7 Hz, 2 H), 4.46-4.55 (m, 1 H), 5.25 (t, J = 11 Hz, 1 H), 5.68 (dt, J = 15, 7 Hz, 1 H), 5.90 (t, J = 11 Hz, 1 H), 6.23 (ddd, J = 1, 11, 15 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  136.3, 133.2, 128.1, 125.6, 68.8, 38.6, 32.8, 31.8, 31.3, 28.9, 25.0, 22.6, 22.5, 14.0, 6.8, 4.9; IR (neat) 3025, 1238, 744, 725 cm<sup>-1</sup>; Anal. calcd for C<sub>21</sub>H<sub>42</sub>OSi: C, 74.48; H, 12.50. Found: C, 74.46; H, 12.40.

(7Z, 9E)-6-((*tert*-Butyldiphenylsilyl)oxy)-7,9-pentadecadiene (15c). According to the procedure for 15a, coupling of bromide 1c (100 mg, 0.22 mmol) and borate 10g, prepared from boronate ester 9g (70 mg, 0.33 mmol) and MeLi (0.18 mL, 1.80 M in Et<sub>2</sub>O, 0.32 mmol) in THF (0.9 mL), using NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (13 mg, 0.020 mmol) was carried out at room temperature overnight to afford the title compound 15c (86 mg, 84%): <sup>1</sup>H NMR  $\delta$  0.82 (t, J = 7 Hz, 3 H), 0.88 (t, J = 7 Hz, 3 H), 1.04 (s, 9 H), 1.08-1.64 (m, 14 H), 1.91 (q, J = 7 Hz, 2 H), 4.47-4.55 (m, 1 H), 5.30 (t, J = 10 Hz, 1 H), 5.51 (dt, J = 15, 7 Hz, 1 H), 5.69 (dd, J = 10, 15 Hz, 1 H), 5.79 (t, J = 10 Hz, 1 H), 7.29-7.45 (m, 6 H), 7.62-7.72 (m, 4 H): <sup>13</sup>C NMR  $\delta$  136.2, 136.1, 135.8, 134.8, 134.6, 132.3, 129.6, 129.5, 128.5, 128.4, 127.6, 127.5, 125.7, 69.9, 38.3, 32.6, 31.8, 31.4, 28.8, 27.0, 24.5, 22.5, 19.3, 14.01, 13.98; IR (neat) 3070, 1110, 1066, 822, 734 cm<sup>-1</sup>. Anal. calcd for C<sub>31</sub>H<sub>46</sub>OSi: C, 80.46; H, 10.02. Found: C, 80.62; H, 9.98.

(2Z, 4E)-((*tert*-Butyldimethylsilyl)oxy)-1-cyclohexyl-2,4-decadiene (16). According to the procedure for 15a, coupling of bromide 1d (100 mg, 0.30 mmol) and borate 10g, prepared from boronate ester 9g (88 mg, 0.42 mmol) and MeLi (0.23 mL, 1.8 M in Et<sub>2</sub>O, 0.41 mmol) in THF (1.1 mL), using NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound 16 (77 mg, 73%): <sup>1</sup>H NMR  $\delta$  0.01 (s, 3 H), 0.02 (s, 3 H), 0.80-0.94 (m, 12 H), 1.04-1.94 (m, 17 H), 2.09 (q, *J* = 7 Hz, 2 H), 4.17-4.23 (m, 1 H), 5.21 (t, *J* = 11 Hz, 1 H), 5.66 (dt, *J* = 15, 7 Hz, 1 H), 5.94 (t, *J* = 11 Hz, 1 H), 6.21 (ddd, *J* = 1, 11, 15 Hz, 1 H); <sup>13</sup>C NMR  $\delta$  136.2, 132.2, 128.8, 126.0, 73.3, 44.9, 32.7, 31.3, 28.91, 28.88, 28.85, 26.7, 26.3, 26.2, 25.9, 22.5, 18.2, 14.0, -4.2, -4.9; IR (neat) 3025, 1254, 837, 775 cm<sup>-1</sup>. Anal. calcd for C<sub>22</sub>H<sub>42</sub>OSi: C, 75.36; H, 12.07. Found: C, 75.17; H, 11.82.

(7Z,9Z)-6-((tert-Butyldimethylsilyl)oxy)-7,9-pentadecadiene (17). According to the procedure for 15a, coupling of bromide 1a (100 mg, 0.31 mmol) and borate 12, prepared from boronate ester 11 (95 mg, 0.45 mmol) and MeLi (0.25 mL, 1.80 M in Et<sub>2</sub>O, 0.45 mmol) in THF (1.2 mL), using NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound 17 (86 mg, 82%): <sup>1</sup>H NMR  $\delta$  0.01 (s, 3 H), 0.04 (s, 3 H), 0.84-0.94 (m, 15 H), 1.16-1.64 (m, 14 H), 2.16 (q, *J* = 7 Hz, 2 H), 4.49-4.58 (m, 1 H), 5.32-5.40 (m, 1 H), 5.42-5.53 (m, 1 H), 6.12-6.26 (m, 2 H); <sup>13</sup>C NMR  $\delta$  135.5, 133.6, 123.5, 122.5, 68.8, 38.4, 31.8, 31.4, 29.2, 27.3, 25.9, 25.0, 22.6, 22.5, 18.2, 14.0, -4.3, -4.9; IR (neat) 3040, 3005, 1254, 1078, 835, 775 cm<sup>-1</sup>. Anal. calcd for C<sub>21</sub>H<sub>42</sub>OSi: C, 74.48; H,

12.50. Found: C, 74.21; H, 12.31.

(1E, 3Z)-5-((*tert*-Butyldimethylsilyl)oxy)-1,3-decadiene (18). According to the procedure for 15a, coupling of bromide 1a (100 mg, 0.31 mmol) and borate 14, prepared from boronate ester 13 (97 mg, 0.45 mmol) and MeLi (0.25 mL, 1.8 M in Et<sub>2</sub>O, 0.45 mmol) in THF (1.2 mL), using NiCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound 18 (86 mg, 82%): <sup>1</sup>H NMR  $\delta$  0.05 (s, 3 H), 0.08 (s, 3 H), 0.86-0.91 (m, 12 H), 1.20-1.69 (m, 8 H), 4.59-4.67 (m, 1 H) 5.47 (t, *J* = 11 Hz, 1 H), 6.10 (t, *J* = 11 Hz, 1 H), 6.55 (d, *J* = 16 Hz, 1 H), 7.01 (ddd, *J* = 1, 11, 16 Hz, 1 H), 7.21-7.44 (m, 5 H); <sup>13</sup>C NMR  $\delta$  137.5, 136.5, 133.4, 128.8, 127.8, 126.5, 124.3, 69.3, 38.6, 31.8, 25.9, 25.0, 22.6, 18.2, 14.0, -4.2, -4.8; IR (neat) 3028, 1254, 835, 775 cm<sup>-1</sup>. Anal. calcd for C<sub>22</sub>H<sub>37</sub>OSi: C, 76.90; H, 10.27. Found: C, 76.87; H, 10.42.

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