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ScienceDirect
Tetrahedron 64 (2008) 847–855
Tetrahedron
www.elsevier.com/locate/tet

Synthesis of multiply functionalized benzenes via ruthenium-catalyzed cycloaddition of diiododiynes

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Received 27 June 2007; accepted 17 September 2007
Available online 24 October 2007

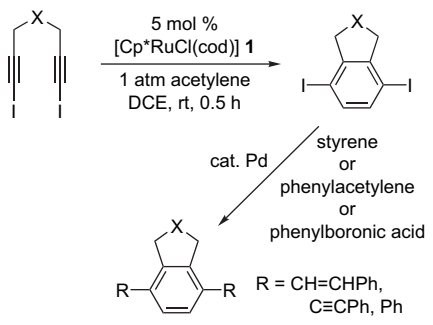
Abstract

Highly functionalized benzenes were precisely synthesized via multi-step processes consisting of ruthenium-catalyzed [2+2+2] cycloaddition of diiododiynes with an ethynylboronate or terminal alkynes, and subsequent chemo- and regio-selective palladium-catalyzed C–C bond-forming reactions of the resulting cycloadducts. The sequential cycloaddition/coupling process was applied to the synthesis of oligo(*p*-phenylene ethynylene)s.

1. Introduction

Despite its synthetic performance assembling highly substituted benzenes in a single operation, transition-metal-*catalyzed* [2+2+2] cyclotrimerization of alkynes has been considered to be less useful in synthetic organic chemistry.[1,2] This is because intermolecular reactions of several different alkynes usually lead to a mixture of cycloadducts as a result of low chemo- and regio-selectivities. Thus, considerable efforts have mainly focused on intramolecular variants with diynes and triynes, providing a reliable route to polycyclic benzene derivatives.[3]

Numerous transition-metal elements have been found to promote alkyne cyclotrimerizations, and most attention has particularly focused on group 9 and 10 transition elements such as Co, Rh, Ir, Ni, and Pd.[1,3] With respect to group 8 triads, however, some stoichiometric and catalytic cyclotrimerizations with limited scope have been reported.[4] Recently, catalytic intramolecular cyclotrimerizations of triynes and 1,6-diynes were accomplished by Blechert, Witulski, and their co-workers with first generation Grubbs catalyst,[5] and by us with Cp*RuCl(cod) (**1**: Cp*=η^5-C_5Me_5, cod=1,5-cyclooctadiene).[6] We further succeeded in applying the Cp*RuCl-catalyzed cyclotrimerization to alkynylboronates to obtain cycloadducts without loss of the boronate moiety, providing powerful synthetic routes to highly functionalized benzenes in combination with various transition-metal-catalyzed transformations of the resultant arylboronates.[7] Then, we also realized for the first time the Cp*RuCl-catalyzed cycloaddition of diiodo-1,6-diynes with acetylene to furnish *p*-diiodobenzenes, which were further subjected to two-fold palladium-catalyzed couplings such as Sonogashira, Mizoroki–Heck, and Suzuki–Miyaura reactions (Scheme 1).[8] Although this sequential process made the assembly of highly conjugated molecules straightforward, the obtained products were limited to symmetrical systems.[8a]



Scheme 1.

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0040-4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2007.09.086

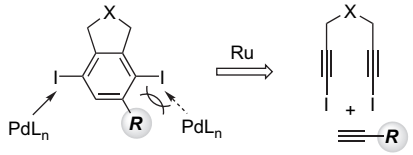


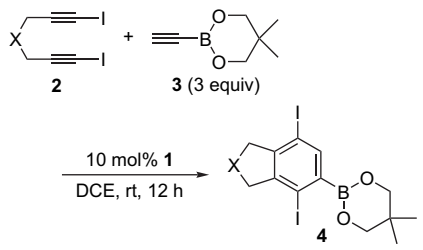
Figure 1.

One can envision that the stepwise derivatization of the two C–I bonds of the diiodobenzenes may lead to a diverse array of unsymmetrical conjugated molecules. Toward this aim, an unsymmetrical cycloadduct derived from a diiododiyne and a terminal alkyne is an ideal scaffold, where one of the two C–I bonds would be strictly discriminated from the other with the difference in their steric environments imposed by the substituent ***R*** (Fig. 1). In addition, if the R group is a boronate, three different catalytic couplings would be sequentially executed on the single aromatic nucleus. In this paper, we wish to report our study along these lines on the synthesis of highly functionalized benzenes from diiododiynes.

2. Results and discussion

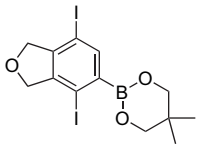
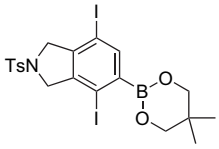
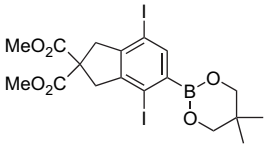
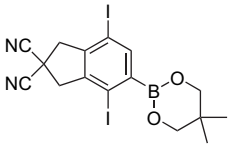
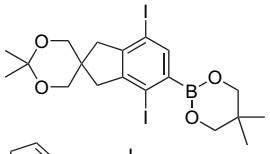
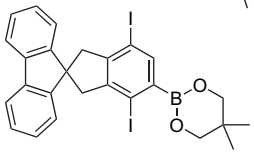
*2.1. Cp*RuCl-catalyzed cycloaddition of diiododiynes with ethynylboronate*

With the goal of developing the efficient synthetic route to highly substituted unsymmetrical benzenes, we first investigated the cycloaddition of the diiododiynes with 2-ethynyl-5,5-dimethyl-1,3,2-dioxaborinane (**3**), yielding unsymmetrical *p*-diiodobenzenes possessing a C–B bond, which would be a useful synthetic handle for further chemoselective functionalization. Diiododiynes **2a–f**, which were used in our previous study,[8a] reacted with 3 equiv of **3** in the presence of 10 mol % **1** at room temperature for 12 h (Scheme 2). Purification by silica gel chromatography gave the desired cycloadducts **4a–f** bearing a boronate moiety as well as two C–I bonds in the yields summarized in Table 1. The ruthenium-catalyzed cycloaddition tolerated functional groups such as an ether, a sulfonamide, an ester, and a nitrile (runs 1–4). As opposed to conventional aromatic iodination under acidic conditions,[9] an acid-sensitive acetal can be used as a protecting group (run 5). Polyaromatic product **4f** was also synthesized in a good yield with an exact substitution pattern (run 6).



Scheme 2.

Table 1
Cycloaddition of diiododiynes **2a–f** with ethynylboronate **3**[a]

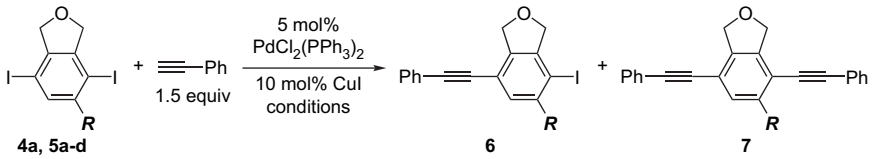
Run	Product	Yield (%)
1		**4a**, 81 (87)[b]
2		**4b**, 85
3		**4c**, 66
4		**4d**, 54
5		**4e**, 73
6		**4f**, 82

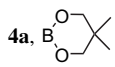
[a] A solution of **2** (0.3 mmol) in DCE was added to a DCE solution of 10 mol % **1** and ethynylboronate **3** (0.9 mmol) by a syringe over 15 min, and the solution was stirred for 12 h at room temperature.
[b] Yield from 5 mmol of **2a**.

2.2. Differentiation of two C–I bonds with Sonogashira coupling and consecutive functionalization of diiodophenylboronate by three different catalytic C–C bond formations

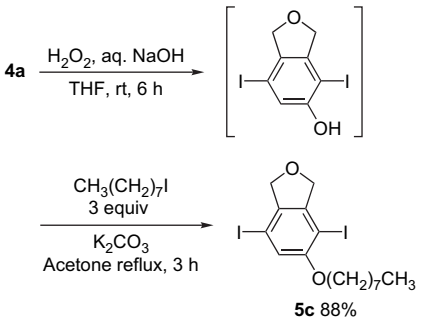
Having obtained the cycloadducts with three reactive C–X bonds (X=I or $B(OR)_2$), we turned our attention to selective transformations of these bonds by taking advantage of palladium-catalyzed cross coupling techniques. At the outset, we attempted the differentiation of the two C–I bonds in different steric environments. Toward this end, Sonogashira coupling is the method of choice,[10] because it enables the formation of a Csp^2–Csp bond without affecting the boronate moiety as reported in the recent literature.[11] In the presence of 5 mol % $PdCl_2(PPh_3)_2$ and 10 mol % CuI, boronate **4a** reacted with 1.5 equiv of phenylacetylene in $^iPr_2NH$ at room temperature (Table 2, run 1). As a result, **4a** was completely consumed within 2 h, but the expected mono coupling product **6a** was accompanied by the undesired double coupling product **7a**. Their isolated yields were 43% and 33%, respectively. To improve

Table 2
Sonogashira coupling of diiodobenzenes **4a**, **5a–d** with phenylacetylene

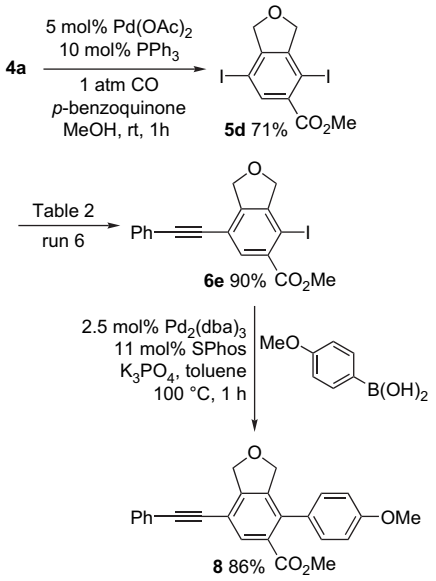


Run	Diiodide, ***R***	Solvent	Additive (1.5 equiv)	T (°C)	*t* (h)	Product, yields (%)	
						6	**7**
1	**4a**, 	$^{i}Pr_2NH$	—	rt	2	**6a**, 43	**7a**, 33
2		^{t}BuOMe	$^{i}Pr_2NH$	0	12	**6a**, 64	**7a**, 17
3	**5a**, ^{n}Bu	^{t}BuOMe	$^{i}Pr_2NH$	0	4	**6b**, 90	**7b**, <5
4	**5b**, Ph	^{t}BuOMe	$^{i}Pr_2NH$	0	8	**6c**, 91	**7c**, <5
5	**5c**, O^{n}Oct	^{t}BuOMe	$^{i}Pr_2NH$	0	4	**6d**, 94	**7d**, <5
6	**5d**, CO_2Me	^{t}BuOMe	$^{i}Pr_2NH$	0	6	**6e**, 90	**7e**, <5

the selectivity, the reaction was repeated at 0 °C otherwise under the same conditions. Although the formation of **7a** was completely suppressed, the reaction failed to go to completion within 24 h, and **6a** turned out to be inseparable from remaining starting material **4a** by silica gel flash chromatography. This result forced us to search for a more efficient Sonogashira-coupling protocol. Thus, with a decreased amount of $^{i}Pr_2NH$ (1.5 equiv), the same coupling reaction was carried out in less coordinating solvent ^{t}BuOMe at 0 °C (run 2). As expected, the reaction reached completion within 12 h, and **6a** was obtained in an increased yield of 64%. Since further attempts failed to improve the yield of **6a**, the impact of the substituent ***R*** on the selectivity was next investigated (runs 3–5). To our surprise, the Sonogashira coupling of *n*-butyl- and phenyl-substituted **5a** and **5b** completed within 4 and 8 h, respectively, under the optimal conditions. In addition, the desired mono coupling products **6b** and **6c** were almost exclusively obtained in more than 90% isolated yields. With these encouraging results in hand, the electronic influence of the substituent ***R*** was further examined (runs 5 and 6). Electron-rich ether **5c** was prepared in 88% yield from boronate **4a** by the treatment with hydrogen peroxide under basic conditions and subsequent etherification of the resultant phenol (Scheme 3), while electron-deficient benzoate **5d** was obtained in 71% yield via Pd(II)-catalyzed methoxycarbonylation of **4a** with our own protocol (Scheme 4).[7d,e] The Sonogashira coupling of **5c** and **5d** uneventfully proceeded under the same



Scheme 3.



Scheme 4.

conditions to selectively afford the corresponding diarylacetylenes **6d** and **6e** in 94% and 90% yields, respectively. These results clearly suggested that lower selectivity for **4a** has no relation to the electronic nature of the boronate moiety. It is tentatively proposed that the palladium species released after the first coupling might be directed to the second coupling by the coordination with the oxygen atom on the boronate goup.[12]

According to the above notion, we concluded that the boronate group should be converted to other groups at the very early stage of the consecutive functionalization of the diiodophenylboronates. Along this line, we carried out first the palladium-catalyzed methoxycarbonylation of **4a** to obtain benzoate **5d**, which then successfully underwent highly selective Sonogashira coupling with phenylacetylene to give **6e** in 90% yield. Finally, Suzuki–Miyaura coupling of **6e** and *p*-methoxyphenylboronic acid was executed in the presence of 2.5 mol % $Pd_2(dba)_3$, 11 mol % SPhos (2-dicyclohexylphosphino-2′,6′-

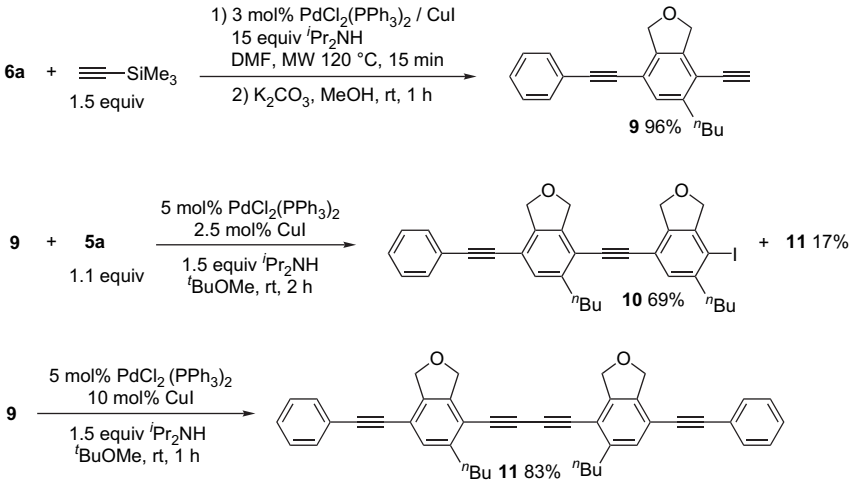
dimethoxybiphenyl),[13] and K_3PO_4 in toluene at 100 °C for 1 h to afford highly substituted biphenyl **8** in 86% yield (Scheme 4).

2.3. Synthesis of oligo(p-phenylene ethynylene)s via iterative Sonogashira coupling

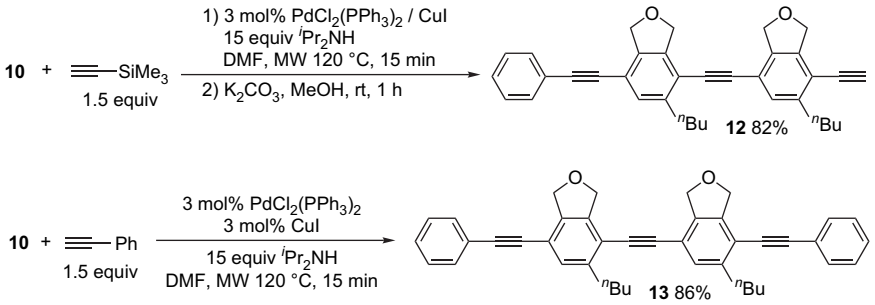
Having secured the site-selective transformation of the unsymmetrical diiodobenzenes, we then attempted the synthesis of oligo(*p*-phenylene ethynylene)s by means of iterative Sonogashira coupling. As highlighted in a recent review of Klok and co-workers, a repetitive coupling strategy is quite advantageous for the synthesis of uniform conjugated oligomers that have attracted considerable interest as molecular electronics.[14] As the starting point, **6b** was subjected to the Sonogashira coupling with trimethylsilylacetylene (Scheme 5). The reaction, however, led to the incomplete conversion of **6b** within 24 h under the conditions optimized for the synthesis of **6**. Thus, we employed the microwave (MW) irradiation conditions that proved to be effective in the recent study by Wang and co-workers.[11] To our delight, **6b** was totally consumed within 15 min upon treatment with 5 mol % $PdCl_2(PPh_3)_2$/CuI and 15 equiv of $^iPr_2NH$ under MW irradiation in DMF at 120 °C, and desilylation with K_2CO_3 in MeOH of the crude coupling product gave the desired terminal alkyne **9** in 96% yield. The next coupling of **9** with diiodide **5a** was carried out at room temperature to furnish **10** in 69% yield along with a noticeable amount of homo dimer **11** (17%). It is worthy to note that the Cu/Pd ratio plays a critical role in the selective formation of **10** over **11**. In fact, our Sonogashira-coupling protocol for the synthesis of **6** (Cu/Pd=2:1) resulted in the exclusive formation of **11** in 73% yield, while 36% of **9** was recovered intact along with **10** and **11** (46% and 9% yields, respectively) upon treatment with a decreased amount of CuI (Cu/Pd=1:5) for 24 h. These results indicate that the copper salt is required for the efficient conversion, while its increased loading facilitates the undesired Glaser-type homo coupling. We have been unable to ascertain why homo coupling became conspicuous as bulkier **9** was used in place of phenylacetylene under exactly the same conditions, but a similar trend has been observed in earlier studies.[15] This type of homo coupling is considered to catalytically proceed in the presence of CuI and adventitious molecular oxygen.[16] To suppress homo coupling, copper-free protocols have been developed.[17] Thus, in the absence of CuI, **9** and 1.1 equiv **5a** was treated with 2.5 mol % $[(\eta^3\text{-}C_3H_5)PdCl]_2$, 10 mol % PPh_3, and 2 equiv of DABCO in DMF at room temperature for 20 h (a modified Soheili's protocol).[17e] This copper-free reaction, however, failed to go to completion, and gave **10** and **11** in 62% and 30% yields, respectively, with the 34% recovery of **5a**. According to the report of Ho and co-workers,[18] we also attempted to inhibit oxidative coupling by carrying out Sonogashira coupling under a reductive atmosphere of H_2+N_2, but no improvement was observed. Finally, slow addition of **9** into the reaction mixture had no favorable effect.

Although the oxidative homo coupling of arylalkynes often hampered the Sonogashira coupling route to oligo(phenylene ethynylene)s, the formed 1,3-diyne derivatives are also valuable rod-like conjugate molecules, having potential applications as functional materials.[19] Therefore, the catalytic protocol providing an easy access to this structural motif is highly important. As shown in Scheme 5, high-yielding and exclusive formation of **11** was achieved, when **9** was simply treated with 5 mol % $PdCl_2(PPh_3)_2$, 10 mol % CuI, and 1.5 equiv of $^iPr_2NH$ in ^{t}BuOMe at room temperature for 1 h.

Further elongation of **10** was uneventfully accomplished by repeating the Sonogashira coupling with trimethylsilylacetylene followed by desilylation, furnishing **12** in 82% yield (Scheme 6). Unfortunately, the subsequent coupling of **12** with **5a** led to an intractable mixture of the starting materials and the expected cross/homo coupling products. The Sonogashira coupling of **10** with phenylacetylene was executed under the MW irradiation conditions to afford unsymmetrical oligo(*p*-phenylene ethynylene) **13** in 86% yield (Scheme 6).



Scheme 5.



Scheme 6.

3. Conclusion

We have succeeded in the selective cycloaddition of diiododiynes with 2-ethynyl-5,5-dimethyl-1,3,2-dioxaborinane under the ruthenium catalysis to obtain diiodophenylboronates in 54–87% yields, and further precise transformations of the cycloadducts into highly functionalized aromatic molecules. We found that a mild Sonogashira-coupling protocol is highly effective for the differentiation of the two C–I bonds of the unsymmetrical cycloadducts, providing that the boronate moiety is converted into other groups prior to the site-selective Sonogashira coupling. Finally, we synthesized several oligo(*p*-phenylene ethynylene)s by means of the iterative Sonogashira-coupling strategy.

4. Experimental

4.1. General

Flash chromatography was performed with a silica gel column (Cica silica gel 60N) eluted with mixed solvents [hexane/AcOEt]. TLC analyses were performed with Merck TLC plate silica gel 60 F254. ^{1}H and ^{13}C NMR spectra were measured on a Gemini 2000 NMR spectrometers as $CDCl_3$ solutions at 25 °C. ^{1}H NMR chemical shifts are reported in terms of chemical shift (δ, ppm) relative to the singlet at 7.26 ppm for chloroform. Splitting patterns are designated as follows: s, singlet; d, doublet; t, triplet; q, quartet; quint, quinted; sext, sextet; sept, septet; m, multiplet. Coupling constants are reported in hertz. ^{13}C NMR spectra were fully decoupled and are reported in terms of chemical shift (δ, ppm) relative to the triplet at 77.0 ppm for $CDCl_3$. Mass spectra were recorded on a JEOL JMS-T100CS mass spectrometer as MeOH solutions. Elemental analyses were performed with a Perkin–Elmer 2400II CHNS/O elemental analyzer. Melting points were obtained by a Yamato Melting Point Apparatus MP-12 and are uncorrected. Microwave irradiation experiments were carried out with a single-mode microwave reactor (CEM Discover Lab-Mate). Closed reaction vessels were used, and the temperature was monitored by an on-line IR detector. 1,2-Dichloroethane, ^{t}BuOMe, ^{i}Pr$_2$NH, and DMF were distilled from CaH_2, and degassed before use. 2-Ethynyl-5,5-dimethyl-1,3,2-dioxaborinane (**3**) and diiododiynes **2a**–**f**, and diiodobenzenes **5a**,**b**, **14** were prepared according to previously reported procedures.[7e,8a]

4.2. Synthesis of Cp*RuCl(cod) (*1*)

In a 100 mL flask, $[Cp^*RuCl_2]_n$[20] (1.35 g, 2.20 mmol) and 1,5-cyclooctadiene (15 mL, 122.5 mmol) were heated in degassed refluxing EtOH for 1 h under Ar atmosphere. After cooling to room temperature, the solvent was roughly removed by a rotary evaporator, and the residue was subjected to short column chromatography on silica gel (ca. 10 g) eluted with dichloromethane to remove excess 1,5-cyclooctadiene and insoluble materials. The orange band was collected and the concentrated rapidly to ca. one third volume by a rotary evaporator. To the concentrated solution was added small volume of ether and the solution was rapidly cooled in dry ice/EtOH bath to give rise to precipitates. The precipitates were collected by filtration and washed with ether. Finally, the desired complex **1** was obtained as golden micro plates (1.09 g, 65%). Analytical data of **1** was reported in the original report by Suzuki and Moro-oka.[20]

4.3. Representative procedure for cycloaddition of diiododiynes *2* with ethynylboronate *3*

To a solution of Cp*RuCl(cod) (**1**) (11.4 mg, 0.030 mmol) and ethynylboronate **3** (124.5 mg, 0.902 mmol) in dry degassed 1,2-dichloroethane (1.5 mL) was added a solution of diiododiyne **2a** (104.2 mg, 0.301 mmol) in dry degassed 1,2-dichloroethane (2 mL) over 20 min via a syringe at room temperature under Ar atmosphere. The solution was stirred at room temperature under Ar atmosphere for 12 h, and then, the solvent was removed under reduced pressure. The residue was purified by silica gel flash column chromatography (hexane/AcOEt 20:1–10:1) to give **4a** (118.5 mg, 81%) as a colorless solid: mp 151.0–151.5 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.07 (s, 6H), 3.79 (s, 4H), 5.14 (s, 4H), 7.73 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 22.0, 31.7, 72.4, 79.4, 80.4, 87.1, 92.5, 142.9, 145.0, 145.1; MS (ESI): calcd for $C_{13}H_{15}BI_2O_3$ (483.9), found *m/z* 522.9 $[M+K]^+$; EA calcd (%) for $C_{13}H_{15}BI_2O_3$ (483.88): C 32.27, H 3.12; found: C 32.22, H 3.00.

4.3.1. Compound *4b*

Mp 196.5 °C decomp. (eluent, hexane/AcOEt 10:1–3:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.04 (s, 6H), 2.42 (s, 3H), 3.76 (s, 4H), 4.65 (s, 4H), 7.34 (d, J=8.4 Hz, 2H), 7.68 (s, 1H), 7.79 (d, J=8.4 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$):

δ 21.4, 21.8, 31.6, 59.8, 60.8, 72.4, 89.3, 94.9, 127.6, 130.1, 133.7, 142.3, 142.4, 143.4, 144.1; MS (ESI): calcd for $C_{17}H_{16}BI_2NO_4S$ as a dimethyl boronate (597.0), found *m/z* 619.9 $[M+Na]^+$; EA calcd (%) for $C_{20}H_{22}BI_2NO_4S$ (637.08): C 37.71, H 3.48, N 2.20; found: C 37.98, H 3.23, N, 2.18.

4.3.2. Compound ***4c***

Mp 164.9–165.8 °C (eluent, hexane/AcOEt 20:1–5:1); ^1H NMR (300 MHz, $CDCl_3$): δ 1.05 (s, 6H), 3.69 (s, 2H), 3.72 (s, 2H), 3.76 (s, 6H), 3.77 (s, 4H), 7.64 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 21.8, 31.6, 47.0, 48.2, 53.1, 56.3, 72.4, 92.7, 98.2, 142.9, 145.4, 145.7, 171.6; MS (ESI): calcd for $C_{15}H_{17}BI_2O_6$ as a dimethyl boronate (557.9), found *m/z* 580.9 $[M+Na]^+$; EA calcd (%) for $C_{18}H_{21}BI_2O_6$ (597.98): C 36.15, H 3.54; found: C 36.31, H 3.61.

4.3.3. Compound ***4d***

Mp 195.4–196.5 °C (eluent, hexane/AcOEt 10:1–5:1); ^1H NMR (300 MHz, $CDCl_3$): δ 1.07 (s, 6H), 3.80 (s, 4H), 3.85 (s, 2H), 3.88 (s, 2H), 7.78 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 21.7, 29.8, 31.6, 50.5, 51.7, 72.4, 92.2, 97.9, 115.7, 142.0, 144.3; MS (ESI): calcd for $C_{13}H_{11}BI_2N_2O_2$ as a dimethyl boronate (491.9), found *m/z* 514.8 $[M+Na]^+$; EA calcd (%) for $C_{16}H_{15}BI_2N_2O_2$ (531.92): C 36.13, H 2.84, N 5.27; found: C 36.34, H 2.73, N, 5.07.

4.3.4. Compound ***4e***

Mp 154.5–156.0 °C (eluent, hexane/AcOEt 20:1–10:1); ^1H NMR (300 MHz, $CDCl_3$): δ 1.05 (s, 6H), 1.47 (s, 6H), 2.97 (s, 2H), 3.00 (s, 2H), 3.73 (s, 4H), 3.77 (s, 4H), 7.62 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 21.8, 23.2, 24.1, 31.6, 38.3, 47.0, 47.9, 68.6, 72.4, 94.2, 98.0, 99.6, 142.5, 147.0, 147.3; MS (ESI): calcd for $C_{16}H_{21}BI_2O_4$ as a dimethyl boronate (542.0), found *m/z* 564.9 $[M+Na]^+$; EA calcd (%) for $C_{19}H_{25}BI_2O_4$ (582.02): C 39.21, H 4.33; found: C 39.14, H 4.18.

4.3.5. Compound ***4f***

Mp 214 °C decomp. (eluent, hexane/AcOEt 10:1–5:1); ^1H NMR (300 MHz, $CDCl_3$): δ 1.10 (s, 6H), 3.56 (s, 2H), 3.58 (s, 2H), 3.83 (s, 4H), 7.24–7.39 (m, 6H), 7.71 (s, 1H), 7.75 (d, *J*=6 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 21.9, 31.7, 52.1, 53.2, 53.5, 72.5, 93.5, 98.9, 119.9, 122.5, 127.7, 127.9, 139.7, 142.7, 148.5, 148.7, 151.9; MS (ESI): calcd for $C_{23}H_{19}BI_2O_2$ as a dimethyl boronate (592.0), found *m/z* 614.9 $[M+Na]^+$; EA calcd (%) for $C_{26}H_{23}BI_2O_2$ (632.08): C 49.40, H 3.67; found: C 49.11, H 3.96.

4.4. Synthesis of diiodobenzene ***5c*** *from* ***4a***

To a solution of **4a** (1.452 g, 3.00 mmol) in THF (20 mL) was added a mixture of 1 M aq NaOH and 30% hydrogen peroxide (2:1 v/v, 30 mL) at ambient temperature, and the reaction mixture was stirred for 6 h. The reaction mixture was diluted with AcOEt (20 mL) and washed with satd NH_4Cl (50 mL). The aqueous layer was acidified with 1 M HCl, and extracted with AcOEt (20 mL×2). The combined organic layer was washed with brine (50 mL), dried with $MgSO_4$, and concentrated in vacuo. The crude product was then treated with *n*-octyliodide (2.161 g, 9.00 mmol) and K_2CO_3 (2.490 g, 18.0 mmol) in dry acetone at ambient temperature. After refluxing for 3 h, the reaction mixture was washed with satd NH_4Cl (50 mL), and the aqueous layer was extracted with AcOEt (20 mL×3). The organic layer was combined, dried with $MgSO_4$, and concentrated in vacuo. The residue was purified by silica gel flash column chromatography (hexane/AcOEt 50:1–10:1) to give **5c** (1.314 g, 88%) as colorless crystals: mp 56.8–58.5 °C; ^1H NMR (300 MHz, $CDCl_3$): δ 0.89 (t, *J*=7.2 Hz, 3H), 1.21–1.55 (m, 10H), 1.83 (quint, *J*=7.2 Hz, 2H), 3.99 (t, *J*=6.3 Hz, 2H), 5.09 (d, *J*=1.5 Hz, 2H), 5.11 (d, *J*=1.5 Hz, 2H), 6.95 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 14.0, 22.5, 25.9, 28.9, 29.1 (2C), 31.7, 70.0, 78.7, 79.7, 79.8, 86.6, 119.7, 136.5, 146.0, 157.7; MS (ESI): calcd for $C_{16}H_{22}I_2O_2$ (500.0), found *m/z* 523.0 $[M+Na]^+$; EA calcd (%) for $C_{16}H_{22}I_2O_2$ (500.15): C 38.42, H 4.43; found: C 38.38, H 4.22.

4.5. Synthesis of diiodobenzene ***5d*** *from* ***4a***

To the degassed solution of **4a** (483.9 mg, 1.00 mmol) in dry MeOH (20 mL) were added $Pd(OAc)_2$ (24.5 mg, 0.0506 mmol), PPh_3 (26.2 mg, 0.0999 mmol), and *p*-benzoquinone (108.2 mg, 1.00 mmol), and the reaction mixture was stirred at room temperature under CO atmosphere for 1 h. The solution was diluted with AcOEt (20 mL), and washed with satd Na_2CO_3 (50 mL). The aqueous layer was extracted with AcOEt (20 mL×2). The combined organic layer was washed with brine (50 mL), and died with $MgSO_4$. The solvent was removed in vacuo, and the crude material was purified by silica gel flash column chromatography (hexane/AcOEt 50:1–10:1) to give **5d** (303.2 mg, 71%) as a colorless solid: mp 121.1–122.0 °C; ^1H NMR (300 MHz, $CDCl_3$): δ 3.93 (s, 3H), 5.18–5.22 (m, 4H), 8.05 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 52.6, 79.3, 80.8, 86.4, 87.5, 135.0, 139.2, 147.1, 147.4, 165.3; MS (ESI): calcd for $C_{10}H_8I_2O_3$ (429.9), found *m/z* 452.9 $[M+Na]^+$; EA calcd (%) for $C_{10}H_8I_2O_3$ (429.98): C 27.93, H 1.88; found: C 28.04, H 1.73.

4.6. Representative procedure for Sonogashira coupling of cycloadducts ***4a***, ***5a–d*** *with phenylacetylene*

A solution of $PdCl_2(PPh_3)_2$ (10.6 mg, 0.0151 mmol), CuI (5.76 mg, 0.0302 mmol), **4a** (145.2 mg, 0.300 mmol), phenylacetylene (46.0 mg, 0.450 mmol), and $^iPr_2NH$ (0.063 mL, 0.45 mmol) in degassed ^{t}BuOMe (5.0 mL) was stirred at 0 °C for 12 h. The reaction mixture was diluted with AcOEt (20 mL), and washed with satd NH_4Cl (10 mL). The aqueous layer was extracted with AcOEt (20 mL×2). The combined organic layer was then washed with brine (20 mL) and dried with $MgSO_4$. After removing the solvent in vacuo, the residue was purified by flash column chromatography on silica gel eluted with hexane/AcOEt 20:1–10:1) to give **6a** (87.9 mg, 64%) as a pale-yellow solid: mp 122.5–123.5 °C; ^1H NMR

(300 MHz, $CDCl_3$): δ 1.08 (s, 6H), 3.81 (s, 4H), 5.07 (m, 2H), 5.39 (m, 2H), 7.32–7.37 (m, 3H), 7.48–7.51 (m, 2H), 7.56 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 21.7, 31.4, 72.2, 75.3, 79.4, 85.8, 92.7, 93.9, 116.0, 122.7, 128.3, 128.5, 131.5, 137.3, 142.6, 144.4; MS (ESI): calcd for $C_{18}H_{16}BIO_3$ as a dimethyl boronate (418.0), found *m/z* 441.0 $[M+Na]^+$; EA calcd (%) for $C_{21}H_{20}BIO_3$ (458.10): C 55.06, H 4.40; found: C 54.91, H 4.20.

Further elution (hexane/AcOEt 10:1–5:1) gave **7a** (22.4 mg, 17%) as a orange solid: mp 120 °C decomp.; ^1H NMR (300 MHz, $CDCl_3$): δ 1.08 (s, 6H), 3.85 (s, 4H), 5.31 (s, 4H), 7.34–7.37 (m, 6H), 7.49–7.52 (m, 4H), 7.86 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 21.8, 31.8, 72.5, 74.6, 74.8, 86.7, 87.8, 94.2, 96.4, 115.9, 120.6, 123.0, 123.6, 127.7, 128.4, 128.5, 128.6, 131.7, 135.3, 137.1, 142.2, 143.0; MS (ESI): calcd for $C_{26}H_{21}BO_3$ as a dimethyl boronate (392.2), found *m/z* 415.2 $[M+Na]^+$; EA calcd (%) for $C_{29}H_{25}BO_3$ (432.32): C 80.57, H 5.83; found: C 81.08, H 5.17.

4.6.1. Compound *6b*

Mp 64.5–65.0 °C (eluent, hexane/AcOEt 70:1–50:1); ^1H NMR (300 MHz, $CDCl_3$): δ 0.98 (t, *J*=7.2 Hz, 3H), 1.44 (sext, *J*=7.2 Hz, 2H), 1.59 (quint, *J*=7.2 Hz, 2H), 2.72 (t, *J*=7.2 Hz, 2H), 5.06 (s, 2H), 5.38 (s, 2H), 7.22 (s, 1H), 7.34–7.37 (m, 3H), 7.49–7.53 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 13.8, 22.3, 32.3, 38.1, 75.5, 79.4, 85.8, 93.5, 93.7, 116.6, 122.7, 128.5, 128.7, 130.7, 131.7, 139.2, 144.7, 144.9; MS (ESI): calcd for $C_{20}H_{19}IO$ (402.1), found *m/z* 425.0 $[M+Na]^+$; EA calcd (%) for $C_{20}H_{19}IO$ (402.27): C 59.71, H 4.76; found: C 59.93, H 4.29.

4.6.2. Compound *6c*

Mp 120.0–125.5 °C decomp. (eluent, hexane/AcOEt 70:1–50:1); ^1H NMR (300 MHz, $CDCl_3$): δ 5.13 (s, 2H), 5.46 (s, 2H), 7.33–7.50 (m, 11H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 75.5, 79.6, 85.5, 91.6, 94.3, 116.7, 122.6, 128.0, 128.2, 128.5, 128.9, 129.4, 131.6, 131.7, 140.4, 142.8, 145.3, 146.1; MS (ESI): calcd for $C_{22}H_{15}IO$ (422.0), found *m/z* 445.0 $[M+Na]^+$; EA calcd (%) for $C_{22}H_{15}IO$ (422.26): C 62.58, H 3.58; found: C 62.47, H 3.57.

4.6.3. Compound *6d*

Mp 51.7–54.5 °C (eluent, hexane/AcOEt 70:1); ^1H NMR (300 MHz, $CDCl_3$): δ 0.89 (t, *J*=7.2 Hz, 3H), 1.21–1.55 (m, 10H), 1.85 (quint, *J*=7.2 Hz, 2H), 4.04 (t, *J*=6.3 Hz, 2H), 5.04 (s, 2H), 5.33 (s, 2H), 6.78 (s, 1H), 7.34–7.37 (m, 3H), 7.49–7.53 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 14.0, 22.5, 25.9, 29.0, 29.1, 31.7, 69.8, 75.0, 78.7, 80.2, 86.0, 93.6, 113.2, 117.0, 122.7, 128.5, 128.8, 131.7, 134.1, 145.9, 157.2; MS (ESI): calcd for $C_{24}H_{27}IO_2$ (474.1), found *m/z* 497.1 $[M+Na]^+$; EA calcd (%) for $C_{24}H_{27}IO_2$ (474.37): C 60.77, H 5.74; found: C 60.84, H 5.28.

4.6.4. Compound *6e*

Mp 119.5–121.5 °C (eluent, hexane/AcOEt 70:1–10:1); ^1H NMR (300 MHz, $CDCl_3$): δ 3.95 (s, 3H), 5.12 (m, 2H), 5.42 (m, 2H), 7.34–7.39 (m, 3H), 7.49–7.53 (m, 2H), 7.86 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 52.5, 75.4, 79.9, 84.7, 87.3, 95.1, 117.0, 122.3, 128.6, 129.1, 131.8, 133.3, 133.9, 144.4, 146.9, 166.2; MS (ESI): calcd for $C_{18}H_{13}IO_3$ (404.0), found *m/z* 427.0 $[M+Na]^+$; EA calcd (%) for $C_{18}H_{13}IO_3$ (404.20): C 53.49, H 3.24; found: C 53.59, H 3.07.

4.7. Suzuki–Miyaura coupling of *6e* with p-methoxyphenylboronic acid

A solution of $Pd_2(dba)_3\cdot CHCl_3$ (7.78 mg, 0.00752 mmol), SPhos (13.5 mg, 0.0329 mmol), **6e** (121.3 mg, 0.300 mmol), *p*-methoxyphenylboronic acid (68.5 mg, 0.451 mmol), and K_3PO_4 (254.5 mg, 1.20 mmol) in degassed toluene (5 mL) was stirred at 100 °C for 1 h. The reaction mixture was diluted with AcOEt (20 mL), and washed with satd NH_4Cl (50 mL). The aqueous layer was extracted with AcOEt (20 mL×2). The combined organic layer was then washed with brine (50 mL) and dried with $MgSO_4$. After removing the solvent in vacuo, the residue was purified by flash column chromatography on silica gel eluted with hexane/AcOEt 20:1–5:1 to give **8** (99.0 mg, 86%) as a colorless solid: mp 157.5–158.1 °C; ^1H NMR (300 MHz, $CDCl_3$): δ 3.66 (s, 3H), 3.85 (s, 3H), 4.99 (m, 2H), 5.31 (m, 2H), 6.94 (d, *J*=9 Hz, 2H), 7.14 (d, *J*=9 Hz, 2H), 7.35–7.39 (m, 3H), 7.50–7.55 (m, 2H), 7.95 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 52.0, 55.1, 74.2, 74.3, 85.5, 93.9, 113.8, 115.8, 122.7, 128.5, 128.9, 129.0, 130.7, 130.8, 131.8, 132.7, 136.3, 140.1, 144.7, 159.2, 167.9; MS (ESI): calcd for $C_{25}H_{20}O_4$ (384.1), found *m/z* 407.1 $[M+Na]^+$; EA calcd (%) for $C_{25}H_{20}O_4$ (384.42): C 78.11, H 5.24; found: C 78.26, H 4.92.

4.8. Representative procedure for Sonogashira coupling with microwave irradiation

A solution of $PdCl_2(PPh_3)_2$ (42.1 mg, 0.0600 mmol), CuI (11.3 mg, 0.0593 mmol), **6b** (766.0 mg, 1.90 mmol), trimethylsilylacetylene (295 mg, 3.00 mmol), and $^iPr_2NH$ (4.0 mL, 29.0 mmol) in degassed DMF (1.0 mL) was heated at 120 °C for 15 min with a microwave reactor. The reaction mixture was diluted with AcOEt (20 mL), and washed with satd NH_4Cl (50 mL). The aqueous layer was extracted with AcOEt (20 mL×2). The combined organic layer was then washed with brine (50 mL) and dried with $MgSO_4$. After removing the solvent in vacuo, the residue was then treated with K_2CO_3 (1.11 g, 8.00 mmol) in MeOH (20 mL) at room temperature for 1 h. The reaction mixture was diluted with AcOEt (20 mL) and washed with 1 N NaOH (50 mL). The aqueous layer was extracted with AcOEt (20 mL×2). The combined organic layer was then washed with satd NH_4Cl (50 mL), and dried with $MgSO_4$. After removing the solvent in vacuo, the residue was purified by flash column chromatography on silica gel eluted with hexane/AcOEt 70:1–20:1 to give **9** (546.9 mg, 96%) as a pale-yellow solid: mp 72.0–72.5 °C; ^1H NMR (300 MHz, $CDCl_3$): δ 0.95 (t, *J*=7.2 Hz, 3H), 1.39 (sext, *J*=7.2 Hz, 2H), 1.64 (quint, *J*=7.2 Hz, 2H), 2.79 (t, *J*=7.2 Hz, 2H), 3.47 (s, 1H), 5.21 (s, 2H), 5.24 (s, 2H), 7.26 (s, 1H), 7.34–7.37 (m, 3H), 7.49–7.53 (m, 2H);

^{13}C NMR (75 MHz, $CDCl_3$): δ 13.8, 22.3, 32.8, 33.4, 74.3, 74.6, 79.4, 85.5, 86.4, 94.2, 115.1, 116.8, 122.8, 128.5, 128.8, 130.7, 131.7, 138.9, 143.1, 145.1; MS (ESI): calcd for $C_{22}H_{20}O$ (300.2), found *m/z* 323.2 $[M+Na]^+$; EA calcd (%) for $C_{22}H_{20}O$ (300.39): C 87.96, H 6.71; found: C 88.00, H 6.27.

4.8.1. Compound ***12***

Mp 128–131 °C decomp. (eluent, hexane/AcOEt 50:1–10:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.96 (t, J=7.2 Hz, 3H), 0.97 (t, J=7.2 Hz, 3H), 1.41 (sext, J=7.2 Hz, 2H), 1.43 (sext, J=7.2 Hz, 2H), 1.59–1.74 (m, 4H), 2.81 (t, J=7.2 Hz, 2H), 2.83 (t, J=7.2 Hz, 2H), 3.49 (s, 1H), 5.22 (s, 4H), 5.26 (s, 2H), 5.27 (s, 2H), 7.22 (s, 1H), 7.30 (s, 1H), 7.34–7.38 (m, 3H), 7.49–7.54 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 13.9, 14.0, 22.5, 22.6, 32.8, 32.9, 33.5, 33.8, 74.3, 74.4, 74.5, 74.6, 79.3, 85.8, 86.5, 90.0, 94.4, 94.9, 115.4, 115.5, 116.4, 116.7, 122.7, 128.4, 128.7, 130.5, 130.8, 131.6, 138.6, 138.9, 142.1, 143.1, 144.2, 145.2; MS (ESI): calcd for $C_{36}H_{34}O_2$ (498.3), found *m/z* 521.3 $[M+Na]^+$; EA calcd (%) for $C_{36}H_{34}O_2$ (498.65): C 86.71, H 6.87; found: C 86.54, H 7.43.

4.8.2. Compound ***13***

Mp 145–148 °C decomp. (eluent, hexane/AcOEt 10:1–5:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.98 (t, J=7.2 Hz, 6H), 1.43–1.51 (m, 4H), 1.65–1.76 (m, 4H), 2.85 (t, J=7.2 Hz, 2H), 2.87 (t, J=7.2 Hz, 2H), 5.27 (s, 8H), 7.25 (s, 1H), 7.30 (s, 1H), 7.35–7.40 (m, 6H), 7.49–7.54 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 13.8, 13.9, 22.5, 32.8, 32.9, 33.7, 74.4, 74.5, 74.6, 74.7, 85.2, 86.6, 90.0, 94.4, 95.2, 98.3, 115.8, 115.9, 116.7, 122.8, 123.0, 128.5, 128.6, 128.8, 130.7, 130.9, 131.6, 131.8, 138.7, 139.0, 142.3, 142.4, 144.3, 144.6; MS (ESI): calcd for $C_{42}H_{38}O_2$ (574.3), found *m/z* 597.3 $[M+Na]^+$; EA calcd (%) for $C_{42}H_{38}O_2$ (574.75): C 87.77, H 6.66; found: C 87.76, H 6.21.

4.9. Sonogashira coupling of ***9*** *with* ***5a***

A solution of $PdCl_2(PPh_3)_2$ (3.52 mg, 0.00501 mmol), CuI (0.48 mg, 0.0025 mmol), **9** (30.0 mg, 0.0999 mmol), **5a** (47.1 mg, 0.110 mmol), and ^{i}Pr$_2$NH (0.021 mL, 0.15 mmol) in degassed ^{t}BuOMe (2.0 mL) was stirred at room temperature for 2 h. The reaction mixture was diluted with AcOEt (10 mL), and washed with satd NH_4Cl (20 mL). The aqueous layer was extracted with AcOEt (20 mL×2). The combined organic layer was then washed with brine (20 mL) and dried with $MgSO_4$. After removing the solvent in vacuo, the residue was purified by flash column chromatography on silica gel eluted with hexane/AcOEt 100:1–70:1) to recover **5a** (9.2 mg, 20%).

Further elution (hexane/AcOEt 50:1–20:1) gave **10** (41.3 mg, 69%) as a colorless solid: mp 143.5–145.5 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.97 (t, J=7.2 Hz, 3H), 0.98 (t, J=7.2 Hz, 3H), 1.42 (sext, J=7.2 Hz, 2H), 1.44 (sext, J=7.2 Hz, 2H), 1.56–1.74 (m, 4H), 2.73 (t, J=7.2 Hz, 2H), 2.82 (t, J=7.2 Hz, 2H), 5.07 (s, 2H), 5.25 (s, 2H), 5.27 (s, 2H), 5.36 (s, 2H), 7.17 (s, 1H), 7.29 (s, 1H), 7.34–7.38 (m, 3H), 7.49–7.54 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 13.8, 13.9, 22.3, 22.5, 32.4, 32.8, 33.7, 39.2, 74.4, 74.6, 75.4, 79.5, 86.6, 89.6, 93.9, 94.3, 94.5, 115.6, 116.3, 116.8, 122.8, 128.5, 128.8, 130.5, 130.9, 131.7, 139.0, 139.1, 142.3, 144.3, 145.0, 145.2; MS (ESI): calcd for $C_{34}H_{33}IO_2$ (600.2), found *m/z* 623.2 $[M+Na]^+$; EA calcd (%) for $C_{34}H_{33}IO_2$ (600.53): C 68.00, H 5.54; found: C 68.20, H 5.23.

Further elution (hexane/AcOEt 10:1) gave **11** (5.05 mg, 17%) as a yellow solid: mp 166.5–168.0 °C decomp.; ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.98 (t, J=7.2 Hz, 3H), 1.42 (sext, J=7.2 Hz, 2H), 1.67 (quint, J=7.2 Hz, 2H), 2.82 (t, J=7.2 Hz, 2H), 5.25 (s, 4H), 7.28 (s, 2H), 7.34–7.38 (m, 6H), 7.49–7.54 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 13.8, 22.3, 32.9, 33.6, 74.3, 74.5, 79.9, 81.4, 86.5, 95.0, 114.6, 117.5, 122.7, 128.6, 128.9, 130.9, 131.8, 139.2, 143.7, 146.3; MS (ESI): calcd for $C_{44}H_{38}O_2$ (598.3), found *m/z* 621.3 $[M+Na]^+$; EA calcd (%) for $C_{44}H_{38}O_2$ (598.77): C 88.26, H 6.40; found: C 88.52, H 5.96.

4.10. Homo coupling of ***9***

A solution of $PdCl_2(PPh_3)_2$ (7.25 mg, 0.0103 mmol), CuI (4.20 mg, 0.0221 mmol), **9** (60.1 mg, 0.200 mmol), and ^{i}Pr$_2$NH (0.042 mL, 0.30 mmol) in degassed ^{t}BuOMe (3.0 mL) was stirred at room temperature for 1 h. The reaction mixture was diluted with AcOEt (10 mL), and washed with satd NH_4Cl (10 mL). The aqueous layer was extracted with AcOEt (10 mL×2). The combined organic layer was then washed with brine (20 mL) and dried with $MgSO_4$. After removing the solvent in vacuo, the residue was purified by recrystallization from AcOEt to give **11** (49.7 mg, 83%) as a yellow solid.

Acknowledgements

This research was partially supported by the MEXT, Grant-in-Aid for Young Scientists (A) (17685008), and Tokyo Tech Award for Challenging Research, 2006. We thank Profs. T. Ikariya and S. Kuwata for use of the ESI mass spectrometer, and Profs. K. Tomooka and K. Igawa for use of the NMR spectrometer. We also thank Profs. H. Suzuki, T. Takao, and M. Oishi for elemental analyses.

References and notes

1. For reviews of cyclotrimerization, see: (a) Shore, N. E. *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Paquette, L. A., Eds.; Pergamon: Oxford, 1991; Vol. 5, pp 1129–1162; (b) Grotjahn, D. B. *Comprehensive Organometallic Chemistry II*; Hegedus, L. S., Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Pergamon: Oxford, 1995; Vol. 12, pp 741–770.
2. Carruthers, W.; Coldham, I. *Modern Methods of Organic Synthesis*, 4th ed.; Cambridge University Press: Cambridge, 2004; p 89.
3. For reviews of intramolecular cyclotrimerization, see: (a) Saito, S.; Yamamoto, Y. *Chem. Rev.* **2000**, *100*, 2901–2915; (b) Yamamoto, Y. *Curr. Org. Chem.* **2005**, *9*, 503–519; (c) Kotha, S.; Brahmachary, E.; Lahiri, K. *Eur. J. Org. Chem.* **2005**, 4741–4767.

4. (a) Lindner, E.; Jansen, R.-M.; Mayer, H. A.; Hiller, W.; Fawzi, R. *Organometallics* **1989**, *8*, 2355–2360; (b) Lindner, E.; Kühbauch, H. *J. Organomet. Chem.* **1991**, *403*, C9–C14; (c) Ren, C. Y.; Cheng, W. C.; Chan, W. C.; Yeung, C. H.; Lau, C. P. *J. Mol. Catal.* **1990**, *59*, L1–L8; (d) Bohanna, C.; Esteruelas, M. A.; Herrero, J.; López, A. M.; Oro, L. A. *J. Organomet. Chem.* **1995**, *498*, 199–206; For recent examples, see: (e) Breschi, C.; Piparo, L.; Pertici, P.; Caporusso, A. M.; Vitulli, G. *J. Organomet. Chem.* **2000**, *607*, 57–63; (f) Rüba, E.; Schmid, R.; Kirchner, K.; Calhorda, M. J. *J. Organomet. Chem.* **2003**, *682*, 204–211; (g) Ura, Y.; Sato, Y.; Shiotsuki, M.; Kondo, T.; Mitusdo, T. *J. Mol. Catal. A* **2004**, *209*, 35–39; (h) Ura, Y.; Sato, Y.; Tsujita, H.; Kondo, T.; Imachi, M.; Mitsudo, T. *J. Mol. Catal. A* **2004**, *239*, 166–171.
5. (a) Peters, J.-U.; Blechert, S. *Chem. Commun.* **1997**, 1983–1984; (b) Das, S. K.; Roy, R. *Tetrahedron Lett.* **1999**, *40*, 4015–4018; (c) Witulski, B.; Stengel, T.; Fernández-Hernández, J. M. *Chem. Commun.* **2000**, 1965–1966; (d) Hoven, G. B.; Efskind, J.; Rømming, C.; Undheim, K. *J. Org. Chem.* **2002**, *67*, 2459–2463.
6. (a) Yamamoto, Y.; Ogawa, R.; Itoh, K. *Chem. Commun.* **2000**, 549–550; (b) Yamamoto, Y.; Hata, K.; Arakawa, T.; Itoh, K. *Chem. Commun.* **2003**, 1290–1291; (c) Yamamoto, Y.; Arakawa, T.; Ogawa, R.; Itoh, K. *J. Am. Chem. Soc.* **2003**, *125*, 12143–12160; (d) Yamamoto, Y.; Kinpara, K.; Saigoku, T.; Nishiyama, H.; Itoh, K. *Org. Biomol. Chem.* **2004**, *2*, 1287–1294; (e) Yamamoto, Y.; Saigoku, T.; Nishiyama, H.; Itoh, K. *Org. Biomol. Chem.* **2005**, *3*, 1768–1775.
7. (a) Yamamoto, Y.; Ishii, J.; Nishiyama, H.; Itoh, K. *J. Am. Chem. Soc.* **2004**, *126*, 3712–3713; (b) Yamamoto, Y.; Ishii, J.; Nishiyama, H.; Itoh, K. *J. Am. Chem. Soc.* **2005**, *127*, 9625–9631; (c) Yamamoto, Y.; Ishii, J.; Nishiyama, H.; Itoh, K. *Tetrahedron* **2005**, *61*, 11501–11510; (d) Yamamoto, Y.; Hattori, K.; Ishii, J.; Nishiyama, H.; Itoh, K. *Chem. Commun.* **2005**, 4438–4440; (e) Yamamoto, Y.; Hattori, K.; Ishii, J.; Nishiyama, H. *Tetrahedron* **2006**, *62*, 4294–4305; For other examples of transition-metal-cataylzed [2+2+2] cycloadditions of alkynylboronates leading to arylboronates, see: (f) Madreas, A.; Pritzkow, H.; Siebert, W. *Angew. Chem., Int. Ed.* **1996**, *35*, 1501–1503; (g) Ester, C.; Maderna, A.; Pritzkow, H.; Siebert, W. *Eur. J. Inorg. Chem.* **2000**, 1177–1184; (h) Gu, Y.; Pritzkow, H.; Siebert, W. *Eur. J. Inorg. Chem.* **2001**, 373–379; (i) Goswami, A.; Maier, C.-J.; Pritzkow, H.; Siebert, W. *Eur. J. Inorg. Chem.* **2004**, 2635–2645; (j) Goswami, A.; Pritzkow, H.; Rominger, F.; Siebert, W. *Eur. J. Inorg. Chem.* **2004**, 4223–4231; (k) Gandon, V.; Leca, D.; Aechtner, T.; Vollhardt, K. P. C.; Malacria, M.; Aubert, C. *Org. Lett.* **2004**, *6*, 3405–3407.
8. (a) Yamamoto, Y.; Hattori, K.; Nishiyama, H. *J. Am. Chem. Soc.* **2006**, *128*, 8336–8340; Also, see: (b) Yamamoto, Y.; Hashimoto, T.; Hattori, K.; Kikuchi, M.; Nishiyama, H. *Org. Lett.* **2006**, *8*, 3565–3568.
9. Smith, M. B.; March, J. *March's Advanced Organic Chemistry*, 5th ed.; Wiley: New York, NY, 2001; Chapter 11, p 704 and references cited therein.
10. (a) Sonogashira, K.; Tohda, Y.; Hagihara, H. *Tetrahedron Lett.* **1975**, *16*, 4467–4470; For recent reviews, see: (b) Chinchilla, R.; Nájera, C. *Chem. Rev.* **2007**, *107*, 874–922; (c) Doucet, H.; Hierso, J.-C. *Angew. Chem., Int. Ed.* **2007**, *46*, 834–871.
11. Zheng, S.-L.; Reid, S.; Lin, N.; Wang, B. *Tetrahedron Lett.* **2006**, *47*, 2331–2335.
12. Unique reactivity associated with a boronate group was observed for the rhodium-catalyzed hydrogenation of alkenylboronates, see: Moran, W. J.; Morken, J. P. *Org. Lett.* **2006**, *8*, 2413–2415.
13. Walker, S. D.; Barder, T. E.; Martinelli, J. R.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2004**, *43*, 1871–1876.
14. Franz, N.; Kreutzer, G.; Klok, H.-A. *Synlett* **2006**, 1793–1815.
15. For examples, see: (a) Xu, Z.; Moore, J. S. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 246–248; (b) Yu, C. J.; Chong, Y.; Kayyem, J. F.; Gozin, M. *J. Org. Chem.* **1999**, *64*, 2070–2079; (c) Shultz, D. A.; Gwaltney, K. P.; Lee, H. *J. Org. Chem.* **1998**, *63*, 4034–4038.
16. (a) Fairlamb, I. J. S.; Bäuerlein, P. S.; Marrison, L. R.; Dickinson, J. M. *Chem. Commun.* **2003**, 632–633; (b) Batsanov, A. S.; Collings, J. C.; Fairlamb, I. J. S.; Holland, J. P.; Howard, J. A. K.; Lin, Z.; Marder, T. B.; Parsons, A. C.; Ward, R. M.; Zhu, J. *J. Org. Chem.* **2005**, *70*, 703–706 and references cited therein.
17. Selected examples, see: (a) Böhm, V. P. W.; Herrmann, W. A. *Eur. J. Org. Chem.* **2000**, 3679–3681; (b) Alonso, D. A.; Nájera, C.; Pacheco, M. C. *Tetrahedron Lett.* **2002**, *43*, 9365–9368; (c) Méry, D.; Heuzé, K.; Astruc, D. *Chem. Commun.* **2003**, 1934–1935; (d) Heuzé, K.; Méry, D.; Gauss, D.; Astruc, D. *Chem. Commun.* **2003**, 2274–2275; (e) Soheili, A.; Albaneze-Walker, J.; Murry, J. A.; Dormer, P. G.; Hughes, D. L. *Org. Lett.* **2003**, *5*, 4191–4194; (f) Alonso, D. A.; Nájera, C.; Pacheco, M. C. *Adv. Synth. Catal.* **2003**, *345*, 1146–1158; (g) Li, J.-H.; Liang, Y.; Xie, Y.-X. *J. Org. Chem.* **2005**, *70*, 4393–4396; (h) Ruiz, J.; Cutillas, N.; López, F.; López, G.; Bautista, D. *Organometallics* **2006**, *25*, 5768–5773.
18. Elangovan, A.; Wang, Y.-H.; Ho, T.-I. *Org. Lett.* **2003**, *5*, 1841–1844.
19. For a review, see: Siemsen, P.; Livingston, R. C.; Diederich, F. *Angew. Chem., Int. Ed.* **2000**, *39*, 2632–2657.
20. Oshima, N.; Suzuki, H.; Moro-oka, Y. *Chem. Lett.* **1984**, 1161–1164.