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Three Different Dimerizations of 2-Bromo-3-methyl-1,4-naphthoquinones

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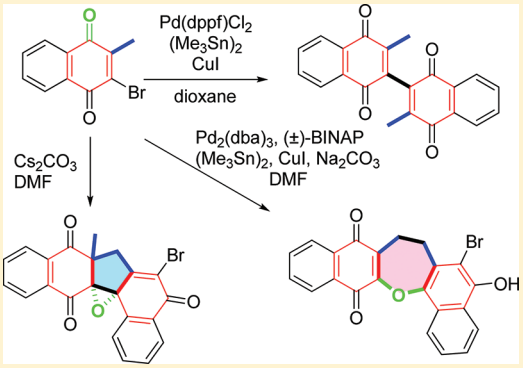
Supporting Information

ABSTRACT: Three types of dimeric naphthoquinones, which possess structurally diverse skeletons, can be prepared in one step from 2-bromo-3-methyl-1,4-naphthoquinones. 2,2′-Dimeric naphthoquinones were prepared by a one-pot Stille-type reaction via vinylstannanes. Oxepines are formed by unexpected domino reactions via 1,4-dihydroxynaphthalene species. Epoxides are formed by a Michael/Darzens reaction via the *o*-quinone methides.



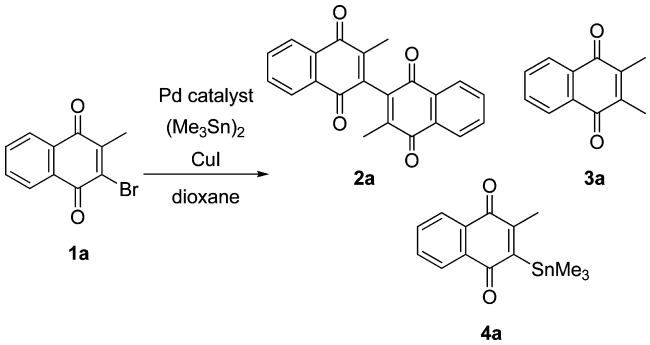
INTRODUCTION

Naphthoquinones are known to dimerize in various ways, depending on their structure and the particular set of conditions.[1,2] However, the products of the dimerizations are difficult to predict or control, and only a few methods for efficient and selective synthesis of dimeric naphthoquinones have been reported.[1c] Moreover, little is known of the dimerization reactions of brominated naphthoquinones. We were interested in direct homocoupling of 2-bromo-1,4-naphthoquinones to synthesize symmetrical 2,2′-dimeric naphthoquinones such as bivitamin K_3[3] and biplumbagin.[4] This synthetic approach clearly has advantages in terms of redox economy over traditional oxidative coupling of 4-alkoxy-1-naphthols.[2b] In addition, 2-bromo-3-methyl-1,4-naphthoquinones (**1**) can serve as a potential starting material for generating structurally diverse naphthoquinone dimers because they contain numerous reactive groups, allowing for a variety of dimerizations. In this paper, we describe novel and selective dimerizations of **1**.

RESULTS AND DISCUSSION

After a systematic survey[5] of homocoupling of **1a**,[6] we found that a Stille-type reaction was effective (Table 1). Treatment of **1a** with hexamethylditin (1.1 equiv) and CuI (1.0 equiv) in the presence of [1,1′-bis(diphenylphosphino)ferrocene]palladium dichloride ($Pd(dppf)Cl_2$) (0.2 equiv) in dioxane gave the desired **2a**[3,7] in 70% yield (entry 1). In this reaction, 2,3-dimethyl-1,4-naphthoquinone (**3a**)[8] was also obtained in 13% yield. The use of $Pd(PPh_3)_4$ decreased the yield of **2a** and increased the yield of **3a** (entry 2). The use of $Pd(PPh_3)_2Cl_2$ (0.1 equiv) as a catalyst, in the absence of CuI, gave **4a**, a

Table 1. Stille-Type Homocoupling Reaction of 1a[a]



entry	Pd catalyst	temp (°C)	yield (%) 2a[b]	3a[c]	4a[b]
1	$Pd(dppf)Cl_2$	80	70	13	
2	$Pd(PPh_3)_4$	80	54	20	
3[d]	$Pd(PPh_3)_2Cl_2$	100			64

[a]Unless otherwise indicated, the reactions were carried out in the presence of Pd catalyst (0.2 equiv), $(Me_3Sn)_2$ (1.1 equiv), and CuI (1.0 equiv). [b]Yields of the isolated product. [c]Yields estimated by ^1H NMR using 2,5-dimethylfuran as internal standard. [d]Used 0.1 equiv of $Pd(PPh_3)_2Cl_2$ without CuI.

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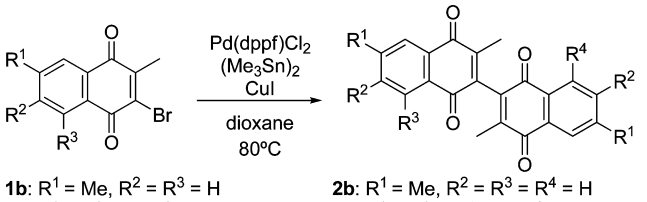
Table 2. Formation of Homodimers 2 from 1[a]



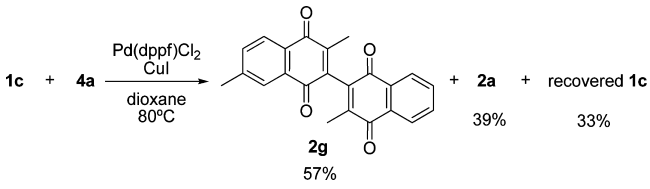
1b: R^1 = Me, R^2 = R^3 = H
1c: R^1 = R^3 = H, R^2 = Me
1d: R^1 = R^2 = H, R^3 = OAc
1e: R^1 = R^2 = H, R^3 = OMe
1f : R^1 = R^2 = H, R^3 = OH

2b: R^1 = Me, R^2 = R^3 = R^4 = H
2c: R^1 = R^3 = R^4 = H, R^2 = Me
2d: R^1 = R^2 = H, R^3 = R^4 = OAc
2d′: R^1 = R^2 = H, R^3 = OAc, R^4 = OH
2e: R^1 = R^2 = H, R^3 = R^4 = OMe
2f : R^1 = R^2 = H, R^3 = R^4 = OH

entry	substrate **1**	product **2**	yield (%)[b]
1	**1b**	**2b**	58
2	**1c**	**2c**	65
3	**1d**	**2d** and **2d′**	**2d**: 41, **2d′**: 40
4	**1e**	**2e**	72
5	**1f**	**2f**	12

[a]The reactions were carried out in the presence of $Pd(dppf)Cl_2$ (0.2 equiv), $(Me_3Sn)_2$ (1.1 equiv), and CuI (1.0 equiv). [b]Yields of the isolated product.

Scheme 1. Crossover Reaction between Vinyl Bromide 1c and Vinylstannane 4a for Mechanistic Studies on the Formation of 2,2′-Dimeric Naphthoquinones



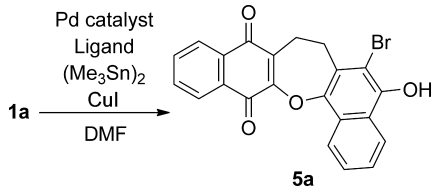
plausible intermediate of the homocoupling, in 64% yield (entry 3).

Using optimal conditions (Table 1, entry 1), various 2-bromo-3-methyl-1,4-naphthoquinones (**1**) were subjected to the homodimerization reaction (Table 2). The dimerization of **1b** or **1c**, which have a methyl group in the benzene ring, gave the desired dimer **2b** or **2c** in moderate yields (entries 1 and 2). The reaction of the acetyloxy derivative **1d** afforded **2d** and the mono-deacetylated product **2d′** in 41% and 40% yields, respectively (entry 3). The dimerization of the methoxy derivative **1e**[9] gave **2e**[10] in 72% yield (entry 4). Because of the instability of 5-hydroxy-3-bromo-2-methyl-1,4-naphthoquinone (**1f**)[11] under the reaction conditions, the yield of **2f**[12] was low (entry 5).

To analyze the mechanism of the homodimerization reaction, the crossover reaction between **1c** and **4a** was performed to afford the heterodimer **2g**, homodimer **2a**, and recovered **1c** in 57%, 39%, and 33%, respectively (Scheme 1). This result suggests that compound **2** was formed by both Stille coupling between **1** and **4** and oxidative dimerization[13] of stannanes **4**.

During the course of our investigations of Stille-type homocoupling, we found a novel dimerization of **1a** (Table 3). When the reaction was carried out using $Pd(dppf)Cl_2$ (0.1 equiv) in DMF, the oxepine **5a** was obtained in 36% yield as the sole product (entry 1). The structure of **5a** was confirmed by X-ray crystallography (see the Supporting Information). The yield

Table 3. Formation of Oxepines 5a from 1a[a]



entry	Pd catalyst/ligand	yield[b] (%)
1	$Pd(dppf)Cl_2$/–	36
2	$Pd_2(dba)_3$/(±)-BINAP	47
3[c]	$Pd_2(dba)_3$/(±)-BINAP	96

[a]Unless otherwise indicated, the reactions were carried out in the presence of Pd catalyst (0.1 equiv), $(Me_3Sn)_2$ (1.1 equiv), and CuI (1.0 equiv) with or without (±)-BINAP (0.1 equiv). [b]Yields of the isolated product. [c]With 1.0 equiv of Na_2CO_3.

was slightly improved when tris(dibenzylideneacetone)-dipalladium ($Pd_2(dba)_3$) (0.05 equiv) and (±)-2,2′-bis-(diphenylphosphino)-1,1′-binaphthyl (BINAP) (0.1 equiv) were used as the catalyst and ligand, respectively (entry 2). We found that the addition of Na_2CO_3 significantly improved the yield of **5a** (entry 3). Although the use of CuBr instead of CuI gave **5a** in 87% yield, the use of $CuBr_2$ gave **5a** in only 13% yield, suggesting that Cu(I) activated **1a** to give oxepine formation. The reaction was quenched with acetic anhydride (Ac_2O) before completion to give acetylated oxepine **6** and 1,4-diacetylnaphthalene **7** in 11% and 10% yields, respectively, along with recovered starting material **1a** (50%) (Scheme 2). Isolation of compound **7** indicates that 1,4-dihydroxynaphthalene species are intermediates in oxepine formation.

We next examined the effects of the reagents used on the oxepine formation (Table 4). The reaction in the absence of hexamethylditin afforded a complex mixture (entry 1). Although the reaction proceeded in the absence of CuI or (±)-BINAP, there was a decrease in yield (entries 2 and 3). Interestingly, the oxepine **5a** was obtained in 82% yield when the reaction was conducted without $Pd_2(dba)_3$ (entry 4). These results suggested that (±)-BINAP might coordinate with copper ion.[14]

Using optimized conditions, the influence of additional functional groups on oxepine formation was examined (Table 5). Although the reaction can tolerate a methyl group in the benzene ring, oxepine **5b** or **5c** were only obtained in moderate yield (entry 1 and 2, respectively). The reaction of **1d** resulted in a poor yield of **5d**. Unfortunately, the reaction of **1e** or **1f** led to decomposition of the substrate.

To rationalize the unexpected formation of **5a**, a mixture of vinyl bromide **1c** and vinylstannane **4a** was subjected to the same reaction, producing **3a** and **5c** in 19% and 55% yields, respectively (Scheme 3). This result indicates that the oxepines are not derived from vinylstannanes but from vinyl bromides. We found that oxepine **5a** was obtained by treatment of **1a** with *t*-BuOK in THF (Scheme 4A). Furthermore, irradiation of a solution of **1a** and hexamethylditin in DMF with a white fluorescent lamp afforded **5a** in 39% yield (Scheme 4B). The photodimerization of **1a** did not occur in the absence of hexamethylditin, indicating that a photoinduced electron transfer from hexamethylditin to an excited state of naphthoquinone **1a** is involved in the photodimerization.[15] Irradiation of **1a** and hexamethylditin in the presence of Ac_2O gave 1,4-diacetylnaphthalene **7** in 48% yield (Scheme 4C). This result suggests that 1,4-dihydroxynaphthalene species are intermediates in photoinduced oxepine formation.

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Scheme 2. Trapping Experiments with Acetic Anhydride in Oxepine Formation

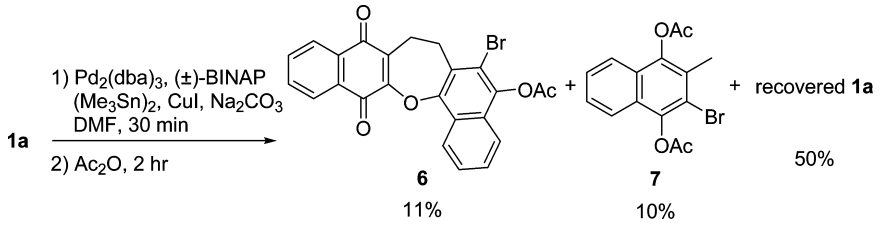
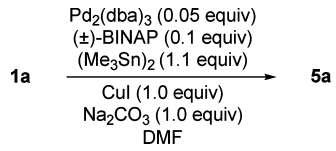


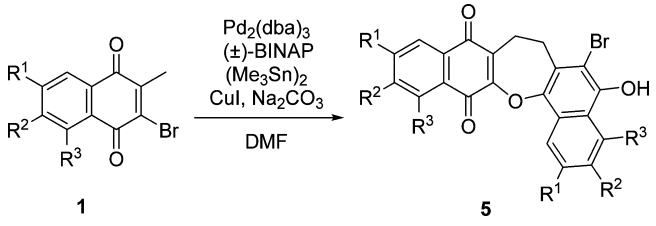
Table 4. Effects of Reagents on Formation of Oxepine 5a[a]



entry	$Pd_2(dba)_3$	(±)-BINAP	$(Me_3Sn)_2$	CuI	Na_2CO_3	yield[b] (%)
1[c]	+	+	−	+	+	−
2	+	+	+	−	+	27
3	+	−	+	+	+	43
4	−	+	+	+	+	82

[a]The plus sign indicates the presence of the reagent, and the minus sign indicates the absence of the reagent or product. [b]Yields of the isolated product. [c]Complex mixture.

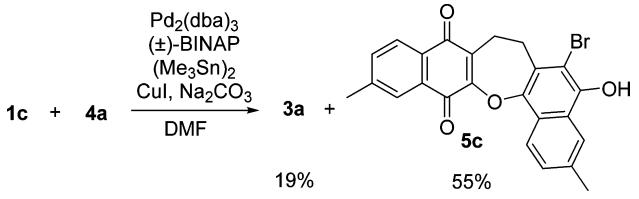
Table 5. Formation of Oxepines from 2-Bromo-3-methyl-1,4-napthoquinones[a,b]



entry	substrate **1**	product **5**	yield[b] (%)
1	**1b**	**5b**: R^1 = Me, R^2 = R^3 = H	51
2	**1c**	**5c**: R^1 = R^3 = H, R^2 = Me	47
3	**1d**	**5d**: R^1 = R^2 = H, R^3 = OAc	26

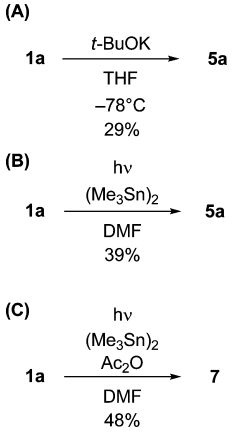
[a]The reactions were carried out in the presence of $Pd_2(dba)_3$ (0.05 equiv), (±)-BINAP (0.1 equiv), $(Me_3Sn)_2$ (1.1 equiv), and CuI (1.0 equiv). [b]Yields of the isolated product.

Scheme 3. Crossover Reaction Study of Oxepine Formation for Mechanistic Analysis



Our proposed mechanism for the oxepine formation is shown in Scheme 5. Oxepine formation by *t*-BuOK in THF starts with the formation of the *o*-quinone methide derivative **A** (Scheme 5A). The *o*-quinone methide attacks the enone moiety of another *o*-quinone methide to give the hydroquinone dianion **B**.[1c] Finally 1,4-addition of the hydroquinone anion to the *β*-bromo enone, followed by elimination of a bromide anion, affords the oxepine **5a**. Photoinduced oxepine formation starts

Scheme 4. Formation of 5a by Treatment of 1a with *t*-BuOK in THF (A) and Irradiation of 1a and Hexamethylditin in the Presence (B) or Absence (C) of Acetic Anhydride



with generation of the excited triplet state (**1a***) of bromonaphthoquinone **1a** (Scheme 5B).[15] Reaction of **1a*** with hexamethylditin would give a semiquinone radical anion **C** and a radical cation of hexamethylditin, which could produce a 1,4-bis(trimethylstannoxy)naphthoquinone **D**.[15b] Elimination of trimethyltin hydride from **D**, followed by dimerization of the resulting *o*-quinone methides **E**, would give a stannyl ether **F**. The conversion of **D** into **E** might involve homolytic cleavage of the Sn−O bond, followed by hydrogen abstraction from the methyl group by the resulting trimethyltin radical. Hydrolysis of **F** would afford **5a**. Oxepine formation from hexamethylditin, CuI, (±)-BINAP, and Na_2CO_3 in DMF would start with formation of an adduct of **1** with CuI (Scheme 5C).[16] The resulting complex **1**·CuI would react with hexamethylditin to give 1,4-dihydroxynaphthalene species **G**. The intermediate **G** could then generate the *o*-quinone methide **H**. Formation of an ethylene bridge, followed by intramolecular seven-membered ether ring formation, would afford **5**. A palladium catalyst might activate **1** by coordination[17] or might accelerate the final intramolecular ether formation.[18] Formation of a Pd enolate at the carbonyl group adjacent to the methyl group, followed by *β*-hydride elimination, might provide the quinone methide E or H.[19]

We found another novel dimerization of **1a** in the course of our investigations of oxepine formation (Table 6). Treatment of **1a** with Na_2CO_3 in DMF gave an epoxide dimer **8a** in 52% yield (entry 1). The structure of **8a** was unambiguously determined by X-ray crystallography; an *anti* relationship between the methyl group and the epoxide was indicated (see the Supporting Information). The use of K_2CO_3 or Rb_2CO_3 as a base slightly improves the yield of **8a** (entries 2 and 3). The yield was improved to 85% by using Cs_2CO_3 (entry 4).

The formation of epoxide dimers **8** from various 2-bromo-3-methyl-1,4-naphthoquinones was examined (Table 7). The

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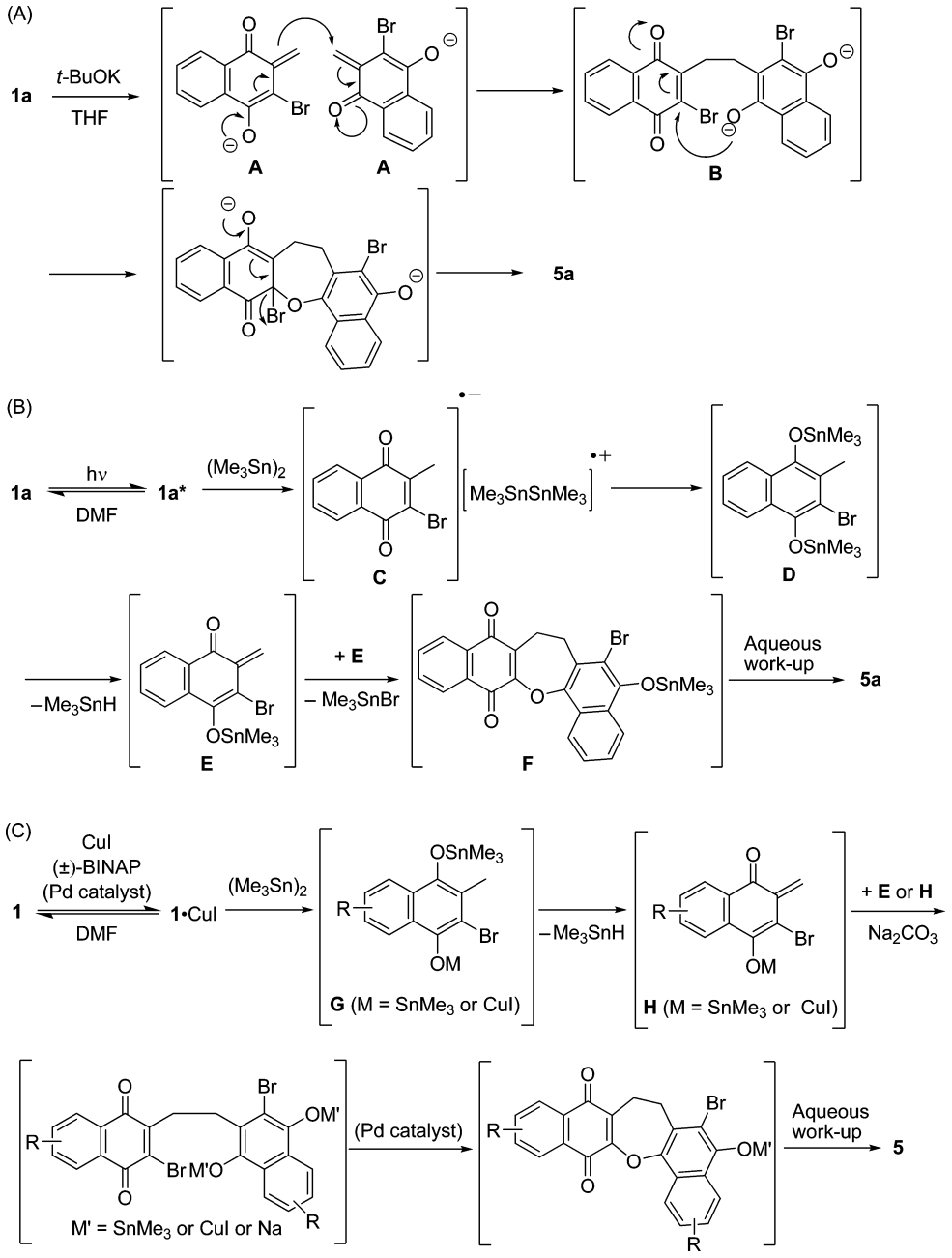
Scheme 5. Proposed Mechanism for Formation of Oxepine 5a from 1a by Treatment with *t*-BuOK in THF (A), Formation of 5a by Irradiation of 1a and $(Me_3Sn)_2$ (B), and Formation of 5 by Treatment with $(Me_3Sn)_2$, CuI, (±)-BINAP, and Na_2CO_3 in DMF (C)



epoxides **8b** and **8c** were obtained in good yields from **1b** and **1c**, respectively (entry 1 and 2). However, the yield decreased when compound **1d** or **1e** was the substrate (entry 3 and 4). Compound **1f** decomposed under the basic conditions used in this reaction.

The mechanism for the formation of epoxide dimer **8** is shown in Scheme 6. Treatment of **1** with Cs_2CO_3 establishes an equilibrium between **1** and the *o*-quinone methide **I**. The *o*-quinone methide **I** attacks the enone of **1**, and the resulting enolate undergoes an intramolecular Darzens reaction to yield the epoxide dimer **8**.[20]

■ CONCLUSION

We have developed three novel dimerization reactions of 2-bromo-3-methyl-1,4-naphthoquinones (**1**). Moreover, we have shown that structurally diverse skeletons can be constructed from **1** in a single step. Stille-type homocoupling is a convenient method for the preparation of 2,2′-dimeric naphthoquinones **2**. The unprecedented formation of oxepines **5** and epoxides **8** can be rationalized by unique domino reactions. The resulting highly functionalized oxepines and epoxides can serve as useful building blocks for the construction of combinatorial libraries. Exploration of synthetic uses of these reactions, as well as biological evaluations of the core skeletons, are in progress.

■ EXPERIMENTAL SECTION

General Information. All nonaqueous reactions were carried out using distilled solvents under a N_2 atmosphere in dried glassware, unless otherwise noted. Analytical TLC was performed on glass plates

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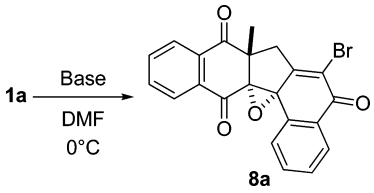
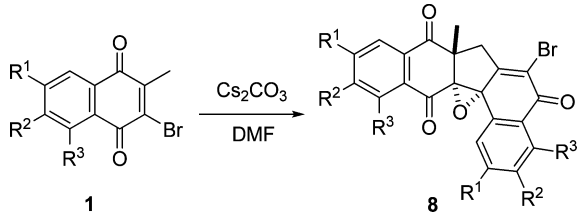
Table 6. Optimization of Formation of Epoxide Dimer 8a[a]



entry	base	time (min)	yield[b] (%)
1[c,d]	Na_2CO_3	180	52
2	K_2CO_3	60	68
3	Rb_2CO_3	45	66
4	Cs_2CO_3	30	85

[a]The reactions were carried out using 1.5 equiv of base. [b]Yields of the isolated product. [c]The reaction was carried out at 0 °C for 90 min and at rt for 90 min. [d]17% of **1a** was recovered.

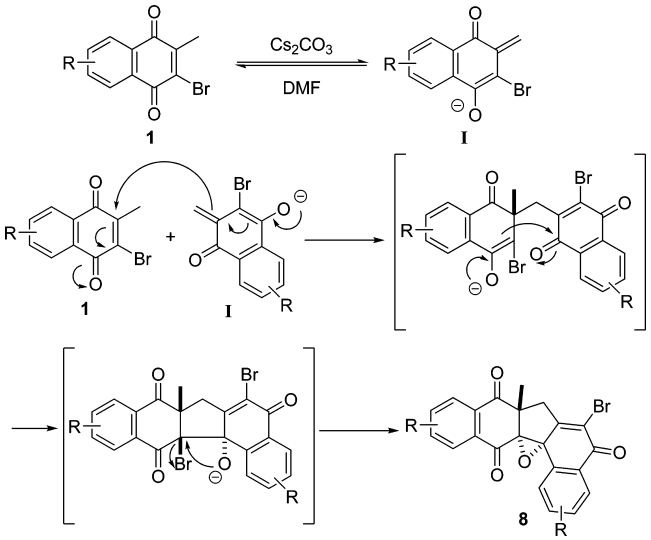
Table 7. Formation of Epoxides from 2-Bromo-3-methyl-1,4-naphthoquinones[a,b]



entry	substrate **1**	product **8**	yield[b] (%)
1	**1b**	**8b**: R^1 = Me, R^2 = R^3 = H	71
2	**1c**	**8c**: R^1 = R^3 = H, R^2 = Me	68
3	**1d**	**8d**: R^1 = R^2 = H, R^3 = OAc	24
4	**1e**	**8e**: R^1 = R^2 = H, R^3 = OMe	23

[a]The reactions were carried out using 1.5 equiv of Cs_2CO_3. [b]Yields of the isolated product.

Scheme 6. Proposed Mechanism for Formation of Epoxides 8 from 1



coated with silica gel. Flash chromatography was carried out on silica gel (230–400 mesh). NMR spectra were recorded on a 270 or 600 MHz spectrometer. Chemical shifts are expressed as δ (ppm) relative to Me_4Si or the residual solvent resonance, and coupling constants (J) are expressed in hertz. The following abbreviations are used for spin multiplicity: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, and br = broad. IR spectra were recorded on a FT-IR spectrometer and are reported in wavenumbers (cm^{-1}). High-resolution mass spectra (HRMS) were obtained on a magnetic sector mass spectrometer using electron impact ionization (EI) or a TOF mass spectrometer using electrospray ionization (ESI).

2-Bromo-3,6-dimethyl-1,4-naphthoquinone (1b). Br_2 (0.10 mL, 1.94 mmol) was added to a solution of 2,7-dimethylnaphthoquinone[21] (186 mg, 1.00 mmol) in AcOH (10 mL) at rt. The mixture was stirred at rt for 12 h. The reaction was quenched by the addition of water, and the solid was removed by filtration. The solid was dissolved in $CHCl_3$. The resulting solution was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was dissolved in pyridine (5 mL), and the mixture was stirred at 0 °C for 20 min. The reaction was quenched by the addition of 1 M HCl aqueous solution, and the mixture was diluted with EtOAc. After the layers were separated, the aqueous layer was extracted with EtOAc (× 2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by flash column chromatography (toluene/hexane = 2/3 to 2/1) to give **1b** (219 mg, 83%) as a yellow solid: mp = 111–112 °C; IR (KBr) ν_{max} = 3188, 3059, 2922, 1672, 1595, 1298, 1277, 1022, 872, 847, 785, 717 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.04 (d, J = 8.0 Hz, 1H), 7.91 (s, 1H), 7.52 (d, J = 8.0 Hz, 1H), 2.50 (s, 3H), 2.38 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 182.0, 177.0, 148.0, 145.2, 139.0, 134.4, 131.3, 128.8, 127.6, 127.3, 21.9, 17.9; HRMS (EI) calcd for $C_{12}H_9{}^{79}BrO_2$ ([M]$^+$) 263.9786, found 263.9786.

3-Bromo-2,6-dimethyl-1,4-naphthoquinone (1c). Br_2 (1.50 mL, 29.1 mmol) was added to a solution of 2,6-dimethylnaphthoquinone[21] (2.79 g, 15.0 mmol) in AcOH (100 mL) at rt. The mixture was stirred at rt for 13 h. The reaction was quenched by the addition of water, and the solid was removed by filtration. The solid was dissolved in $CHCl_3$. The resulting solution was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was dissolved in pyridine (10 mL), and the mixture was stirred at 0 °C for 30 min and at rt for 15 min. The reaction was quenched by the addition of 1 M HCl aqueous solution, and the mixture was diluted with EtOAc. After the layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by flash column chromatography (toluene/hexane = 2/3 to 2/1) to give **1c** (2.21 g, 56%) as a yellow solid: mp = 115–116 °C; IR (KBr) ν_{max} = 3062, 2922, 1674, 1655, 1294, 1026, 910, 843, 781, 717 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 7.95 (d, J = 7.8 Hz, 1H), 7.89 (s, 1H), 7.51 (d, J = 7.8 Hz, 1H), 2.49 (s, 3H), 2.36 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 181.4, 177.4, 148.2, 144.9, 138.5, 134.6, 130.8, 129.0, 127.6, 127.0, 21.8, 17.8; HRMS (EI) calcd for $C_{12}H_9{}^{81}BrO_2$ ([M]$^+$) 265.9766, found 265.9765.

5-Acetyloxy-3-bromo-2-methyl-1,4-naphthoquinone (1d). Ac_2O (12 mL) was added to a solution of **1f**[11] (400 mg, 1.50 mmol) in pyridine (6 mL) at 0 °C. The mixture was stirred at rt for 1 h. The reaction was quenched by the addition of 1 M HCl aqueous solution, and the mixture was diluted with EtOAc. The suspension was filtered through Celite. After the layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by flash column chromatography (EtOAc/hexane = 1/8) to give **1d** (421 mg, 91%) as a yellow solid: mp = 153–155 °C; IR (KBr) ν_{max} = 3095, 2925, 1768, 1672, 1604, 1587, 1444, 1304, 1250, 1188, 1022, 920, 879, 792, 754 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.10 (dd, J = 7.9 Hz, 1.4 Hz, 1H), 7.77 (dd, J = 7.9 Hz, 7.9 Hz, 1H), 7.39 (dd, J = 7.9 Hz, 1.4 Hz, 1H), 2.49 (s, 3H), 2.39 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 181.0, 175.6, 169.2, 149.9, 147.4, 139.9, 134.9, 133.1, 129.6, 125.5, 122.5, 21.2, 17.8; HRMS (EI) calcd for $C_{13}H_9{}^{79}BrO_4$ ([M]$^+$) 307.9684, found 307.9674.

General Procedure for Stille-Type Homocoupling Reaction (Tables 1 and 2). A Pd catalyst (0.2 or 0.1 equiv) was added to a solution of **1** (1.0 equiv) and hexamethylditin (1.1 equiv) in the presence or absence of CuI (1.0 equiv) in degassed dioxane at rt. The mixture was stirred at the indicated temperature (80 or 100 °C) under a N_2 atmosphere until no further TLC changes were observed. The

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reaction was quenched by the addition of water, and the mixture was diluted with EtOAc. The mixture was filtered through Celite. After the layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (EtOAc/hexane). The structures of **2a**,[7] **2e**,[10] **2f**,[12] and **3a**[8] were confirmed by comparison of the ^{1}H NMR data with reported data.

3,3′-Dimethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2a). Following the general procedure, the homocoupling reaction of **1a** (30.1 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol) and CuI (22.9 mg, 120 μmol) in the presence of Pd(dppf)Cl_2 (17.6 mg, 24 μmol) for 7 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/15 to 1/5) to give **3a** (14.3 mg, 70%) as a yellow solid: mp = 249−250 °C (lit.[7] mp = 249−251 °C); ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 8.20−8.16 (m, 2H), 8.12−8.07 (m, 2H), 7.82−7.72 (m, 4H), 2.07 (s, 6H); ^{13}C NMR (CDCl3, 67.8 MHz) δ =184.3 (2C), 182.4 (2C), 145.6 (2C), 140.4 (2C), 133.84 (2C), 133.77 (2C), 131.8 (2C), 131.8(2C), 126.6 (2C), 126.5 (2C), 14.5 (2C).

3,3′,6,6′-Tetramethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2b). Following the general procedure, the homocoupling reaction of **1b** (31.8 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol) and CuI (22.9 mg, 120 μmol) in the presence of Pd(dppf)Cl_2 (17.6 mg, 24 μmol) for 7 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/15 to 1/5) to give **2b** (12.8 mg, 58%) as a yellow solid: mp = 203−204 °C; IR (KBr) ν_{max} = 3197, 3057, 2958, 2924, 2860, 1664, 1599, 1377, 1344, 1290, 1151, 1022, 849, 714 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 7.98 (d, J = 7.9 Hz, 2H), 7.96 (s, 2H), 7.55 (d, J = 7.9 Hz, 2H), 2.53 (s, 6H), 2.04 (s, 6H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 184.6 (2C), 182.3 (2C), 145.3 (2C), 144.9 (2C), 140.5 (2C), 134.4 (2C), 131.9 (2C), 129.6 (2C), 126.83 (2C), 126.76 (2C), 22.0 (2C), 14.4 (2C); HRMS (EI) calcd for $C_{24}H_{18}O_4$ ([M]$^+$) 370.1205, found 370.1204.

3,3′,7,7′-Tetramethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2c). Following the general procedure, the homocoupling reaction of **1c** (95.4 mg, 360 μmol) using hexamethylditin (130 mg, 396 μmol) and CuI (68.6 mg, 360 μmol) in the presence of Pd(dppf)Cl_2 (52.7 mg, 72 μmol) for 7 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/15 to 1/5) to give **2c** (43.4 mg, 65%) as a yellow solid: mp = 256−258 °C; IR (KBr) ν_{max} = 3199, 3059, 3010, 2960, 2925, 1662, 1599, 1375, 1327, 1292, 1169, 958, 843, 714 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 8.06 (d, J = 7.8 Hz, 2H), 7.88 (s, 2H), 7.56 (d, J = 7.8 Hz, 2H), 2.50 (s, 6H), 2.04 (s, 6H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 184.1 (2C), 182.7 (2C), 145.6 (2C), 144.9 (2C), 140.3 (2C), 134.5 (2C), 131.8 (2C), 129.8 (2C), 126.9 (2C), 126.7 (2C), 22.0 (2C), 14.4 (2C); HRMS (EI) calcd for $C_{24}H_{18}O_4$ ([M]$^+$) 370.1205, found 370.1207.

8,8′-Diacetyloxy-3,3′-dimethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2d). Following the general procedure, the homocoupling reaction of **1d** (37.1 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol) and CuI (22.9 mg, 120 μmol) in the presence of Pd(dppf)Cl_2 (17.1 mg, 24 μmol) for 10 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/12) to give **2d** (11.3 mg, 41%) as an orange solid and **2d′** (10.0 mg, 40%) as a yellow solid. **2d**: mp = 230−231 °C dec; IR (KBr) ν_{max} = 3076, 3049, 2962, 2925, 1763, 1664, 1647, 1628, 1614, 1593, 1458, 1369, 1288, 1257, 1200, 1024, 744 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 8.12 (dd, J = 7.8 Hz, 1.4 Hz, 2H), 7.77 (dd, J = 7.8 Hz, 7.8 Hz, 2H), 7.38 (dd, J = 7.8 Hz, 1.4 Hz, 2H), 2.36 (s, 6H), 2.00 (s, 6H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 183.6 (2C), 180.8 (2C), 169.1 (2C), 149.4 (2C), 144.7 (2C), 141.3 (2C), 134.6 (2C), 133.6 (2C), 129.5 (2C), 125.0 (2C), 123.3 (2C), 21.2 (2C), 14.2 (2C); HRMS (EI) calcd for $C_{26}H_{18}O_8$ ([M]$^+$) 458.1002, found 458.1001.

8-Acetyloxy-8′-hydroxy-3,3′-dimethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2d′): mp = 226−228 °C dec; IR (KBr) ν_{max} = 3440, 3080, 3022, 1770, 1664, 1593, 1369, 1325, 1267, 1190, 1022, 875 750, 732 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 11.82 (s, 1H), 8.14 (dd, J = 8.1 Hz, 1.4 Hz, 1H), 7.79 (dd, J = 8.1 Hz, 8.1 Hz, 1H), 7.71 (dd, J = 8.1 Hz, 1.4 Hz, 1H), 7.65 (dd, J = 8.1 Hz, 8.1 Hz, 1H), 7.40 (dd, J = 8.1 Hz, 1.4 Hz, 1H), 7.28 (dd, J = 8.1 Hz, 1.4 Hz, 1H), 2.37 (s, 3H), 2.05 (s, 3H), 2.04 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 187.3, 183.45, 183.39, 180.9, 169.1, 161.3, 149.5, 147.2, 144.9, 140.6, 140.2, 136.3, 134.7, 133.6, 131.9, 129.7, 125.1, 124.3, 123.2, 119.4, 114.7, 21.2, 14.5, 14.3; HRMS (EI) calcd for $C_{24}H_{16}O_7$ ([M]$^+$) 416.0896, found 416.0894.

8,8′-Dimethoxy-3,3′-dimethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2e). Following the general procedure, the homocoupling reaction of **1e** (33.7 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol) and CuI (22.9 mg, 120 μmol) in the presence of Pd(dppf)Cl_2 (17.6 mg, 24 μmol) for 13.5 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/5 to 1/1) to give **2e** (17.4 mg, 72%) as a yellow solid: mp = 273−275 °C (lit.[10] 261−263 °C); ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 7.81 (dd, J = 8.0 Hz, 1.1 Hz, 2H), 7.69 (dd, J = 8.0 Hz, 2H), 7.28 (dd, J = 8.0, 1.1 Hz, 2H), 3.95 (s, 6H), 2.01 (s, 6H); ^{13}C NMR ($CDCl_3$, 67.8 MHz): δ = 184.6 (2C), 181.8 (2C), 159.6 (2C), 142.8 (2C), 142.7 (2C), 134.8 (2C), 134.1 (2C), 119.6 (2C), 119.2 (2C), 117.6 (2C), 56.4 (2C), 13.9 (2C).

8,8′-Dihydroxy-3,3′-dimethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2f). Following the general procedure, the homocoupling reaction of **1f** (32.0 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol) and CuI (22.9 mg, 120 μmol) in the presence of Pd(dppf)Cl_2 (17.6 mg, 24 μmol) for 7 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/15 to 1/5) to give **2f** (2.6 mg, 12%) as a yellow solid: mp = 212−213 °C (lit.[12] mp = 212−214 °C); ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 11.8 (s, 2H), 7.73 (t, J = 8.0 Hz, 2H), 7.66 (dd, J = 8.0 Hz, 1.4 Hz, 2H), 7.29 (dd, J = 8.0 Hz, 1.4 Hz, 2H), 2.08 (s, 6H); ^{13}C NMR (CDCl3, 67.8 MHz) δ = 187.4 (2C), 183.3 (2C), 161.4 (2C), 147.4 (2C), 139.5 (2C), 136.5 (2C), 131.8 (2C), 124.4 (2C), 119.5 (2C), 114.6 (2C), 14.6 (2C).

2-Methyl-3-(trimethylstannyl)-1,4-naphthoquinone (4a). Following the general procedure, the reaction of **1a** (50.0 mg, 119 μmol) with hexamethylditin (71.1 mg, 217 μmol) in the presence of Pd(PPh_3)$_2Cl_2$ (14.0 mg, 12 μmol) for 1 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/15) to give **4a** (43.0 mg, 64%) as a yellow solid: mp = 69−70 °C; IR (KBr) ν_{max} = 3070, 2981, 2912, 1657, 1635, 1591, 1284, 1180, 1093, 951, 781, 698, 528 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 8.09−8.04 (m, 1H), 8.04−7.98 (m, 1H), 7.72−7.66 (m, 2H), 2.28 (s, 3H), 0.39 (s, 9H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 188.8, 183.2, 157.5, 156.7, 133.13, 133.09, 132.8, 132.2, 126.4, 126.3, 18.3, −6.03 (3C); HRMS (EI) calcd for $C_{14}H_{16}O_2{}^{120}Sn$ ([M]$^+$) 336.0175, found 336.0178.

Crossover Reaction between 1c and 4a (Scheme 1). Pd(dppf)Cl_2 (8.8 mg, 12.0 μmol) was added to a solution of **1c** (15.9 mg, 60.0 μmol), **4a** (20.1 mg, 60.0 μmol), and CuI (11.4 mg, 59.9 μmol) in degassed dioxane at rt. The mixture was stirred at 80 °C under a N_2 atmosphere for 2.5 h. The reaction was quenched by the addition of water, and the mixture was diluted with EtOAc. The mixture was filtered through Celite. After the layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The crude product was purified using silica-gel column chromatography (EtOAc/hexane = 1/10) to give an inseparable mixture of **2g** and **2a** (16.2 mg), and recovered **1c** (5.3 mg, 33%). Yields of **2g** and **2a** were estimated by ^{1}H NMR using 2,5-dimethylfuran as an internal standard.

3,3′,7-Trimethyl[2,2′-binaphthalene]-1,1′,4,4′-tetrone (2g): mp = 224−226 °C; IR (KBr) ν_{max} = 3062, 3057, 2925, 1662, 1597, 1375, 1329, 1286, 958 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ = 8.20−8.15 (m, 1H), 8.12−8.09 (m, 1H), 8.06 (d, J = 7.6 Hz, 1H), 7.88 (brs, 1H), 7.80−7.72 (m, 2H), 7.56 (brd, J = 7.6 Hz, 1H), 2.50 (s, 3H), 2.08−2.03 (m, 6H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 184.3, 184.1, 182.7, 182.4, 145.6, 144.9, 140.5, 140.2, 134.5, 133.8 (2C), 133.7, 132.0, 131.8, 131.7, 129.8, 126.9, 126.7, 126.6, 126.5, 22.0, 14.4 (2C); HRMS (ESI) calcd for $C_{23}H_{16}O_4Na$ ([M + Na]$^+$) 379.0940, found 379.0958.

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General Procedure for the Formation of Oxepine Dimers 5. (±)-BINAP (0.1 equiv) was added to a solution of **1** (1.0 equiv), hexamethylditin (1.1 equiv), CuI (1.0 equiv), and Na_2CO_3 (1.0 equiv) in degassed DMF, followed by addition of $Pd_2(dba)_3$ (0.05 equiv), at rt. The mixture was stirred at rt under a N_2 atmosphere until no further TLC changes were observed. The reaction was quenched by the addition of water, and the mixture was diluted with EtOAc. The mixture was filtered through Celite. After the layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (EtOAc/hexane).

6-Bromo-5-hydroxy-7,8-dihydrodinaphth[1,2-*b*:2′,3′-*f*]-oxepine-9,14-dione (5a). Following the general procedure, the reaction of **1a** (30.1 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol), CuI (22.9 mg, 120 μmol), and Na_2CO_3 (12.7 mg, 120 μmol) in the presence of $Pd_2(dba)_3$ (5.5 mg, 6.00 μmol) and (±)-BINAP for 1 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/10) to give **5a** (24.3 mg, 96%) as an orange solid: mp = 166−168 °C; IR (KBr) ν_{max} = 3500, 3450, 3240, 3064, 2987, 2923, 1662, 1619, 1585, 1390, 1292, 1257, 1196, 1153, 958, 904, 769 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.61 (brd, J = 8.2 Hz, 1H), 8.21−8.16 (m, 2H), 8.08−8.04 (m, 1H), 7.75−7.70 (m, 2H), 7.65−7.59 (m, 1H), 7.54−7.45 (m, 1H), 6.04 (s, 1H), 3.54 (m, 2H), 3.00 (m, 2H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 185.1, 179.8, 155.2, 146.1, 145.5, 133.8, 133.4, 131.6, 130.6, 130.0, 128.4, 127.7, 126.8, 126.34, 126.29, 126.2, 122.6, 122.04, 122.01, 104.6, 28.2, 25.7; HRMS (ESI) calcd for $C_{22}H_{13}{}^{79}BrO_4Na$ ([M + Na]$^+$) 442.9889, found 442.9868.

6-Bromo-5-hydroxy-2,11-dimethyl-7,8-dihydrodinaphth-[1,2-*b*:2′,3′-*f*]oxepine-9,14-dione (5b). Following the general procedure, the reaction of **1b** (95.4 mg, 360 μmol) using hexamethylditin (130 mg, 396 μmol), CuI (68.6 mg, 360 μmol), and Na_2CO_3 (38.2 mg, 360 μmol) in the presence of $Pd_2(dba)_3$ (16.5 mg, 18.0 μmol) and (±)-BINAP for 4 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/10) to give **5b** (41.3 mg, 51%) as a yellow solid: mp = 208−210 °C dec; IR (KBr) ν_{max} = 3506, 3199, 3057, 3026, 2981, 2933, 2920, 2891, 2860, 1668, 1649, 1620, 1601, 1419, 1300, 1282, 1259, 1207, 1084, 968, 933, 879, 809, 737 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.35 (brs, 1H), 8.07 (d, J = 8.1 Hz, 1H), 8.05 (d, J = 8.1 Hz, 1H), 7.83 (brs, 1H), 7.51 (brd, J = 8.1 Hz, 1H), 7.33 (brd, J = 8.1 Hz, 1H), 5.98 (s, 1H), 3.50 (m, 2H), 2.96 (m, 2H), 2.57 (s, 3H), 2.48 (s, 3H); ^{13}C NMR (DMSO, 67.8 MHz) δ = 184.5, 179.1, 154.4, 147.3, 144.8, 144.0, 136.5, 134.1, 131.0, 129.4, 129.4, 128.0, 127.9, 126.3, 126.0, 125.8, 122.3, 122.0, 120.5, 105.0, 27.7, 25.3, 21.8, 21.4; HRMS (EI) calcd for $C_{24}H_{17}{}^{81}BrO_4$ ([M]$^+$) 450.0293, found 450.0290.

6-Bromo-5-hydroxy-3,12-dimethyl-7,8-dihydrodinaphth-[1,2-*b*:2′,3′-*f*]oxepine-9,14-dione (5c). Following the general procedure, the reaction of **1c** (31.8 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol), CuI (22.9 mg, 120 μmol), and Na_2CO_3 (12.7 mg, 120 μmol) in the presence of $Pd_2(dba)_3$ (5.5 mg, 6.00 mmol) and (±)-BINAP for 2 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/10) to give **5c** (12.6 mg, 47%) as a yellow solid: mp = 213−215 °C dec; IR (KBr) ν_{max} = 3452, 3199, 3062, 2921, 1674, 1655, 1595, 1295, 1205, 1163, 1026, 910, 842, 781, 717 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.47 (d, J = 8.4 Hz, 1H), 7.96−7.90 (m, 3H), 7.48 (ddd, J = 7.8 Hz, 1.8 Hz, 0.8 Hz, 1H), 7.42 (dd, J = 8.6 Hz, 1.8 Hz, 1H), 5.97 (1H, s), 3.52−3.45 (m, 2H), 2.99−2.92 (m, 2H), 2.52 (s, 3H), 2.49 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 185.1, 180.3, 155.2, 145.7, 145.6, 144.5, 136.3, 134.6, 130.5, 130.0, 129.9, 129.4, 127.4, 126.7, 126.4, 125.1, 122.8, 122.0, 121.0, 104.7, 28.1, 25.9, 21.94, 21.88; HRMS (EI) calcd for $C_{24}H_{17}{}^{81}BrO_4$ ([M]$^+$) 450.0293, found 450.0290.

4,13-Diacetyloxy-6-bromo-5-hydroxy-7,8-dihydrodinaphth-[1,2-*b*:2′,3′-*f*]oxepine-9,14-dione (5d). Following the general procedure, the reaction of **1d** (37.1 mg, 120 μmol) using hexamethylditin (43.2 mg, 132 μmol), CuI (22.9 mg, 120 μmol), and Na_2CO_3 (12.7 mg, 120 μmol) in the presence of $Pd_2(dba)_3$ (5.5 mg, 6.00 μmol) and (±)-BINAP for 2 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/2 to 1/1) to give **5d** (8.4 mg, 26%) as an orange solid: mp = 137−138 °C dec; IR (KBr) ν_{max} = 2929, 1766, 1674, 1657, 1624, 1595, 1371, 1201, 1066, 951, 893, 760 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.54 (dd, J = 8.4 Hz, 1.1 Hz, 1H), 8.03 (dd, J = 8.1 Hz, 1.4 Hz, 1H), 7.72 (dd, J = 8.1 Hz, 8.1 Hz, 1H), 7.57 (dd, J = 8.4 Hz, 7.6 Hz, 1H), 7.36 (dd, J = 8.1, 1.4 Hz, 1H), 7.16 (dd, J = 8.1 Hz, 1.1 Hz, 1H), 6.65 (s, 1H), 3.51 (m, 2H), 2.95 (m, 2H), 2.56 (s, 3H), 2.40 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 184.3, 178.0, 169.5, 169.2, 155.1, 149.6, 145.42, 145.36, 145.2, 134.9, 133.3, 129.8, 129.3, 129.0, 128.9, 127.5, 124.8, 122.1, 120.8, 120.3, 116.3, 107.3, 28.4, 25.6, 21.3 (2C); HRMS (EI) calcd for $C_{26}H_{17}{}^{81}BrO_8$ ([M]$^+$) 538.0091, found 538.0084.

Trapping Experiments with Acetic Anhydride in Oxepine Formation (Scheme 2). (±)-BINAP (7.5 mg, 12.0 μmol) was added to a solution of **1a** (30.1 mg, 120 μmol), hexamethylditin (43.2 mg, 132 μmol), 22.9 mg, 120 μmol), and Na_2CO_3 (12.7 mg, 120 μmol) in degassed DMF, followed by addition of $Pd_2(dba)_3$ (5.5 mg, 6.00 μmol), at rt. The mixture was stirred at rt under a N_2 atmosphere for 0.5 h. Then Ac_2O (113 μL, 1.20 mmol) was added to the reaction mixture. After being stirred for an additional 2 h, the reaction was quenched by the addition of water, and the mixture was diluted with EtOAc. The mixture was filtered through Celite. After the layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (EtOAc/hexane =1/10) to give **6** (2.7 mg, 10%) as a yellow solid and **7** (4.4 mg, 11%) as a white solid.

5-Acetyloxy-6-bromo-7,8-dihydrodinaphth[1,2-*b*:2′,3′-*f*]-oxepine-9,14-dione (6): mp = 242−244 °C; IR (KBr) ν_{max} = 3068, 2983, 2931, 1772, 1672, 1660, 1622, 1591, 1362, 1294, 1259, 1190, 1072, 958, 903, 766, 719 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.73 (brd, J = 7.3 Hz, 1H), 8.24−8.23 (m, 1H), 8.22−8.21 (m, 1H), 7.75−7.74 (m, 1H), 7.73−7.72 (m, 1H), 7.71−7.70 (m, 1H), 3.61 (m, 2H), 3.02 (m, 2H), 2.52 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 185.0, 179.8, 168.1, 154.8, 150.0, 142.1, 134.0, 133.5, 131.6, 130.64, 130.61, 129.3, 127.7, 127.6, 126.9, 126.6, 126.4, 126.3, 122.8, 120.9, 114.7, 28.1, 25.5, 20.8; HRMS (FAB$^+$) calcd for $C_{24}H_{16}{}^{79}BrO_5$ ([M + H]$^+$) 465.0183, found 463.0176.

1,4-Diacetyloxy-2-bromo-3-methylnaphthalene (7): mp = 214−216 °C; IR (KBr) ν_{max} = 3074, 2979, 2931, 1757, 1593, 1429, 1360, 1207, 1163, 1074, 1012, 962, 900, 760 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 7.76−7.73 (m, 2H), 7.51−7.49 (m, 2H), 2.49 (s, 3H), 2.47 (s, 3H), 2.40 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 168.4, 168.0, 142.6, 142.3, 127.3, 127.2, 126.9, 126.5, 126.4, 121.4, 121.3, 117.0, 20.8, 20.6, 17.4; HRMS (EI) calcd for $C_{15}H_{13}{}^{81}BrO_4$ ([M]$^+$) 337.9978, found 337.9978.

Crossover Reaction Study of Oxepine Formation (Scheme 3). (±)-BINAP (7.5 mg, 12.0 μmol) was added to a solution of **4a** (20.1 mg, 60.0 μmol), **1c** (15.9 mg, 60.0 μmol), hexamethylditin (27 μL, 130 μmol), CuI (22.8 mg, 120 μmol), and Na_2CO_3 (12.7 mg, 120 μmol) in degassed DMF (2 mL), followed by addition of $Pd_2(dba)_3$ (5.5 mg, 6.00 μmol), at rt. The mixture was stirred under a N_2 atmosphere for 1.5 h. The reaction was quenched by the addition of water, and the mixture was diluted with EtOAc. The mixture was filtered through Celite. After the layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (EtOAc/hexane = 1/10 to 1/4) to give **3a** (2.1 mg, 19%) and **5c** (7.4 mg, 55%).

Reaction of 1a with *t*-BuOK (Scheme 4A). To a solution of **1a** (50.0 mg, 199 μmol) and in DMF was added *t*-BuOK (37.0 mg, 330 μmol) at −78 °C. The mixture was stirred at the same temperature for 15 min under N_2 atmosphere. The reaction was quenched by the addition of 1 M HCl aqueous solution, and the mixture was diluted with EtOAc. After the aqueous layer was extracted with EtOAc (×2), the combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was

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purified by column chromatography (EtOAc/hexane = 1/5) to give **3a** (12.3 mg, 29%).

Photoreaction of 1a with Hexamethylditin (Scheme 4B). A solution of **1a** (50.2 mg, 200 μmol) and hexamethylditin (131 mg, 400 μmol) in DMF (3 mL) was irradiated with a white fluorescent lamp for 28 h. The mixture was diluted with EtOAc. The organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (EtOAc/hexane = 1/5) to give **5a** (16.3 mg, 39%).

Photoreaction of 1a with Hexamethylditin in the Presence of Acetic Anhydride (Scheme 4C). A solution of **1a** (50.3 mg, 200 μmol), hexamethylditin (133 mg, 405 μmol), and Ac_2O (94 μL, 994 μmol) in DMF (3 mL) was irradiated with a white fluorescent lamp for 29 h. The mixture was diluted with EtOAc. The organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (EtOAc/hexane = 1/5) to give **7** (32.1 mg, 48%).

General Procedure for the Formation of Epoxide Dimers 8 (Tables 6 and 7). Base (1.5 equiv) was added to a solution of **1** (1.0 equiv) in DMF at 0 °C. The mixture was stirred at rt under N_2 atmosphere until no further change in TLC was observed. The reaction was quenched by the addition of water, and the mixture was diluted with EtOAc. The mixture was filtered through Celite. The layers were separated, the aqueous layer was extracted with EtOAc (×2). The combined organic layer was washed with water (×2) and brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (EtOAc/hexane).

(7a*R,13a*R**,13b*S**)-6-Bromo-13a,13b-epoxy-7a-methyl-7*H*-dibenzo[*b*,*g*]fluorene-5,8,13-trione (8a).** Following the general procedure, the reaction of **1a** (50.0 mg, 199 μmol) with Cs_2CO_3 (98.0 mg, 301 μmol) for 0.5 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/5) to give **8a** (35.7 mg, 85%) as a yellow solid: mp = 182−184 °C; IR (KBr) ν_{max} = 3064, 2968, 2915, 2854, 1707, 1664, 1267, 1257, 1196, 1093, 991, 850, 769, 739, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.34−8.28 (m, 1H), 8.26−8.16 (m, 2H), 7.95−7.83 (m, 2H), 7.72−7.57 (m, 3H), 3.32 (d, *J* = 16.7 Hz, 1H), 2.30 (d, *J* = 16.7 Hz, 1H), 1.42 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 196.3, 187.9, 176.5, 155.4, 135.8, 135.6, 134.5, 133.8, 132.5, 132.4, 131.5, 129.9, 128.3, 128.2, 127.6, 127.1, 126.2, 78.3, 68.1, 55.8, 36.6, 21.9; HRMS (ESI) calcd for $C_{22}H_{13}{}^{81}BrO_4Na$ ([M + Na]$^+$) 444.9868, found 444.9871.

(7a*R,13a*R**,13b*S**)-6-Bromo-13a,13b-epoxy-2,7a,10-trimethyl-7*H*-dibenzo[*b*,*g*]fluorene-5,8,13-trione (8b).** Following the general procedure, the reaction of **1b** (53.0 mg, 200 μmol) with Cs_2CO_3 (97.7 mg, 300 μmol) for 1 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/5) to give **8b** (32.0 mg, 71%) as a yellow solid: mp = 215 °C dec; IR (KBr) ν_{max} = 2968, 2925, 1704, 1664, 1601, 1282, 1261, 1147, 1026, 899, 829, 769, 750 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.19 (d, *J* = 8.1 Hz, 1H), 8.10 (d, *J* = 8.1 Hz, 1H), 8.01 (s, 1H), 7.66 (d, *J* = 8.1 Hz, 1H), 7.44 (s, 1H), 7.40 (d, *J* = 8.1 Hz, 1H), 3.29 (d, *J* = 16.7 Hz, 1H), 2.94 (d, *J* = 16.7 Hz, 1H), 2.57 (s, 3H), 2.49 (s, 3H), 1.39 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 196.8, 187.6, 176.5, 155.2, 147.2, 143.6, 135.2, 133.7, 131.5, 130.9, 130.2, 128.6, 128.2, 128.0, 127.3, 126.2, 78.4, 68.1, 55.8, 36.6, 22.12, 22.06, 22.0; HRMS (ESI) calcd for $C_{24}H_{17}{}^{81}BrO_4Na$ ([M + Na]$^+$) 473.0181, found 473.0188.

(7a*R,13a*R**,13b*S**)-6-Bromo-13a,13b-epoxy-3,7a,11-trimethyl-7*H*-dibenzo[*b*,*g*]fluorene-5,8,13-trione (8c).** Following the general procedure, the reaction of **1c** (53.0 mg, 200 μmol) with Cs_2CO_3 (98.0 mg, 301 μmol) for 1 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane = 1/5) to give **8c** (30.7 mg, 68%) as a yellow solid: mp = 218−219 °C dec; IR (KBr) ν_{max} = 2972, 2924, 2854, 1707, 1666, 1599, 1267, 1163, 991, 904, 829, 746 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.12 (d, *J* = 7.8 Hz, 1H), 8.10 (s, 1H), 7.97 (s, 1H), 7.69 (d, *J* = 7.8 Hz, 1H), 7.51 (d, *J* = 8.1 Hz, 1H), 7.47 (d, *J* = 8.1 Hz, 1H), 3.29 (d, *J* = 16.7 Hz, 1H), 2.94 (d, *J* = 16.7 Hz, 1H), 2.56 (s, 3H), 2.48 (s, 3H), 1.39 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 196.3, 188.4, 176.8, 155.6, 145.9, 140.3, 136.3, 135.9, 133.5, 132.3, 131.5, 128.7, 128.5, 128.4, 127.6, 127.3, 126.2, 78.5, 68.2, 55.7, 36.7, 22.0, 21.9, 21.5; HRMS (ESI) calcd for $C_{24}H_{17}{}^{79}BrO_4Na$ ([M + Na]$^+$) 471.0202, found 471.0204.

(7a*R,13a*R**,13b*S**)-4,12-Diacetyloxy-6-bromo-13a,13b-epoxy-7a-methyl-7*H*-dibenzo[*b*,*g*]fluorene-5,8,13-trione (8d).** Following the general procedure, the reaction of **1d** (61.8 mg, 200 μmol) with Cs_2CO_3 (97.7 mg, 300 μmol) for 1 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane =1/2 to 1/1) to give **8d** (13.0 mg, 24%) as a yellow solid: mp = 152−153 °C; IR (KBr) ν_{max} = 3072, 3016, 2964, 2929, 2854, 1766, 1710, 1672, 1194, 1026, 928, 879, 835 746 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 8.18 (d, *J* = 7.8 Hz, 1H), 7.89 (t, *J* = 8.1 Hz, 1H), 7.64 (t, *J* = 7.8 Hz, 1H), 7.48 (d, *J* = 8.1 Hz, 1 H), 7.36 (d, *J* = 8.1 Hz, 1 H), 7.22 (d, *J* = 7.8 Hz, 1 H), 3.28 (d, *J* = 16.7 Hz, 1 H), 2.91 (d, *J* = 16.7 Hz, 1 H), 2.48 (s, 3 H), 2.41 (s, 3 H), 1.42 (s, 3H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ = 195.3, 185.5, 174.9, 169.7, 169.1, 153.8, 150.7, 149.6, 136.2, 135.3, 133.7, 133.3, 129.9, 127.9, 126.9, 126.6, 125.7, 125.5, 124.3, 79.2, 67.5, 55.8, 36.8, 21.29, 21.27, 21.1; HRMS (ESI) calcd for $C_{26}H_{17}{}^{81}BrO_8Na$ ([M + Na]$^+$) 560.9978, found 560.9986.

(7a*R,13a*R**,13b*S**)-6-Bromo-13a,13b-epoxy-4,12-dimethoxy-7a-methyl-7*H*-dibenzo[*b*,*g*]fluorene-5,8,13-trione (8e).** Following the general procedure, the reaction of **1e** (28.1 mg, 100 μmol) with Cs_2CO_3 (48.9 mg, 150 μmol) for 4 h gave the crude product. The crude product was purified by silica gel column chromatography (EtOAc/hexane =1/2 to 1/1) to give **8e** (5.5 mg, 23%) as a yellow solid: mp = 163−164 °C dec; IR (KBr) ν_{max} = 3087, 3012, 2972, 2941, 2842, 1701, 1662, 1581, 1432, 1392, 1277, 1277, 1213, 1186, 1049, 999, 811, 775 754 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ = 7.85 (dd, *J* = 7.8 Hz, 1.4 Hz, 1H), 7.79 (dd, *J* = 7.8 Hz, 7.8 Hz, 1H), 7.59 (dd, *J* = 7.8 Hz, 7.8 Hz, 1H), 7.37 (dd, *J* = 7.8 Hz, 1.4 Hz, 1H), 7.11 (d, *J* = 7.8 Hz, 1H), 7.06 (d, *J* = 7.8 Hz, 1H), 4.05 (s, 3H), 3.99 (s, 3H), 3.24 (d, *J* = 16.9 Hz, 1H), 2.88 (d, *J* = 16.9 Hz, 1H), 1.41 (s, 3H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ= 196.6, 185.8, 175.5, 161.0, 159.8, 152.1, 136.1, 135.9, 134.2, 133.7, 127.7, 124.7, 121.4, 120.6, 119.8, 118.1, 113.5, 80.2, 68.0, 56.6, 56.4, 55.7, 36.7, 21.1; HRMS (ESI) calcd for $C_{24}H_{17}{}^{81}BrO_6Na$ ([M + Na]$^+$) 505.0080, found 505.0074.

■ ASSOCIATED CONTENT

Supporting Information

^1H and ^{13}C NMR spectra for all new compounds, ORTEP drawings and X-ray crystallographic data for **5a** and **8a** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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