DOI: 10.1002/adsc.201300482

Rhodium-Catalyzed Cross-Coupling of Alkenyl Halides with Arylboron Compounds

Takanori Matsuda,[a,*] Kentaro Suzuki,[a] and Norio Miura[a]

[a] Department of Applied Chemistry, Tokyo University of Science, 1–3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan
Fax: (+81)-3-5261-4631; e-mail: mtd@rs.tus.ac.jp

Received: June 3, 2013; Revised: September 24, 2013; Published online: November 13, 2013

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201300482.

Abstract: The rhodium(I)-catalyzed reaction between arylboronic esters and excess 1,2-dichloroethene selectively afforded (2-chlorovinyl)arenes. Double arylation yielding 1,2-diarylethenes was observed when 1,2-dibromoethene was reacted with 2.5 equivalents of arylboronic acid.

Keywords: alkenes; boron; cross-coupling; rhodium; synthetic methods

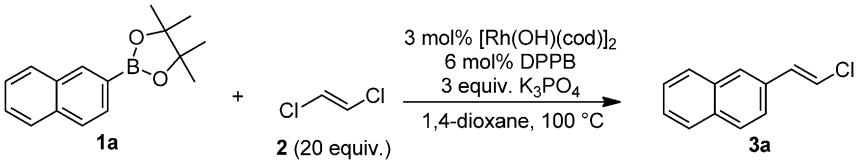
β-Arylvinyl halides are useful synthetic intermediates for the introduction of β-arylvinyl moieties.[1] Barluenga et al. developed a simple synthesis of β-arylvinyl chlorides by palladium-catalyzed cross-coupling of 1,2-dichloroethene with arylboronic acids.[1h] However, the reaction gave stilbenes (1,2-diarylethenes) as by-products through double arylation even with an excess (4 equiv.) of 1,2-dichloroethene. Nonetheless, stilbenes remain an important class of compounds for various applications.[2]

Rhodium-catalyzed addition reactions of organoboron compounds to carbon-carbon multiple bonds have become an immensely useful tool in contemporary organic synthesis.[3] There are also reports of rhodium-catalyzed substitution reactions with organoboron compounds that have been achieved by a direct (cross-coupling) or formal (addition/elimination) manner. Herein, we report the rhodium-catalyzed substitution reaction of alkenyl halides with arylboron compounds. The reaction selectively forms (2-chlorovinyl)arenes *via* the mono-selective cross-coupling reaction of 1,2-dichloroethene with arylboronic esters. Furthermore, double arylation furnishing stilbenes has been realized by coupling of 1,2-diboromoethene with arylboronic acids using rhodium catalysts.

Our initial investigation focused on the cross-coupling reaction of arylboron compounds with readily available alkenyl halides in the presence of rhodium(I) complex catalysts. It was found that $[Rh(OH)(cod)]_2$ (cod = cycloocta-1,5-diene, 3 mol%, 6 mol% Rh) and 1,4-bis(diphenylphosphino)butane (DPPB, 6 mol%), in the presence of K_3PO_4 (3 equiv.), catalyzed the cross-coupling reaction between 2-naphthylboronic acid pinacol ester (**1a**) and (*E*)-1,2-dichloroethene (**2**, 20 equiv., bp 48 °C) at 100 °C in 1,4-dioxane (Table 1, entry 1). 2-(2-Chlorovinyl)naphthalene (**3a**) was isolated in 85% yield with high *E* selectivity. No formation of dinaphthylethenes by double arylation of **2** was observed by GC analysis. As can be seen in entries 1–3, the use of DPPB as the ligand was essential to obtain good results. The product **3a** was prepared on a gram scale in a comparable yield with only 1 mol% of $[Rh(OH)(cod)]_2$ and purified by recrystallization from hexane (entry 4). Reducing the amount of **2** to 5 equiv. led to a lower yield, albeit without formation of the double arylation product (entry 5). No reaction occurred in the absence of K_3PO_4 (entry 6), while K_2CO_3 worked equally well (entry 7). The choice of solvent also had an effect on the efficiency of the reaction; the yield was reduced to 48% when toluene was used as the solvent instead of 1,4-dioxane (entry 8). Use of (*Z*)-1,2-dichloroethene led to a deterioration in the yield with predominant formation of the (*Z*)-isomer (entry 9). The corresponding boronic acid (**1′a**) and borate salt (**1″a**) could be used in the cross-coupling reaction (entries 10 and 11).

With the optimized reaction conditions, various arylboronates **1** were then subjected to the cross-coupling reaction with **2** (Table 2). Similar to **1a**, 6-methoxynaphthylboronate **1b** also participated in the rhodium(I)-catalyzed monoarylation of **2** to furnish **3b** in excellent yield (entry 1). Arylation with phenylboronate (**1c**) and 4-methyl-, 4-phenyl-, and 4-vinylphenylboronates (**1d–f**) afforded the corresponding (2-chlorovinyl)arenes **3c–f** in 56–85% yields with stereoselectivities greater than 10:1 (entries 2–5). The highly sterically hindered mesitylboronate **1g** could also provide the coupling product **3g** in 64% yield

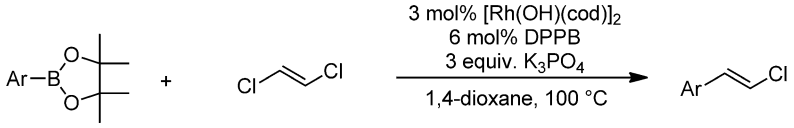
Table 1. Rhodium(I)-catalyzed cross-coupling of 2-naphthylboronate **1a** and (*E*)-1,2-dichloroethene (**2**).[a]



Entry	Variation from the standard conditions	Time [h]	Yield [%][b]	E:Z[c]
1	none	4.5	85	98:2
2	without DPPB	14	24	*E* only
3	PPh_3 (12 mol%) instead of DPPB	21	trace[d]	–
4[e]	gram scale with 1 mol% $[Rh(OH)(cod)]_2$	8.5	79	*E* only
5	5 equiv. of **2**	7	70	97:3
6	without K_3PO_4	12	no reaction	-
7	K_2CO_3 instead of K_3PO_4	3	85	98:2
8	toluene instead of 1,4-dioxane	14	48	99:1
9	(*Z*)-1,2-dichloroethene instead of **2**	6	50	23:77
10	(2-naphthyl)$B(OH)_2$ (**1′a**) instead of **1a**	20	62	94:6
11	NaB(2-naphthyl)$_4$ (**1″a**) instead of **1a**	3	156[f]	97:3

[a] *Standard conditions:* **1a** (0.10 mmol), **2** (2.0 mmol), $[Rh(OH)(cod)]_2$ (3 μmol, 6 mol% Rh), DPPB (6 μmol), and K_3PO_4 (0.30 mmol) in 1,4-dioxane (0.5 mL) at 100 °C.
[b] Isolated yield.
[c] Determined by ^{1}H NMR.
[d] Not isolated.
[e] **1a** (7.0 mmol), **2** (140 mmol), $[Rh(OH)(cod)]_2$ (0.07 mmol, 2 mol% Rh), DPPB (0.14 mmol), and K_3PO_4 (21.0 mmol) in 1,4-dioxane (35 mL) at 100 °C.
[f] Yield based on the amount of **1″a**.

Table 2. Synthesis of 2-(2-chlorovinyl)arenes **3** by rhodium(I)-catalyzed monoarylation of **2**.



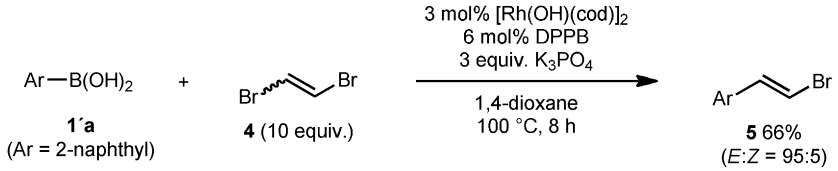
Entry	Ar (**1**)	Time [h]	**3**	Yield [%][a]	E:Z[b]
1	6-(MeO)naphthalen-2-yl (**1b**)	9	**3b**	90	>50:1
2	Ph (**1c**)	15	**3c**	76[c]	>50:1
3	4-MeC_6H_4 (**1d**)	15	**3d**	85[c]	15:1
4	4-biphenyl (**1e**)	8	**3e**	74	40:1
5	4-vinylC_6H_4 (**1f**)	7	**3f**	56	10:1
6	2,4,6-$Me_3C_6H_2$ (**1g**)	5	**3g**	64	>50:1
7	2-(pent-1-yn-1-yl)C_6H_4 (**1h**)	7	**3h**	49	>50:1
8	4-$MeOC_6H_4$ (**1i**)	22	**3i**	36	30:1
9	4-$MeO_2CC_6H_4$ (**1j**)	7	**3j**	20	10:1

[a] Isolated yield unless otherwise noted.[b] Determined by ^{1}H NMR.[c] NMR yield.

(entry 6). The reaction of 2-alkynylphenylboronate **1h** with **2** proceeded with the alkyne moiety intact and formed enyne **3h** (entry 7). Unfortunately, arylboronates **1i** and **1j** bearing electron-donating (entry 8) and electron-withdrawing (entry 9) substituents, respectively, suffered from low yields.

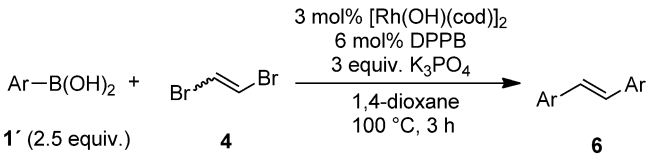
For cross-coupling with 1,2-dibromoethene (**4**, E:Z = 30:70), arylboronic acids were the preferred coupling partner compared with arylboronates. The reaction of 2-naphthylboronic acid (**1′a**) and **4** (10 equiv.) produced 2-(2-bromovinyl)naphthalene (**5**) in 66% yield with an E:Z ratio of 19:1 (Scheme 1).[4,5]

When **4** was treated with 2.5 equiv. of arylboronic acids under identical conditions, cross-coupling occurred at both the C–Br bonds of **4** to yield symmetrical (*E*)-stilbenes **6** (Table 3). A range of arylboronic



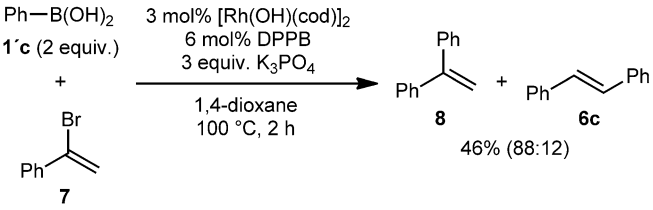
Scheme 1. Monoarylation of 1,2-dibromoethene (**4**) with **1′a**.

Table 3. Synthesis of (*E*)-stilbene derivatives **6** by rhodium(I)-catalyzed double arylation of **4**.



Entry	Ar (**1′**)	**6**[a]	Yield [%][b]
1	Ph (**1′c**)	**6c**	75
2	4-MeC_6H_4 (**1′d**)	**6d**	78
3	4-MeOC_6H_4 (**1′i**)	**6i**	60
4	4-FC_6H_4 (**1′k**)	**6k**	64
5	3-MeC_6H_4 (**1′l**)	**6l**	65
6	3-AcC_6H_4 (**1′m**)	**6m**	72[c]
7	2-naphthyl (**1′a**)	**6a**	57
8	3-thienyl (**1′n**)	**6n**	85
9	(*E*)-*β*-styryl (**1′o**)	**6o**	58

[a] Virtually, only the (*E*)-isomers were obtained.
[b] Isolated yield.
[c] Isolated as a 70:30 mixture with the biaryl by-product.

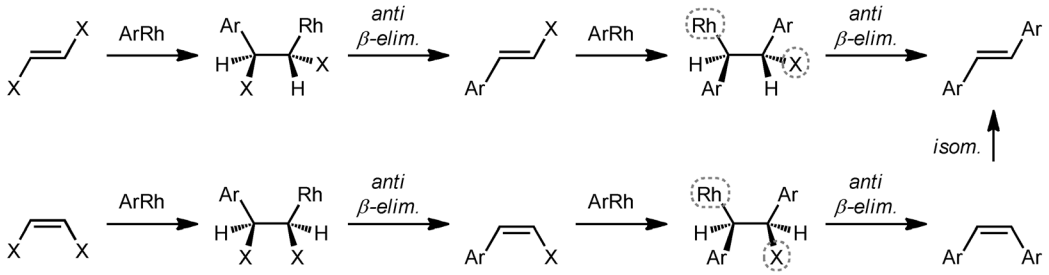


Scheme 2. Reaction of α-bromostyrene (**7**) with **1′c**.

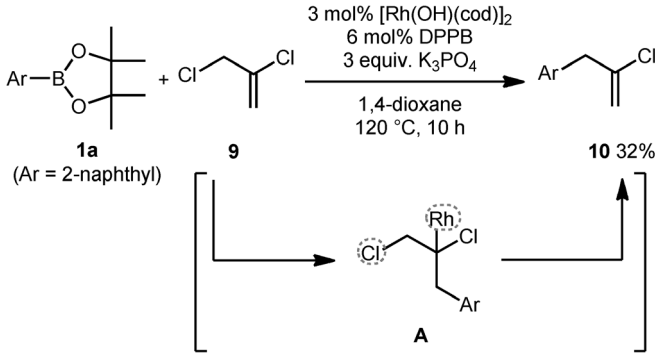
acids **1′** participated in the double arylation of **4** to afford stilbene derivatives **6** in moderate to good yields (entries 1–6). 1,2-Di(2-naphthyl)ethene (**6a**) and 1,2-di(3-thienyl)ethene (**6n**) were also synthesized through double arylation (entries 7 and 8). Furthermore, the method was successfully applied to the preparation of diphenylhexatriene **6o** by reaction of (*E*)-*β*-styrylboronic acid (**1′o**) (entry 9).

To gain information on the arylation reaction, α-bromostyrene (**7**) was subjected to coupling with **1′c**, and the reaction gave an 88:12 mixture of 1,1-diphenylethene (**8**) and (*E*)-stilbene (**6c**) in a 46% combined yield (Scheme 2). The formation of the latter product would support that the arylation proceeded at least partially through a mechanism similar to that of the rhodium-catalyzed *cine*-substitution reactions of alkenyl sulfones[6] and alkenyl acetates,[7] where addition/β-elimination mechanisms were proposed for the transformation.

McNeil et al. reported that the rhodium(I)-phosphine-catalyzed dechlorination of 1,2-dichloroethene with Et_3SiH proceeds *via* addition/β-chlorine elimination, and both *syn*- and *anti*-elimination can occur for the rhodium(I)-based pathway.[8] Therefore, it would be possible to assume that the present rhodium(I)-catalyzed arylation of alkenyl halides proceeds *via* a sequence of *syn* addition of an arylrhodium(I) species (ArRh) across a C=C bond followed by β-halogen elimination in an *anti* fashion (Scheme 3).[9] In this mechanism, (*E*)- and (*Z*)-1,2-dihaloethenes lead to (*E*)- and (*Z*)-(2-halovinyl)arenes, respectively, *via anti* β-halogen elimination. Likewise, (*E*)- and (*Z*)-(2-halovinyl)arenes follow this mechanism to deliver (*E*)- and (*Z*)-stilbenes, respectively. Exclusive formation of (*E*)-stilbenes, irrespective of the stereochemistry of **4**, can be accounted for by considering an isomerization of (*Z*)-stilbenes to the corresponding thermodynamically stable (*E*)-isomers under the reaction conditions. This has been confirmed by an independent experiment.[10]



Scheme 3. Proposed mechanism for rhodium(I)-catalyzed arylation of 1,2-dihaloethenes involving *anti* β-halogen elimination.

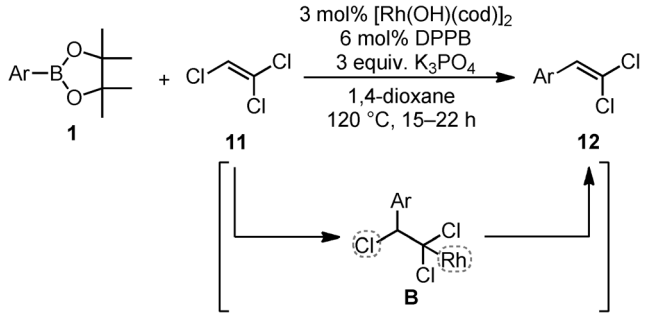


Scheme 4. Rhodium(I)-catalyzed arylation of 2,3-dichloropropene (**7**) with **1a** (**1a**:**9** = 1.5:1).

We applied the rhodium(I)-catalyzed cross-coupling method to other alkenyl halides. 2,3-Dichloropropene (**9**) reacted with **1a** to afford 2-(2-chloroallyl)naphthalene (**10**) in 32% yield (Scheme 4), while (*E*)-1,3-dichloropropene failed to undergo cross-coupling with **1a**. If the addition/elimination mechanism operates, the formation of **10** can be explained by intermediate **A**.

The reaction of trichloroethene (**11**) with **1a** selectively occurred at the C(2)−Cl bond of **9**, giving 2-(2,2-dichlorovinyl)naphthalene (**12a**) in 47% yield (Table 4, entry 1).[11,12] This selectivity is in stark contrast to palladium-catalyzed cross-coupling of tribromoethene with phenylboronic acid,[1g,13] where the *trans* C(1)−Br bond selectively reacted to afford (*Z*)-(1,2-dibromovinyl)benzene. Based upon the mechanism depicted in Scheme 3, it is conceivable that the reaction proceeded by way of intermediate **B**. We could synthesize several other (2,2-dichlorovinyl)-arenes **12** by the C-2 selective arylation (entries 2–6).

Table 4. Synthesis of (2,2-dichlorovinyl)arenes **12** by rhodium(I)-catalyzed arylation of **11** (**1**:**11** = 1:5).



Entry	Ar (**1**)	**12**	Yield [%][a]
1	2-naphthyl (**1a**)	**12a**	47
2	6-(MeO)naphthalen-2-yl (**1b**)	**12b**	59
3	4-biphenyl (**1e**)	**12e**	42
4	1-naphthyl (**1p**)	**12p**	54
5	2-methylnaphthalen-1-yl (**1q**)	**12q**	59
6	4-(*t*Bu)C_6H_4 (**1r**)	**12r**	45

[a] Isolated yield.

A rhodium(I) catalyst prepared from $[RhCl(cod)]_2$ and 1,3-bis(diphenylphosphino)propane was reported to catalyze the cross-coupling of arylboronic acids with aryl halides; however, the detailed mechanism was not provided.[14] Indeed, arylboronic acid **1′a** coupled with bromobenzene under our optimized reaction conditions (100 °C, 9 h, 58% yield of 2-phenylnaphthalene) but not with chlorobenzene. The reaction with the aryl halide appears to proceed *via* a mechanism that does not necessitate the addition/elimination process. In consideration of the results, elucidation of the precise mechanism by which arylation of alkenyl halides proceeds would require more experimentation.

In summary, we have demonstrated that 1,2-dihaloethenes are simple, yet valuable, precursors for the synthesis of β-arylvinyl halides and 1,2-diarylethenes by rhodium(I)-catalyzed arylation using arylboron compounds.

Experimental Section

General Procedure for Monoarylation (Table 2)

A Schlenk tube was charged with arylboronic ester **1** (0.10 mmol), $[Rh(OH)(cod)]_2$ (3.0 μmol), DPPB (6.0 μmol), and K_3PO_4 (0.30 mmol). The tube was evacuated and backfilled with nitrogen. 1,4-Dioxane (0.50 mL) and 1,2-dichloroethene (**2**, 2.0 mmol) were added *via* syringe through the septum. The mixture was stirred at 100 °C for the indicated period of time. The reaction mixture was filtered through a plug of Florisil® washing with hexane-AcOEt (10:1), and the filtrate was concentrated. The residue was purified by preparative TLC on silica gel to afford (2-chlorovinyl)arene **3**. The product could be obtained by recrystallization from hexane when the reaction was performed on gram-scale.

General Procesure for Double Arylation (Table 3)

A Schlenk tube was charged with arylboronic acid **1′** (0.25 mmol), $[Rh(OH)(cod)]_2$ (3.0 μmol), DPPB (6.0 μmol), and K_3PO_4 (0.30 mmol). The tube was evacuated and backfilled with nitrogen. 1,4-Dioxane (0.50 mL) and 1,2-dibromoethene (0.10 mmol) were added *via* syringe through the septum. The mixture was stirred at 100 °C for 3 h. The reaction mixture was filtered through a plug of Florisil® washing with hexane-AcOEt (10:1), and the filtrate was concentrated. The residue was purified by preparative TLC on silica gel to afford 1,2-diarylethene **6**.

Acknowledgements

We thank Manac Inc. for financial support.

References

[1] For previous synthetic approaches to 2-(2-chlorovinyl)arenes, see: a) N. A. Petasis, I. A. Zavialov, *Tetrahedron Lett.* **1996**, *37*, 567; b) K. Takai, T. Ichiguchi, S. Hikasa, *Synlett* **1999**, 1268; c) C. Kuang, H. Senboku, M. Tokuda, *Synlett* **2000**, 1439; d) H.-W. You, K.-J. Lee, *Synlett* **2001**, 105; e) R. Baati, D. K. Barma, U. M. Krishna, C. Mioskowski, J. R. Falck, *Tetrahedron Lett.* **2002**, *43*, 959; f) J. P. Das, S. Roy, *J. Org. Chem.* **2002**, *67*, 7861; g) M. G. Organ, H. Ghasemi, C. Valente, *Tetrahedron* **2004**, *60*, 9453; h) J. Barluenga, P. Moriel, F. Aznar, C. Valdés, *Adv. Synth. Catal.* **2006**, *348*, 347; i) M.-E. Lebrun, P. Le Marquand, C. Berthelette, *J. Org. Chem.* **2006**, *71*, 2009; j) M. R. Heinrich, O. Blank, D. Ullrich, M. Kirschstein, *J. Org. Chem.* **2007**, *72*, 9609; k) V. Sashuk, C. Samojłowicz, A. Szadkowska, K. Grela, *Chem. Commun.* **2008**, 2468; l) J. A. Bull, J. J. Mousseau, A. B. Charette, *Org. Lett.* **2008**, *10*, 5485; m) G. A. Molander, L. N. Cavalcanti, *J. Org. Chem.* **2011**, *76*, 7195.

[2] G. Likhtenshtein, *Stilbenes*, Wiley-VCH, Weinheim, **2010**.

[3] For reviews, see: a) P. Tian, H.-Q. Dong, G.-Q. Lin, *ACS Catal.* **2012**, *2*, 95; b) H. J. Edwards, J. D. Hargrave, S. D. Penrose, C. G. Frost, *Chem. Soc. Rev.* **2010**, *39*, 2093; c) S. W. Youn, *Eur. J. Org. Chem.* **2009**, 2597; d) T. Miura, M. Murakami, *Chem. Commun.* **2007**, 217; e) T. Hayashi, K. Yamasaki, *Chem. Rev.* **2003**, *103*, 2829; f) K. Fagnou, M. Lautens, *Chem. Rev.* **2003**, *103*, 169.

[4] When **1a** was used, the reaction required a longer time (33 h) to obtain **5** in 58% yield.

[5] The yield of **5** was considerably reduced (36%) when 5 equiv. of **4** were employed.

[6] K. Yoshida, T. Hayashi, *J. Am. Chem. Soc.* **2003**, *125*, 2872.

[7] J.-Y. Yu, R. Shimizu, R. Kuwano, *Angew. Chem.* **2010**, *122*, 6540; *Angew. Chem. Int. Ed.* **2010**, *49*, 6396.

[8] A. A. Peterson, K. A. Thoreson, K. McNeill, *Organometallics* **2009**, *28*, 5982.

[9] For *anti* β-elimination occurring with organorhodium(I) species, see a) M. Murakami, H. Igawa, *Helv. Chim. Acta* **2002**, *85*, 4182; b) T. Miura, Y. Takahashi, M. Murakami, *Chem. Commun.* **2007**, 595; c) T. Nishimura, Y. Takiguchi, T. Hayashi, *J. Am. Chem. Soc.* **2012**, *134*, 9086. See also ref.[6]

[10] (*Z*)-Stilbene was completely converted into (*E*)-stilbene under the reaction conditions after 24 h. On the other hand, isomerization of (*Z*)-2-(2-chlorovinyl)naphthalene was not obvious.

[11] The structure of **10a** was proved by its independent synthesis *via* dichloromethylenation of 2-naphthaldehyde.

[12] The synthesis of 2-(2,2-dichlorovinyl)arenes *via* aryl radicals generated from aryldiazonium salts was reported. See ref.[1j]

[13] The rhodium(I)-catalyzed reaction of **1a** with tribromoethene gave a 3:1 mixture of 2-(2,2-dibromovinyl)naphthalene and (*Z*)-(1,2-dibromovinyl)naphthalene in 22% combined yield.

[14] K. Ueura, T. Satoh, M. Miura, *Org. Lett.* **2005**, *7*, 2229.

