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Note

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Chiral Dinuclear Vanadium Complex-mediated Oxidative Coupling of Resorcinols

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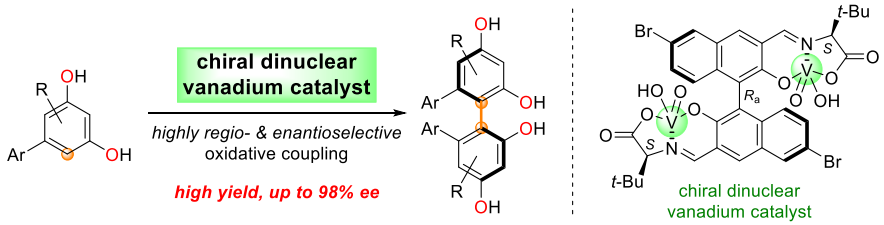
ABSTRACT: A method for the highly regio- and enantioselective oxidative coupling of resorcinols has been established by using dibrominated dinuclear vanadium(V) catalyst **1c** under air. When resorcinols bearing an aryl substituent were applied as substrates to the coupling, axially chiral biresorcinols were obtained as single regioisomers in high yield with up to 98% ee.



Optically pure 1,1'-bi-2-phenol derivatives are an important class of chiral compounds in asymmetric synthesis because these compounds serve as chiral ligands for various transition metals, organocatalysts, and bioactive compounds (Figure 1).[1,2] To date, various synthetic approaches of optically active 1,1'-bi-2-phenol derivatives such as (A) kinetic resolution of racemic compounds or atropselective transformation of prochiral compounds, (B) a chirality transfer such as from central chirality to axial chirality, and (C and D) an enantioselective coupling of phenol derivatives have been developed by numerous chemists (Scheme 1).[1] Among the protocols for the catalytic synthesis of biphenol derivatives, oxidative coupling of phenol derivatives is one of the most straightforward and sustainable protocols as it requires no pre-activation for the coupling partners. However, the number of methods for the enantioselective synthesis of axially chiral biphenols is still limited due to high oxidation potentials requiring strong oxidants and harsh condition, especially when compared to that for the catalytic asymmetric synthesis of 1,1'-bi-2-naphthol (BINOL) using chiral metal catalysts [mononuclear metal catalysts: Smrćina and Kočovský (Cu 1993),[3a] Nakajima (Cu 1999),[3b] Katsuki (Ru 2000, Fe 2009),[3c,d] Kozlowski (Cu 2001),[3e] Uang (V 2001),[3f] Chen (V 2001),[3g] Iwasawa (V 2004),[3h] Habaue (V, Cu 2005),[3i,j] and Pappo (Fe 2016).[3k] dinuclear metal complex: Gong (V 2002),[3l] Gao (Cu 2003),[3m] Sasai and Takizawa (V 2004)[3n]]. Accordingly, significant research efforts have been dedicated to the development of protocols for the oxidative coupling of phenol derivatives[4] using peroxide initiators,[5] hypervalent iodines,[6] and electrochemical methods.[7]

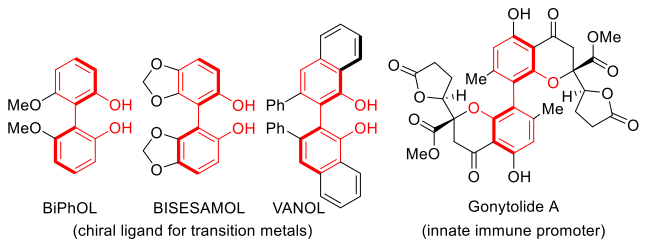
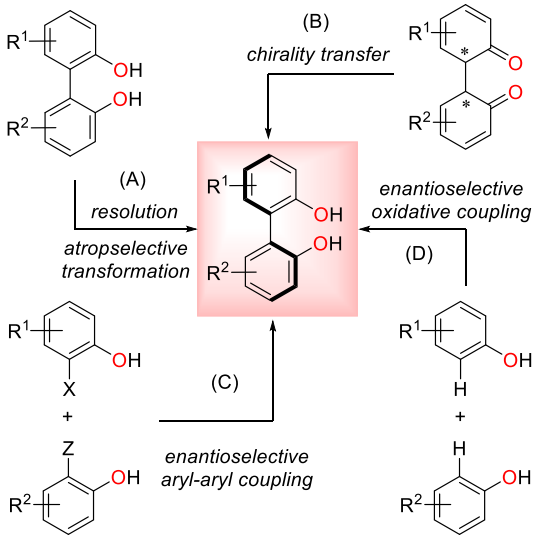


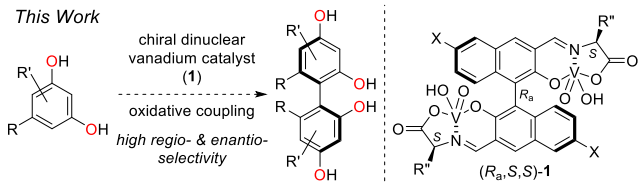
Figure 1. Chiral 1,1'-bi-2-phenol derivatives.

Resorcinol (benzene-1,3-diol) is an important raw material for the synthesis of pharmaceuticals and other organic products. Dimeric resorcinols, i.e., biresorcinols, are also an attractive species because of their high potential as bioactive compounds, chiral reagents, and functional materials.[8] Recently, Kozlowski *et al*. demonstrated the first enantioselective oxidative coupling of these derivatives using 20 to 40 mol% of a chiral mononuclear vanadium complex.[9] However, the regio- and enantioselective oxidative coupling



Scheme 1. Representative strategies for optically active 1,1'-bi-2-phenol derivatives.

of phenols remains challenging owing to their inherently high number of reactive sites leading to regioisomers. Herein, we report the highly regio- and enantioselective oxidative coupling of resorcinols to provide biresorcinols using a chiral dinuclear vanadium catalyst (Scheme 2). When resorcinols bearing an aryl substituent were applied as substrates to the coupling, axially chiral biresorcinols were obtained as single regioisomers in high yield, up to 98% ee.

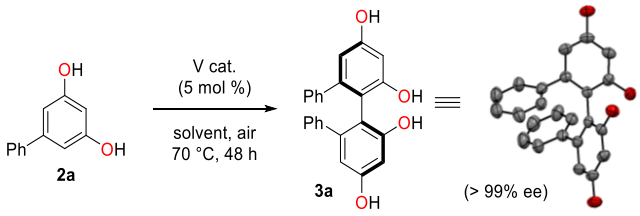


Scheme 2. Enantioselective oxidative coupling of resorcinol derivatives catalyzed by chiral dinuclear vanadium complexes.

We have previously developed chiral dinuclear vanadium complex-mediated enantioselective coupling reactions of 2-naphthol derivatives to produce BINOLs with high enantioselectivities. In that system, the two vanadium atoms in the complex simultaneously activate two molecules of 2-naphthols, resulting in a high reaction rate and high enantioselectivity.[3n,10] In the present study, we initially screened reaction conditions using the resorcinol derivative **2a** as a model substrate (Table 1). Due to low solubility of resorcinols in organic solvent, all reactions led to heterogeneous catalysis. Among the solvents tested (entries 1-6), toluene (PhMe) gave the best results (**3a** in 64% NMR yield with 86% ee) (entry 6). When the diastereomeric complex (*S*a,*S*,*S*)-**1a** was used as a catalyst, both the chemical yield and ee of **3a** decreased (entry 7). The dinuclear vanadium catalyst (*S*,*S*)-**4** possessing a biphenyl skeleton did not improve the outcomes (entry 8). On the basis of these results, it appears that when the axial chirality of the binaphthyl skeleton and the central chirality of amino acid moieties in an (*R*a,*S*,*S*)-configured complex are matched, the coupling reaction is significantly accelerated. Catalyst (*R*a,*S*,*S*)-**1b** bearing an *i*-Pr group instead of a *t*-Bu group on the amino acid moiety led to a lower yield and enantioselectivity (entry 9). Finally, the bromo-substituted catalyst (*R*a,*S*,*S*)-**1c** significantly promoted the reaction to afford the desired product **3a** in 80% isolated yield with 97% ee (entry 10).[11] Under O_2 atmosphere, oligomeric side-products were formed owing to over-oxidative coupling between **3a** and **2a**, resulting in a lower chemical yield of **3a** (entry 11). The reaction at 50 °C decreased the reaction rate (entry 12), while higher reaction temperature also resulted in lower product yield in analogy to the reaction under O_2 (entry 13). Optically pure **3a** is readily obtained by a single recrystallization of the enantiomerically enriched product from EtOAc and hexane (entry 10). The absolute configuration of **3a** provided by (*R*a,*S*,*S*)-**1c** was determined to be the *S* form on the basis of the Flack parameter obtained *via* X-ray crystallographic analysis.

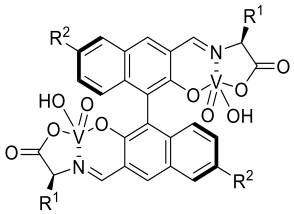
Subsequently, substrate scope and limitations were explored under optimal conditions (Scheme 3). Resorcinol derivatives **2b**–**l** bearing an electron-donating or electron-withdrawing substituent at the *ortho*-, *meta*-, or *para*-position of the aryl group were converted to the corresponding products **3b**–**j** in good yields with high enantioselectivities, excluding **3k** and **3l**. Although the reaction of **2m** possessing a 2-naphthyl group proceeded smoothly to give **3m** in 78% yield with 85% ee, only a trace amount of 1-naphthyl-substituted **3n** was afforded together with the unreacted starting material. Thus, the coupling reaction was suppressed by a bulky substituent close to the coupling position. Methyl-substituted **3o** and **3p** were obtained in 93% yield with 88% ee and 77% yield with 36% ee, respectively. Bromo-substituted **2q** also undergoes the coupling reaction to afford **3q** in 49% yield with 70% ee. This type of reaction also proceeded smoothly on a 1.0 mmol scale as demonstrated for

Table 1. Screening of reaction conditions.[a]

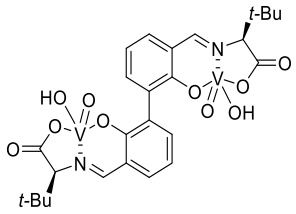


entry	catalyst	Solvent	yield (%)[b]	ee (%)[c]
1	(*R*a,*S*,*S*)-**1a**	$(ClCH_2)_2$	41	65
2	(*R*a,*S*,*S*)-**1a**	$(Cl_2CH)_2$	16	44
3	(*R*a,*S*,*S*)-**1a**	CCl_4	10	97
4	(*R*a,*S*,*S*)-**1a**	*o*-$Cl_2C_6H_4$	25	58
5	(*R*a,*S*,*S*)-**1a**	*o*-$Me_2C_6H_4$	41	73
6	(*R*a,*S*,*S*)-**1a**	PhMe	64	86
7	(*S*a,*S*,*S*)-**1a**	PhMe	15	–27
8	(*S*,*S*)-**4**	PhMe	33	28
9	(*R*a,*S*,*S*)-**1b**	PhMe	19	6
10	(*R*a,*S*,*S*)-**1c**	PhMe	87 (80)[d]	97 (99)[e]
11[f]	(*R*a,*S*,*S*)-**1c**	PhMe	70	90
12[g]	(*R*a,*S*,*S*)-**1c**	PhMe	72	92
13[h]	(*R*a,*S*,*S*)-**1c**	PhMe	80	98

[a]The reaction of **2a** (0.1 mmol) with 5 mol% of vanadium complex (0.005 mmol) was conducted in the solvent (0.5 mL) at 70 °C under air (1 atm). [b]Yields were determined *via* ^{1}H NMR spectroscopy using 1,3,5-trimethoxybenzene as an internal standard. [c]Ee values were determined using HPLC (DAICEL CHIRALPAK IA). [d]Isolated yield. [e]After a single recrystallization from EtOAc and hexane. [f]Under O_2 (1 atm). [g]At 50 °C. [h]At 80 °C.



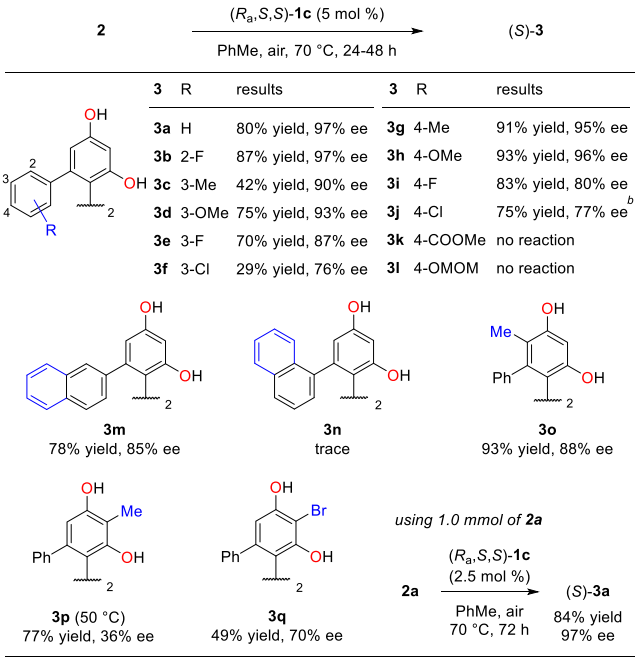
(*R*a,*S*,*S*)-**1a** (R^1 = *t*-Bu, R^2 = H)
(*R*a,*S*,*S*)-**1b** (R^1 = *i*-Pr, R^2 = H)
(*R*a,*S*,*S*)-**1c** (R^1 = *t*-Bu, R^2 = Br)



(*S*,*S*)-**4**

the conversion of **2a** with 2.5 mol% of (*R*a,*S*,*S*)-**1c**, leading to comparable results (Scheme 3, 84% yield, 97% ee).

Accordingly, we conducted several control experiments to get insight into the reaction mechanism (Scheme 4). When a half motif of dinuclear vanadium complex (*S*)-**5** (10 mol%) was used in the coupling of **2a**, 70% conversion of **2a** was achieved with (*R*)-**3a** being afforded in 15% yield with 15% ee (Scheme 4A). Thus, the dinuclear vanadium structure (5 mol%) is important for an effective activation of **2a** and stereocontrol coupling to afford the product **3a** in high yield (87%) with high enantioselectivity (97%). The use of Me-protected **2r**, possessing just one hydroxy group, or the 1,2-dihydroxy derivative **2s** as the starting material gave a complex mixture (Scheme 4B). Thus, the hydroxy groups on 1,3-position of

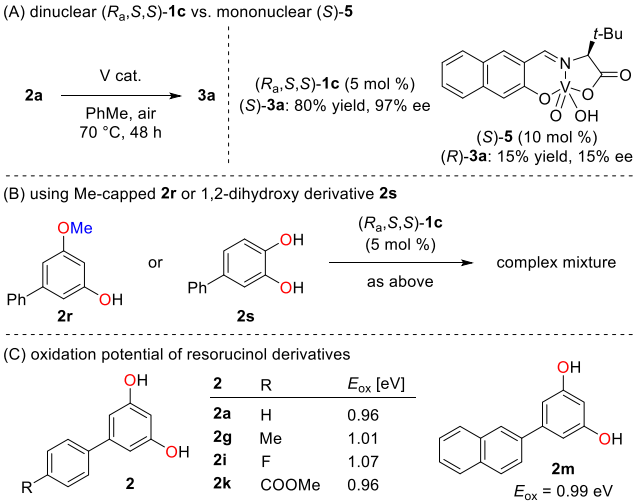


[a]The reaction of **2** (0.1 mmol) with 5 mol % of catalyst (*R*a,*S*,*S*)-**1c** (0.005 mmol) was carried out in PhMe (0.5 mL) at 70 °C under air (1 atm) for 24-48 h. Yield of isolated product. Ee values were determined by HPLC. [b]In PhMe/CCl_4 (2/3).

Scheme 3. Substrate scope and limitations.[a]

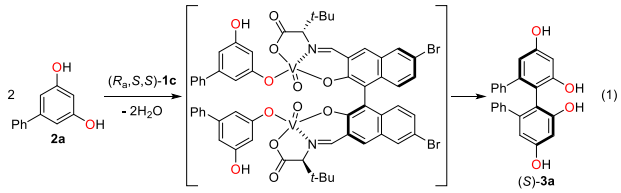
the arene are essential and participate in the dinuclear vanadium activation. Since the present reaction system is heterogeneous in toluene, further mechanistic studies such as kinetic studies to determine the order dependence on the vanadium catalyst could not be performed. To verify whether there is a relation between the reactivity and the oxidation potential of starting materials, cyclic voltammetry analysis was performed (Scheme 4C). Although coupling precursor **2k** (0.99 eV) showed similar oxidation potential value such as **2a** (0.96 eV), **2g** (1.01 eV), **2i** (1.07 eV) and **2m** (0.99 eV), no reaction proceeded and **2k** was recovered quantitatively. Thus, it is difficult to estimate and rationalize the reactivity based on oxidation potential.

Despite the reaction mechanism for the catalytic cycle remaining unclear, the key step for the highly regio- and enantioselective coupling is clearly the C–C bond-forming process. Since our chiral dinuclear vanadium complex distinctively prompted the oxidative



Scheme 4. Additional experiments related to the clarification of the reaction mechanism.

coupling of resorcinol derivatives with high enantiocontrol, the coupling event would proceed through a known dual-activation mechanism[3n,10] involving a 1:2 complex of (*R*a,*S*,*S*)-**1c** and **2a** (eq. 1). As the newly developed bromo-substituted dinuclear vanadium catalyst (*R*a,*S*,*S*)-**1c** proved to be effective for the oxidative coupling of resorcinol derivatives, other phenol derivatives were also investigated. When monohydroxyphenol derivatives 3,5-dimethylphenol and 2,3,5-trimethylphenol, which were coupling precursors reported by Kozlowski et al.,[9b] were employed under our standard conditions, the corresponding coupling products are obtained in very poor yields.



In conclusion, we have developed a protocol for highly regio- and enantioselective oxidative coupling of resorcinol derivatives to produce axially chiral biphenols. Our catalytic system provided complementary results to Kozlowski's report.[9b] The newly developed chiral dinuclear dibromo-vanadium complex exhibited high catalytic activity resulting from its double activation of resorcinol derivatives. Additional investigation of the reaction mechanism from both experimental and theoretical perspectives is now in progress.

EXPERIMENTAL SECTION

1. General Methods. ^{1}H-, ^{13}C-, and ^{19}F-NMR spectra were recorded with JEOL JMN ECS400 FT NMR, JNM ECA600 FT NMR or Bruker AVANCE II (1H-NMR 400, 600 or 700 MHz, ^{13}C-NMR 100, 150 or 175 MHz, ^{19}F-NMR 565 MHz. ^{1}H-NMR spectra are reported as follows: chemical shift in ppm relative to the chemical shift of tetramethylsilane (TMS) at 0 ppm, integration, multiplicities (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet), and coupling constants (Hz). ^{13}C-NMR spectra reported in ppm relative to the central line of triplet for $CDCl_3$ at 77 ppm and of multiplet for CD_3OD at 49 ppm. CF_3CO_2H used as external standards for ^{19}F-NMR. FT-MS spectra were obtained with LTQ Orbitrap XL (Thermo Fisher Scientific). ESI-MS and APCI-MS spectra were recorded on a Thermo Fisher LTQ ORBITRAP XL. Optical rotations were measured with JASCO P-1030 polarimeter. HPLC analyses were performed on a JASCO HPLC system (JASCO PU 980 pump and UV-975 UV/Vis detector) using a mixture of hexane and 2-propanol as eluents. FT-IR spectra were recorded on a JASCO FT-IR system (FT/IR4100). Column chromatography on SiO_2 was performed with Kanto Silica Gel 60 (40-100 μm). Commercially available organic and inorganic compounds were used without further purification. CV was performed in CH_2Cl_2/acetonitrile (10/1) solution containing 0.1 M tetrabutylammonium hexafluorophosphate ($TBAPF_6$) as a supporting electrolyte, on a BAS CV-620C voltammetric analyzer using a platinum disk as the working electrode, platinum wire as the counter electrode, and $Ag/AgNO_3$ as the reference electrode at a scan rate of 100 mV s^{-1}. The measured potentials were calibrated using a ferrocene/ferrocenium (Fc/Fc+) redox couple as an internal standard.

2. Procedure and Experimental Data for Resorcinol derivatives.

Preparation of [1,1'-biphenyl]-3,5-diol (***2a***).[12] A suspension of 1-bromo-3,5-dimethoxybenzene (10.39 g, 47.9 mmol), phenylboronic acid (6.71 g, 55.0 mmol), $Pd(PPh_3)_4$ (1.02 g, 0.880 mmol) and Na_2CO_3 (9.89 g, 93.3 mmol) in THF/water (5/1, 280 mL) was stirred for 12 h under reflux condition. After cooling, the reaction mixture was filtrated through Celite, quenched with sat. NH_4Cl aq.,

and extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by silica column chromatography (hexane/EtOAc = 20/1) to afford 3,5-dimethoxy-1,1'-biphenyl in 50% yield (5.16 g). BBr_3 (1.0 M in CH_2Cl_2, 72 mL, 72 mmol) was added to a solution of 3,5-dimethoxy-1,1'-biphenyl (5.16 g, 24.1 mmol) in CH_2Cl_2 (120 mL) at 0 °C. The mixture was stirred for 12 h at room temperature. After cooling to 0 °C, the reaction was quenched with sat. $NaHCO_3$ aq. The aqueous layer was extracted with CH_2Cl_2. The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by silica column chromatography (hexane/acetone = 2/1) to afford **2a** in 95% yield (4.26 g, white solid). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.29 (s, 2H), 7.53-7.56 (m, 2H), 7.38-7.43 (m, 2H), 7.29-7.34 (m, 1H), 6.61 (d, J = 2.3 Hz, 2H), 6.36 (t, J = 2.3 Hz, 1H).

2b, ***2c***, ***2e***, ***2f***, ***2g***, ***2i***, ***2j***, ***2m***, *and* ***2n*** *were prepared following the procedure for* ***2a***.

*2'-fluoro-[1,1'-biphenyl]-3,5-diol (**2b**).* 155.9 mg, 53% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (600 MHz, Acetone-D6): δ 8.37 (s, 2H), 7.45 (td, J = 7.8, 1.4 Hz, 1H), 7.35-7.38 (m, 1H), 7.24 (td, J = 7.8, 1.4 Hz, 1H), 7.17-7.20 (m, 1H), 6.54 (s, 2H), 6.39 (s, 1H). ^{13}C{^{1}H} NMR (150 MHz, Acetone-D6): δ 160.4 (d, $^1J_{C-F}$ = 246.3 Hz), 159.4, 138.4, 131.4 (d, $^3J_{C-F}$ = 2.9 Hz), 130.0 (d, $^3J_{C-F}$ = 8.6 Hz), 129.9, 125.4 (d, $^4J_{C-F}$ = 3.8 Hz), 116.8 (d, $^2J_{C-F}$ = 23.0 Hz), 108.4, 102.9. ^{19}F{^{1}H} NMR (565 MHz, Acetone-D6): δ -118.6. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{12}H_{10}FO_2$ 205.0659; Found 205.0655. IR (KBr): 3325, 1609, 1510, 1476, 1445, 1162, 1008, 835, 799, 741, 681 cm^{-1}. mp: 98–100 °C.

*3'-methyl-[1,1'-biphenyl]-3,5-diol (**2c**).* 51.9 mg, 28% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.30 (s, 1H), 7.33-7.37 (m, 2H), 7.28 (t, J = 7.3 Hz, 1H), 7.14 (d, J = 7.3 Hz, 1H), 6.59 (d, J = 2.3 Hz, 2H), 6.35 (t, J = 2.3 Hz, 1H), 2.36 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 156.9, 144.1, 140.3, 138.3, 128.6, 128.4, 127.8, 124.1, 107.0, 101.6, 21.5. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{13}H_{13}O_2$ 201.0916; Found 201.0907. IR (KBr): 3380, 1603, 1483, 1256, 1156, 1003, 776, 691 cm^{-1}. mp: 72–74 °C.

*3'-fluoro-[1,1'-biphenyl]-3,5-diol (**2e**).* 162.6 mg, 56% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (600 MHz, Acetone-D6): δ 8.40 (s, 1H), 7.42-7.45 (m, 1H), 7.38 (d, J = 7.6 Hz, 1H), 7.27-7.28 (m, 1H), 7.08 (td, J = 8.2, 2.3 Hz, 1H), 6.60 (d, J = 2.1 Hz, 2H), 6.38 (s, 1H). ^{13}C{^{1}H} NMR (150 MHz, Acetone-D6): δ 164.0 (d, $^1J_{C-F}$ = 243.5 Hz), 159.9, 144.5, 142.6, 131.3 (d, $^3J_{C-F}$ = 8.6 Hz), 123.5, 114.7 (d, $^2J_{C-F}$ = 21.1 Hz), 114.2 (d, $^2J_{C-F}$ = 23.0 Hz), 106.4, 103.1. ^{19}F{^{1}H} NMR (565 MHz, Acetone-D6): δ -114.7. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{12}H_{10}FO_2$ 205.0659; Found 205.0655. IR (KBr): 3232, 1585, 1510, 1475, 1265, 1159, 1007, 797, 679 cm^{-1}. mp: 136–138 °C.

*3'-chloro-[1,1'-biphenyl]-3,5-diol (**2f**).* 216.3 mg, 70% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.39 (s, 2H), 7.55-7.56 (m, 1H), 7.50-7.52 (m, 1H), 7.43 (t, J = 7.8 Hz, 1H), 7.34-7.37 (m, 1H), 6.60 (d, J = 2.3 Hz, 2H), 6.39 (t, J = 2.3 Hz, 1H). ^{13}C{^{1}H} NMR (100 MHz, Acetone-D6): δ 159.9, 144.2, 142.4, 134.9, 131.2, 128.0, 127.4, 126.1, 106.4, 103.2. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{12}H_{10}ClO_2$ 221.0364; Found 221.0360. IR (KBr): 3187, 1604, 1566, 1320, 1211, 1157, 1081, 779, 725 cm^{-1}. mp: 112–114 °C.

*4'-methyl-[1,1'-biphenyl]-3,5-diol (**2g**).*[12] 153.3 mg, 69% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.27 (s, 2H), 7.44 (d, J = 8.2 Hz, 2H), 7.22 (d, J = 8.2 Hz, 2H), 6.58 (d, J = 2.1 Hz, 2H), 6.33 (t, J = 2.1 Hz, 1H), 2.33 (s, 3H).

*4'-fluoro-[1,1'-biphenyl]-3,5-diol (**2i**).*[13] 342.4 mg, 90% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.35 (s, 2H), 7.56-7.61 (m, 2H), 7.14-7.20 (m, 2H), 6.57 (d, J = 2.3 Hz, 2H), 6.36 (t, J = 2.3 Hz, 1H).

*4'-choloro-[1,1'-biphenyl]-3,5-diol (**2j**).*[14] 162.5 mg, 58% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.43 (s, 1H), 7.57 (d, J = 8.7 Hz, 2H), 7.43 (d, J = 8.7 Hz, 2H), 6.59 (d, J = 2.2 Hz, 2H), 6.37 (t, J = 2.2 Hz, 1H).

*5-(naphthalen-2-yl)benzene-1,3-diol (**2m**).* 234.2 mg, 46% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.35 (s, 2H), 8.08 (d, J = 1.8 Hz, 1H), 7.96 (dd, J = 6.9, 2.5 Hz, 1H), 7.95 (d, J = 8.7 Hz, 1H), 7.90 (dd, J = 6.9, 2.5 Hz, 1H), 7.73 (dd, J = 8.7, 1.8 Hz, 1H), 7.47-7.54 (m, 2H), 6.76 (d, J = 2.3 Hz, 2H), 6.41 (t, J = 2.3 Hz, 1H). ^{13}C{^{1}H} NMR (100 MHz, Acetone-D6): δ 159.9, 143.9, 139.4, 134.7, 133.7, 129.1, 129.0, 128.4, 127.1, 126.7, 126.1, 106.7, 102.7. (One carbon is overlapping.) HRMS (ESI) *m/z*: [M + Na]$^+$ Calcd for $C_{16}H_{12}NaO_2$ 259.0730; Found 259.0730. IR (KBr): 3343, 1606, 1475, 1153, 1006, 815, 743, 687 cm^{-1}. mp: 170–172 °C.

*5-(naphthalen-1-yl)benzene-1,3-diol (**2n**).*[15] 352.0 mg, 46% yield (2 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.95 (d, J = 8.2 Hz, 1H), 7.89 (d, J = 8.2 Hz, 1H), 7.85 (d, J = 8.2 Hz, 1H), 7.39-7.52 (m, 4H), 6.54 (d, J = 2.3 Hz, 2H), 6.44 (t, J = 2.3 Hz, 1H), 4.88 (s, 2H).

*Preparation of 3'-methoxy-[1,1'-biphenyl]-3,5-diol (**2d**).* A suspension of 5-bromobenzene-1,3-diol (199.2 mg, 1.05 mmol), (3-methoxyphenyl)boronic acid (185.7 mg, 1.22 mmol), $Pd(PPh_3)_4$ (34.8 mg, 0.030 mmol) and Na_2CO_3 (237.0 mg, 2.24 mmol) in THF/water (5/1, 4.5 mL) was stirred for 12 h under reflux condition. After cooling, the reaction mixture was filtrated through Celite, quenched with sat. NH_4Cl aq., and extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by silica column chromatography (hexane/EtOAc = 3/1) to afford **2d** in 41% yield (93.1 mg, white solid). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33 (t, J = 7.8 Hz, 1H), 7.12 (d, J = 7.8 Hz, 1H), 7.07 (t, J = 2.3 Hz, 1H), 6.90 (dd, J = 7.8, 2.5 Hz, 1H), 6.64 (d, J = 2.3 Hz, 2H), 6.35 (s, 1H), 5.06 (s, 2H), 3.85 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 159.8, 156.9, 143.9, 141.9, 129.7, 119.5, 113.2, 112.7, 107.0, 101.8, 55.3. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{13}H_{13}O_3$ 217.0865; found 217.0856. IR (KBr): 3258, 1597, 1581, 1477, 1287, 1161, 1045, 1005, 693 cm^{-1}. mp: 61–63 °C.

2h *and* ***2l*** *were prepared following the procedure for* ***2d***. ***2r*** *was prepared following the procedure for* ***2d*** *using 3-bromo-5-methoxyphenol instead of 5-bromobenzene-1,3-diol with phenylboronic acid.*

*4'-methyoxy-[1,1'-biphenyl]-3,5-diol (**2h**).*[12] 329.4 mg, 71% yield. White solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (d, J = 8.7 Hz, 2H), 6.95 (d, J = 8.7 Hz, 2H), 6.60 (d, J = 2.1 Hz, 2H), 6.30 (t, J = 2.3 Hz, 1H), 3.85 (s, 3H).

*4'-(methoxymethoxy)-[1,1'-biphenyl]-3,5-diol (**2l**).* 200.4 mg, 57% yield. White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.28 (s, 1H), 7.49 (d, J = 8.7 Hz, 2H), 7.07 (d, J = 8.7 Hz, 2H), 6.56 (d, J = 2.0 Hz, 2H), 6.32 (t, J = 2.0 Hz, 1H), 5.21 (s, 2H), 3.43 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, Acetone-D6): δ 159.7, 157.8, 143.6, 135.5, 128.5, 117.2, 106.0, 102.0, 95.0, 56.0. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{14}H_{14}O_4$ 247.0970; Found 247.0963. IR (KBr): 3402, 3334, 1613, 1450, 1362, 1224, 1173, 1078, 903 cm^{-1}. mp: 172–174 °C.

*5-methoxy-[1,1'-biphenyl]-3-ol (**2r**).*[12] 1.11 g, 93% yield. yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.53-7.56 (m, 2H), 7.40-7.44 (m, 2H), 7.33-7.37 (m, 1H), 6.73-6.72 (m, 1H), 6.66 (t, J = 2.1 Hz, 1H), 6.41 (t, J = 2.1 Hz, 1H), 4.99 (s, 1H), 3.84 (s, 3H).

*Preparation of methyl 3',5'-dihydroxy-[1,1'-biphenyl]-4-carboxylate (**2k**).*[15] The procedure followed that for preparation of compound **2a** to give corresponding carboxylic acid, which is subjected under methylation protocol using conc. H_2SO_4 in MeOH to furnish **2k**. 150.2 mg, 32% yield (in 3 steps from 1-bromo-3,5-dimethoxybenzene). White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.42 (s, 1H), 8.05 (d, J = 8.2 Hz, 2H), 7.69 (d, J = 8.7 Hz, 2H), 6.67 (d, J = 2.3 Hz, 2H), 6.42 (t, J = 2.1 Hz, 1H), 3.89 (s, 3H).

*Preparation of 2-methyl-[1,1'-biphenyl]-3,5-diol (**2o**).* A suspension of 2-bromo-4,6-dimethoxybenzaldehyde (148.1 mg, 0.604 mmol), Hydrazine monohydrate (60 µL, 1.23 mmol) and KOH (105.7 mg, 1.88 mmol) in $(CH_2OH)_2$ (0.3 mL) was stirred for 3 h under reflux condition. After cooling room temperature, water was added to the reaction mixture and the organic layer was extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by silica column chromatography (hexane/EtOAc = 40/1) to afford 1-bromo-3,5-dimethoxy-2-methylbenzene in 54% yield (75.1 mg, colorless oil).

1-bromo-3,5-dimethoxy-2-methylbenzene. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.70 (d, J = 2.3 Hz, 1H), 6.38 (d, J = 2.3 Hz, 1H), 3.79 (s, 3H), 3.77 (s, 3H), 2.22 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 158.7, 158.5, 125.4, 119.1, 108.1, 97.8, 55.7, 55.5, 14.9. HRMS (APCI) *m/z*: $[M - Br]^+$ Calcd for $C_9H_{11}O_2$ 151.0754; Found 151.0753. IR (KBr): 2997, 2964, 1603, 1570, 1488, 1461, 1218, 1150, 1039 cm^{-1}.

A suspension of 1-bromo-3,5-dimethoxy-2-methylbenzene (417.4 mg, 1.81 mmol), phenyl boronic acid (249.3 mg, 2.04 mmol), $Pd(PPh_3)_4$ (52.2 mg, 0.0450 mmol) and Na_2CO_3 (387.3 mg, 3.65 mmol) in THF/water (5/1, 11 mL) was stirred for 12 h under reflux condition. After cooling, the reaction mixture was filtrated through Celite, quenched with sat. NH_4Cl aq., and extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by silica column chromatography (hexane/EtOAc = 40/1) to afford 3,5-dimethoxy-2-methyl-1,1'-biphenyl in 37% yield (153.7 mg, colorless oil).

3,5-dimethoxy-2-methyl-1,1'-biphenyl. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39-7.43 (m, 2H), 7.30-7.36 (m, 3H), 6.47 (d, J = 2.3 Hz, 1H), 6.41 (d, J = 2.3 Hz, 1H), 3.85 (s, 3H), 3.80 (s, 3H), 2.03 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 158.7, 158.0, 143.4, 142.1, 129.2, 128.0, 126.8, 116.6, 105.7, 97.3, 55.6, 55.4, 12.7. HRMS (APCI) *m/z*: $[M + H]^+$ Calcd for $C_{24}H_{16}FO$ 339.1185; found 339.1175. IR (KBr): 2998, 2939, 1603, 1484, 1414, 1221, 1057, 751, 703 cm^{-1}.

BBr_3 (1.0 M in CH_2Cl_2, 1.8 mL, 1.8 mmol) was added to a solution of 3,5-dimethoxy-2-methyl-1,1'-biphenyl (138.3 mg, 0.606 mmol) in CH_2Cl_2 (3.0 mL) at 0 °C. The mixture was stirred for 12 h at room temperature. After cooling to 0 °C, the reaction was quenched with sat. $NaHCO_3$ aq. The aqueous layer was extracted with CH_2Cl_2. The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by silica column chromatography (hexane/EtOAc = 3/1) to afford 2-methyl-[1,1'-biphenyl]-3,5-diol (**2o**) in 97% yield (118.3 mg, white solid).

*2-methyl-[1,1'-biphenyl]-3,5-diol (**2o**).* ^{1}H NMR (400 MHz, Acetone-D6): δ 8.18 (s, 1H), 8.02 (s, 1H), 7.38-7.41 (m, 2H), 7.27-7.33 (m, 3H), 6.41 (d, J = 2.3 Hz, 1H), 6.25 (d, J = 2.3 Hz, 1H), 1.97 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, Acetone-D6): δ 157.2, 156.3, 144.6, 143.3, 129.8, 128.8, 127.4, 113.6, 108.9, 102.2, 12.8. HRMS (APCI) *m/z*: $[M + H]^+$ Calcd for $C_{13}H_{13}O_2$ 201.0916; found 201.0909. IR (KBr): 3425, 3047, 2871, 1601, 1438, 1246, 1113, 972, 831, 759, 618 cm^{-1}. mp: 157–159 °C.

2p[9b], **2q**[16], and **2s**[17] were prepared following reported method.

3. Procedure and Experimental Data for Vanadium Complex (*R*$_a$,*S*,*S*)-1c.

To a solution of (*R*)-2,2'-dihydroxy-[1,1'-binaphthalene]-3,3'-dicarbaldehyde (217.1 mg, 0.634 mmol) in CH_2Cl_2 was added Br_2 (0.12 mL, 2.34 mmol) at 0 °C. The mixture was stirred for 24 h at room temperature. After cooling to 0 °C, the reaction was quenched with 20 % Na_2SO_3 aq. The aqueous layer was extracted with CH_2Cl_2. The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and evaporated under vacuum. The crude product was recrystallized from CH_2Cl_2 to afford (*R*)-6,6'-dibromo-2,2'-dihydroxy-[1,1'-binaphthalene]-3,3'-dicarbaldehyde in 74% yield (234.6 mg, yellow solid).

(R)-6,6'-dibromo-2,2'-dihydroxy-[1,1'-binaphthalene]-3,3'-dicarbaldehyde. ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.60 (s, 1H), 10.19 (s, 1H), 8.26 (s, 1H), 8.16 (d, J = 1.8 Hz, 1H), 7.47 (dd, J = 8.7, 1.8 Hz, 1H), 7.05 (d, J = 8.7 Hz, 1H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 196.6, 154.0, 137.3, 135.7, 133.9, 131.6, 128.6, 126.5, 122.6, 118.4, 116.4. HRMS (APCI) *m/z*: $[M + H]^+$ Calcd for $C_{22}H_{13}Br_2O_4$ 498.9181; found 498.9171. IR (KBr): 3052, 3847, 1654, 1630, 1492, 1340, 1285, 1172, 1069, 929, 797, 485 cm^{-1}. mp: >300 °C. $[\alpha]_D^{18}$ +244.8 (*c* 0.10, $CHCl_3$).

A round-bottomed flask was charged with (*R*)-6,6'-dibromo-2,2'-dihydroxy-[1,1'-binaphthalene]-3,3'-dicarbaldehyde (233.5 mg, 0.467 mmol), L-*tert*-leucine (135.2 mg, 1.03 mmol), $VOSO_4$•xH_2O (372.7 mg, 2.06 mmol), MS 3A (397 mg), CH_3OH (23 mL) under O_2 (balloon). The reaction mixture was refluxed, and the consumption of (*R*)-6,6'-dibromo-2,2'-dihydroxy-[1,1'-binaphthalene]-3,3'-dicarbaldehyde was monitored by ^{1}H NMR. The resulting solution was gradually cooled down to room temperature and filtered through Celite to remove MS 3A. The filtrate was evaporated, and the resulting black solid was dissolved in CH_2Cl_2 and washed with H_2O. The organic phase was dried over anhydrous Na_2SO_4 and concentrated in vacuum to give desired vanadium complex (*R*$_a$,*S*,*S*)-**1c** in 87% yield (361.7 mg, dark green solid).

*(R$_a$,S,S)-**1c**.* ^{1}H NMR (400 MHz, MeOH-d4): δ 8.94 (s, 2H), 8.44 (s, 2H), 8.27 (d, J = 1.8 Hz, 2H), 7.66 (d, J = 9.2 Hz, 2H), 7.48 (dd, J = 9.2, 1.8 Hz, 2H), 4.21 (s, 2H), 1.26 (s, 18H). ^{13}C{^{1}H} NMR (175 MHz, MeOH-d4): δ 167.7, 137.0, 136.8, 133.6, 132.2, 130.5, 129.7, 125.3, 118.8, 118.6, 83.7, 38.8, 28.1. HRMS (APCI) *m/z*: $[M - H_2O + H]^+$ Calcd for $C_{34}H_{31}Br_2N_2O_9V_2$ 870.9270; found 870.9264.

4. Typical Procedure for Enantioselective Oxidative Coupling of Phenols 2. A test tube was charged with resorcinols **2** (0.1 mmol, 1 eq), dinuclear vanadium catalyst (5 mol %) and PhMe (0.5 mL) under air at 70 °C. The mixture was stirred for 24-48 h. The reaction mixture was then filtered through a short pad of silica gel and the solvent was evaporated. The crude product was purified by silica column chromatography (hexane/acetone = 3/2) to afford biresorcinols **3**.

*[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3a**).* 15.6 mg, 84% yield. White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.19 (s, 2H), 7.60 (s, 2H), 6.99-7.08 (m, 6H), 6.68 (d, J = 7.3 Hz, 4H), 6.42 (d, J = 2.3 Hz, 2H), 6.13 (d, J = 2.3 Hz, 2H). ^{13}C{^{1}H} NMR (100 MHz, Acetone-D6): δ 158.3, 158.1, 145.7, 142.7, 129.6, 127.7, 126.8, 114.2, 109.4, 102.1. HRMS (APCI) *m/z*: $[M + H]^+$ Calcd for $C_{24}H_{19}O_4$ 371.1278; found 371.1272. IR (KBr): 1469, 1699, 1588, 1455, 1301, 1168, 1012, 845, 771, 740 cm^{-1}. mp: 243–245 °C. Enantiomeric excess: 97%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 7.0 min, second peak: t_R = 13.7 min. $[\alpha]_D^{20}$ –130.3 (*c* 0.72, EtOAc) for 97% ee.

*2,2'''-difluoro-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3b**).* 17.7 mg, 87% yield. White solid. ^{1}H NMR (600 MHz, Acetone-D6): δ 8.23 (s, 2H), 7.60 (s, 2H), 7.11-7.14 (m, 2H), 6.81-6.86 (m, 4H), 6.69 (t, J = 7.2 Hz, 2H), 6.44 (d, J = 2.4 Hz, 2H), 6.14

(t, J = 2.4 Hz, 2H). $^{13}C\{^1H\}$ NMR (150 MHz, Acetone-D6): δ 160.3 (d, $^1J_{C-F}$ = 245.6 Hz), 158.2, 158.0, 139.0, 132.5 (d, $^3J_{C-F}$ = 2.9 Hz), 129.6 (d, $^2J_{C-F}$ = 14.5 Hz), 129.1 (d, $^3J_{C-F}$ = 7.2 Hz), 123.7 (d, $^4J_{C-F}$ = 2.9 Hz), 115.8 (d, $^2J_{C-F}$ = 21.7 Hz), 114.9, 110.3, 102.7. $^{19}F\{^1H\}$ NMR (565 MHz, Acetone-D6): δ -116.1. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{24}H_{17}F_2O_4$ 407.1089; found 407.1096. IR (KBr): 3412, 1608, 1590, 1461, 1149, 1014, 1001, 749 cm^{-1}. mp: >300 °C. Enantiomeric excess: 97%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 8.1 min, second peak: t_R = 17.5 min. $[\alpha]_D^{20}$ –194.8 (*c* 0.48, EtOAc) for 97% ee.

*3,3'''-dimethyl-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3c**).* 8.4 mg, 42% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.12 (s, 1H), 7.48 (s, 2H), 6.88-6.89 (m, 4H), 6.52-6.55 (m, 2H), 6.43 (s, 2H), 6.41 (d, J = 2.3 Hz, 2H), 6.12 (d, J = 2.3 Hz, 2H), 2.14 (s, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, Acetone-D6): δ 158.3, 158.1, 145.9, 142.6, 136.9, 130.5, 127.4, 127.4, 126.7, 114.3, 109.4, 101.9, 21.4. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{26}H_{23}O_4$ 399.1591; found 399.1588. IR (KBr): 3360, 3047, 2915, 1611, 1446, 1337, 1150, 1013, 784 cm^{-1}. mp: 165–167 °C. Enantiomeric excess: 90%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 4/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 8.6 min, second peak: t_R = 16.3 min. $[\alpha]_D^{24}$ –146.2 (*c* 0.42, EtOAc) for 90% ee.

*3,3'''-dimethoxy-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3d**).* 16.1 mg, 75% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.18 (s, 2H), 7.60 (s, 2H), 6.92 (t, J = 8.2 Hz, 2H), 6.61-6.64 (m, 2H), 6.43 (d, J = 2.3 Hz, 2H), 6.29-6.31 (m, 4H), 6.17 (d, J = 2.3 Hz, 2H), 3.58 (s, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, Acetone-D6): δ 159.5, 158.4, 158.1, 145.6, 144.0, 128.6, 122.0, 114.4, 114.3, 113.4, 109.4, 102.2, 55.0. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{26}H_{23}O_6$ 431.1489; found 431.1494. IR (KBr): 3476, 3050, 2945, 2846, 1581, 1446, 1316, 1166, 1015, 849, 780, 697 cm^{-1}. mp: 231–233 °C. Enantiomeric excess: 93%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 4/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 12.6 min, second peak: t_R = 25.7 min. $[\alpha]_D^{24}$ –171.7 (*c* 0.48, EtOAc) for 93% ee.

*3,3'''-difluoro-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3e**).* 14.2 mg, 70% yield. White solid. ^1H NMR (600 MHz, Acetone-D6): δ 8.31 (s, 2H), 7.86 (s, 2H), 7.05-7.09 (m, 2H), 6.86 (td, J = 8.1, 2.7 Hz, 2H), 6.52 (d, J = 8.1 Hz, 2H), 6.46 (d, J = 2.4 Hz, 2H), 6.41-6.43 (m, 2H), 6.16 (d, J = 2.4 Hz, 2H). $^{13}C\{^1H\}$ NMR (150 MHz, Acetone-D6): δ 162.7 (d, $^1J_{C-F}$ = 242.8 Hz), 158.6, 158.3, 145.0 ($^3J_{C-F}$ = 7.2 Hz), 144.1, 129.5 (d, $^3J_{C-F}$ = 8.7 Hz), 125.5, 116.2 (d, $^2J_{C-F}$ = 21.7 Hz), 114.2, 113.5 (d, $^2J_{C-F}$ = 20.2 Hz), 109.2, 102.6. $^{19}F\{^1H\}$ NMR (565 MHz, Acetone-D6): δ -116.1. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{24}H_{17}F_2O_4$ 407.1089; found 407.1094. IR (KBr): 3351, 1612, 1580, 1460, 1345, 1152, 1013, 800, 785 cm^{-1}. mp: 214–216 °C. Enantiomeric excess: 87%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 6.1 min, second peak: t_R = 10.6 min. $[\alpha]_D^{20}$ –167.0 (*c* 0.40, EtOAc) for 87% ee.

*3,3'''-dichloro-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3f**).* 6.4 mg, 29% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.28 (s, 1H), 7.84 (s, 1H), 7.11-7.14 (m, 2H), 7.06 (t, J = 7.8 Hz, 2H), 6.64-6.68 (m, 4H), 6.47 (d, J = 2.3 Hz, 2H), 6.15 (d, J = 2.3 Hz, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, Acetone-D6): δ 158.7, 158.3, 144.7, 144.0, 133.4, 129.5, 129.4, 128.0, 126.9, 114.2, 109.1, 102.7. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{24}H_{16}Cl_2O_4$ 439.0504; found 439.0495. IR (KBr): 3360, 1594, 1565, 1458, 1343, 1149, 1010, 787 cm^{-1}. mp: decomposed at 95 °C. Enantiomeric excess: 76%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 4/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 9.5 min, second peak: t_R = 18.8 min. $[\alpha]_D^{20}$ –171.9 (*c* 0.22, EtOAc) for 76% ee.

*4,4'''-dimethyl-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3g**).* 18.1 mg, 91% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.12 (s, 2H), 7.43 (s, 2H), 6.84 (d, J = 7.8 Hz, 4H), 6.63 (d, J = 7.8 Hz, 4H), 6.39 (d, J = 2.3 Hz, 2H), 6.13 (d, J = 2.3 Hz, 2H), 2.21 (s, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, Acetone-D6): δ 158.3, 158.0, 145.7, 139.9, 136.1, 129.5, 128.4, 114.2, 109.6, 101.9, 21.0. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{26}H_{23}O_4$ 399.1591; found 399.1596. IR (KBr): 3459, 3047, 2923, 1606, 1584, 1449, 1334, 1245, 1171, 1013, 812 cm^{-1}. mp: 298–300 °C. Enantiomeric excess: 95%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 6.6 min, second peak: t_R = 14.9 min. $[\alpha]_D^{22}$ –111.4 (*c* 0.53, EtOAc) for 95% ee.

*4,4'''-dimethoxy-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3h**).* 20.0 mg, 93% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.11 (s, 2H), 7.40 (s, 2H), 6.65 (d, J = 8.7 Hz, 4H), 6.59 (d, J = 8.7 Hz, 4H), 6.38 (d, J = 2.3 Hz, 2H), 6.13 (d, J = 2.3 Hz, 2H), 3.71 (s, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, Acetone-D6): δ 159.1, 158.3, 157.9, 145.4, 135.2, 130.6, 114.2, 113.2, 109.6, 101.8, 55.3. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{26}H_{23}O_6$ 431.1489; found 431.1496. IR (KBr): 3466, 2925, 1609, 1584, 1516, 1446, 1242, 1173, 1034, 826, 592 cm^{-1}. mp: 252–254 °C. Enantiomeric excess: 96%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 9.2 min, second peak: t_R = 20.0 min. $[\alpha]_D^{22}$ –88.8 (*c* 0.54, EtOAc) for 96% ee.

*4,4'''-difluoro-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3i**).* 16.9 mg, 83% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.22 (s, 1H), 7.70 (s, 1H), 6.77-6.83 (m, 4H), 6.66-6.71 (m, 4H), 6.43 (d, J = 2.3 Hz, 2H), 6.13 (d, J = 2.3 Hz, 2H). $^{13}C\{^1H\}$ NMR (150 MHz, Acetone-D6): δ 162.3 (d, $^1J_{C-F}$ = 242.8 Hz), 158.5, 158.2, 144.4, 138.8, 131.3 (d, $^3J_{C-F}$ = 8.7 Hz), 114.5 (d, $^2J_{C-F}$ = 21.7 Hz), 114.3, 109.3, 102.3. $^{19}F\{^1H\}$ NMR (565 MHz, Acetone-D6): δ -117.3. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{24}H_{17}F_2O_4$ 407.1089; found 407.1085. IR (KBr): 3476, 3424, 1607, 1582, 1514, 1451, 1334, 1227, 1170, 1014, 830 cm^{-1}. mp: 287–289 °C. Enantiomeric excess: 80%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 4/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 8.2 min, second peak: t_R = 18.8 min. $[\alpha]_D^{20}$ –131.6 (*c* 0.53, EtOAc) for 80% ee.

*4,4'''-dichloro-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3j**).* The reaction was performed in PhMe/CCl_4 (2/3). 16.5 mg, 75% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.25 (s, 1H), 7.76 (s, 1H), 7.07 (d, J = 8.2 Hz, 4H), 6.69 (d, J = 8.2 Hz, 4H), 6.44 (d, J = 2.3 Hz, 2H), 6.14 (d, J = 2.3 Hz, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, Acetone-D6): δ 158.6, 158.3, 144.2, 141.4, 132.5, 131.2, 127.9, 114.2, 109.3, 102.6. HRMS (APCI): calcd for $C_{24}H_{17}Cl_2O_4$: *m/z* 439.0498 [M + H]$^+$, found 439.0503. IR (KBr): 3353, 1678, 1612, 1462, 1339, 1271, 1184, 1122, 1088, 1014, 876, 828 cm^{-1}. mp: 280–282 °C. Enantiomeric excess: 77%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 4/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 7.7 min, second peak: t_R = 19.9 min. $[\alpha]_D^{22}$ –172.8 (*c* 0.45, EtOAc) for 77% ee.

*6,6'-di(naphthalen-2-yl)-[1,1'-biphenyl]-2,2',4,4'-tetraol (**3m**).* 18.4 mg, 78% yield. White solid. ^1H NMR (400 MHz, Acetone-D6): δ 8.17 (s, 2H), 7.74-7.79 (m, 4H), 7.50 (d, J = 8.2 Hz, 2H), 7.37-7.44 (m, 6H), 6.87-6.90 (m, 4H), 6.49 (d, J = 2.3 Hz, 2H), 6.15 (d, J = 2.3 Hz, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, Acetone-D6): δ 158.6, 158.3, 145.7, 140.5, 133.8, 133.0, 128.8, 128.4, 128.3, 128.1, 126.7, 126.3, 126.3, 114.6, 109.7, 102.4. HRMS (APCI) *m/z*: [M + H]$^+$ Calcd for $C_{32}H_{23}O_4$ 471.1591; found 471.1596. IR (KBr): 3359, 3055, 1584, 1451, 1335, 1271, 1161, 1132, 1013, 817, 475 cm^{-1}. mp: 284–286 °C. Enantiomeric excess: 85%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min;

25 °C; 254 nm) first peak: t_R = 8.4 min, second peak: t_R = 16.1 min. $[\alpha]_D^{20}$ –25.0 (*c* 0.45, EtOAc) for 85% ee.

*3'',6'-dimethyl-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3o**).* 18.5 mg, 93% yield. White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 7.96 (s, 2H), 7.17-7.21 (m, 4H), 7.05-7.12 (m, 4H), 7.01 (s, 2H), 6.51 (d, *J* = 7.8 Hz, 2H), 6.39 (s, 2H), 1.62 (s, 6H). ^{13}C{^{1}H} NMR (100 MHz, Acetone-D6): δ 156.19, 155.00, 144.92, 141.56, 131.58, 129.55, 127.88, 127.17, 126.86, 114.89, 114.26, 101.83, 13.45. HRMS (APCI) *m/z*: $[M + H]^+$ Calcd for $C_{26}H_{23}O_4$ 399.1591; found 399.1595. IR (KBr): 3469, 3054, 2915, 1594, 1424, 1306, 1250, 1128, 1054, 834, 701 cm^{-1}. mp: 257–259 °C. Enantiomeric excess: 88%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 6.9 min, second peak: t_R = 10.3 min. $[\alpha]_D^{20}$ –176.1 (*c* 0.53, EtOAc) for 88% ee.

*4',5''-dimethyl-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3p**).*[9b] 15.3 mg, 77% yield. White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.15 (s, 2H), 6.97-7.07 (m, 6H), 6.93 (s, 2H), 6.64-6.67 (m, 4H), 6.22 (s, 2H), 2.16 (s, 6H). Enantiomeric excess: 36%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 4/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 21.2 min, second peak: t_R = 25.1 min. $[\alpha]_D^{20}$ +52.6 (*c* 0.46, EtOAc) for 36% ee.

*4',5''-dibromo-[1,1':2',1'':2'',1'''-quaterphenyl]-3',4'',5',6''-tetraol (**3q**).* 12.9 mg, 49% yield. White solid. ^{1}H NMR (400 MHz, Acetone-D6): δ 8.75 (s, 2H), 7.89 (s, 2H), 7.03-7.13 (m, 6H), 6.65-6.67 (m, 4H), 6.30 (s, 2H). ^{13}C{^{1}H} NMR (100 MHz, Acetone-D6): δ 155.2, 155.0, 144.3, 141.6, 129.4, 128.0, 127.3, 114.8, 109.6, 98.4. HRMS (APCI) *m/z*: $[M - Br]^+$ Calcd for $C_{24}H_{16}BrO_4$ 447.0226; found 447.0224. IR (KBr): 3485, 3059, 2958, 1698, 1597, 1560, 1413, 1239, 1178, 1044, 781, 701 cm^{-1}. mp: 123–125 °C. Enantiomeric excess: 70%, determined by HPLC (Chiralpak IA, hexane/2-propanol = 3/1; flow rate 1.0 mL/min; 25 °C; 254 nm) first peak: t_R = 15.9 min, second peak: t_R = 28.5 min. $[\alpha]_D^{20}$ –316.5 (*c* 0.25, EtOAc) for 70% ee.

ASSOCIATED CONTENT

Reaction optimization, compound characterization data, and HPLC chromatograms. This material is available free of charge *via* the Internet at http://pubs.acs.org.

Experimental procedures, spectroscopic data
X-ray crystallographic data for (*S*)-**3a** (CCDC 1849069)

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Notes

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REFERENCES

(1) Recent reviews and reports on syntheses and applications of axually chiral compounds, see: (a) Moustafa, G. A. I.; Oki, Y.; Akai, S. Lipase-Catalyzed Dynamic Kinetic Resolution of C_1- and C_2-Symmetric Racemic Axially Chiral 2,2'-Dihydroxy-1,1'-biaryls. *Angew. Chem. Int. Ed*. **2018**, *57*, 10278–10282. (b) Renzi, P. Organocatalytic Synthesis of Axially Chiral Atropisomers. *Org. Biomol. Chem.* **2017**, *15*, 4506–4516.

(2) Selected reviews on bioactive compounds bearing chiral biaryls, see: (a) Bringmann, G.; Gulder, T.; Gulder, T. A. M.; Breuning, M. Atroposelective Total Synthesis of Axially Chiral Biaryl Natural Products. *Chem. Rev*. **2011**, *111*, 563–639. (b) Kozlowski, M. C.; Morgan, B. J.; Linton, E. C. Total Synthesis of Chiral Biaryl Natural Products by Asymmetric Biaryl Coupling. *Chem. Soc. Rev.* **2009**, *38*, 3193–3207.

(3) Selected examples of the chiral metal-catalyzed oxidative coupling of 2-naphthols (pioneering works), see: (a) Smrćina, M.; Poláková, J.; Vyskoćil, S.; Koćovský, P. Synthesis of Enantiomerically Pure Binaphthyl Derivatives. Mechanism of the Enantioselective, Oxidative Coupling of Naphthols and Designing a Catalytic Cycle. *J. Org. Chem.* **1993**, *58*, 4534–4538. (b) Nakajima, M.; Miyoshi, I.; Kanayama, K.; Hashimoto, S.-i.; Noji, M.; Koga, K. Enantioselective Synthesis of Binaphthol Derivatives by Oxidative Coupling of Naphthol Derivatives Catalyzed by Chiral Diamine·Copper Complexes. *J. Org. Chem.* **1999**, *64*, 2264–2271. (c) Irie, R.; Masutani, K.; Katsuki, T. Asymmetric Aerobic Oxidative Coupling of 2-Naphthol Derivatives Catalyzed by Photo-activated Chiral (NO)Ru(II)-salen Complex. *Synlett* **2000**, 1433–1436. (d) Egami, H.; Katsuki, T. Iron-Catalyzed Asymmetric Aerobic Oxidation: Oxidative Coupling of 2-Naphthols. *J. Am. Chem. Soc.* **2009**, *131*, 6082–6083. (e) Li, X.; Yang, J.; Kozlowski, M. C. Enantioselective Oxidative Biaryl Coupling Reactions Catalyzed by 1,5-Diazadecalin Metal Complexes. *Org. Lett.* **2001**, *3*, 1137–1140. (f) Chu, C.-Y.; Hwang, D.-R.; Wang, S.-K.; Uang, B.-J. Chiral Oxovanadium Complex Catalyzed Enantioselective Oxidative Coupling of 2-Naphthols. *Chem. Commun*. **2001**, 980–981. (g) Hon, S.-W.; Li, C.-H.; Kuo, J.-H.; Barhate, N. B.; Liu, Y.-H.; Wang, Y.; Chen, C.-T. Catalytic Asymmetric Coupling of 2-Naphthols by Chiral Tridentate Oxovanadium(IV) Complexes. *Org. Lett.* **2001**, *3*, 869–872. (h) Tada, M.; Taniike, T.; Kantam, L. M.; Iwasawa, Y. Chiral Self-dimerization of Vanadium Complexes on a SiO_2 Surface: The First Heterogeneous Catalyst for Asymmetric 2-Naphthol Coupling. *Chem. Commun*. **2004**, 2542–2543. (i) Habaue, S.; Murakami, S.; Higashimura, H. New Asymmetric Vanadium Catalyst for Highly Selective Oxidative Coupling Polymerization. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43*, 5872–5878. (j) Temma, T.; Habaue, S. Highly Selective Oxidative Cross-coupling Polymerization with Copper(I)-bisoxazoline Catalysts. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43*, 6287–6294. (k) Narute, S.; Parnes, R.; Toste, F. D.; Pappo, D. Enantioselective Oxidative Homocoupling and Cross-Coupling of 2-Naphthols Catalyzed by Chiral Iron Phosphate Complexes. *J. Am. Chem. Soc.* **2016**, *138*, 16553–16560. (l) Luo, Z.; Liu, Q.; Gong, L.; Cui, X.; Mi, A.; Jiang, Y. The Rational Design of Novel Chiral Oxovanadium(IV) Complexes for Highly Enantioselective Oxidative Coupling of 2-Naphthols. *Chem. Commun*. **2002**, 914–915. (m) Gao, J.; Reibenspies, J. H.; Martell, A. E. Structurally Defined Catalysts for Enantioselective Oxidative Coupling Reactions. *Angew. Chem. Int. Ed.* **2003**, *42*, 6008–6012. (n) Somei, H.; Asano, Y.; Yoshida, T.; Takizawa, S.; Yamataka, H.; Sasai, H. Dual Activation in a Homolytic Coupling Reaction Promoted by an Enantioselective Dinuclear Vanadium(IV) Catalyst. *Tetrahedron Lett.* **2004**, *45*, 1841–1844.

(4) Recent reviews, see: (a) Yang, Y.; Lan, J.; You, J. Oxidative C–H/C–H Coupling Reactions between Two (Hetero)arenes. *Chem. Rev.* **2017**, *117*, 8787–8863. (b) Kozlowski, M. C. Oxidative Coupling in Complexity Building Transforms. *Acc. Chem. Res.* **2017**, *50*, 638–643. (c) Quideau, S.; Deffieux, D.; Pouységu, L. Oxidative Coupling of Phenols and Phenol Ethers. In *Comprehensive Organic Synthesis II*; Knochel, P. and Molander G. A., Eds; Oxford, UK; Elsevier: 2014; p 656.

(5) Recent reports, see: (a) Wu, X.; Iwata, T.; Scharf, A.; Qin, T.; Reichl, K. D.; Porco, J. A., Jr. Asymmetric Synthesis of Gonytolide A: Strategic Use of an Aryl Halide Blocking Group for Oxidative Coupling. *J. Am. Chem. Soc.* **2018**, *140*, 5969–5975. (b) Vershinin, V.; Dyadyuk, A.; Pappo, D. Iron-catalyzed Selective Oxidative Arylation of Phenols and Biphenols. *Tetrahedron* **2017**, *73*, 3660–3668. (c) Shalit, H.; Libman, A.; Pappo, D. *meso*-Tetraphenylporphyrin Iron Chloride Catalyzed Selective Oxidative Cross-Coupling of Phenols. *J. Am. Chem. Soc.* **2017**, *139*, 13404–13413. (d) Mei, R.; Xu, D.; Hu, H.; Song, D.; Zhang, H.; Ma, D.; Xie, X.; She, X. Biomimetic Total Syntheses of (+)-Dihydrolyfoline and (−)-5-*epi*-Dihydrolyfoline. *Org. Lett.* **2015**, *17*, 2230–2233. (e) Grant-Overton, S.; Buss, J. A.; Smith, E. H.; Gutierrez, E. G.; Moorhead, E. J.; Lin, V. S.; Wenzel, A. G. Efficient Microwave Method for the Oxidative Coupling of Phenols. *Synth. Commun.* **2015**, *45*, 331–337.

(6) Recent reviews and reports, see: (a) Kita, Y.; Morimoto, K.; Dohi, T. Metal-free Oxidative Cross-Coupling Reaction of Aromatic Compounds Containing Heteroatoms. *Synlett* **2017**, *28*, 1680–1694. (b) Morimoto, K.; Sakamoto, K.; Ohshika, T.; Dohi, T.; Kita, Y. Organo-Iodine(III)-Catalyzed Oxidative Phenol-Arene and Phenol-Phenol Cross-Coupling Reaction. *Angew. Chem. Int. Ed.* **2016**, *55*, 3652–3656. (c) Morimoto, K.; Sakamoto, K.; Ohnishi, Y.; Miyamoto, T.; Ito, M.; Dohi, T.; Kita, Y. Metal-Free Oxidative para Cross-Coupling of Phenols. *Chem. Eur. J.* **2013**, *19*, 8726–8731.

(7) Recent report, see: (a) Lips, S.; Wiebe, A.; Elsler, B.; Schollmeyer, D.; Dyballa, K. M.; Franke, R.; Waldvogel, S. R. Synthesis of *meta*-Terphenyl-2,2"-diols by Anodic C−C Cross-Coupling Reactions. *Angew. Chem. Int. Ed.* **2016**, *55*, 10872–10876. (b) Elsler, B.; Wiebe, A.; Schollmeyer, D.; Dyballa, K. M.; Franke, R.; Waldvogel, S. R. Source of Selectivity in Oxidative Cross-Coupling of Aryls by Solvent Effect of 1,1,1,3,3,3-Hexafluoropropan-2-ol. *Chem. Eur. J.* **2015**, *21*, 12321–12325. (c) Elsler, B.; Schollmeyer, D.; Dyballa, K. M.; Franke, R.; Waldvogel, S. R. Metal- and Reagent-Free Highly Selective Anodic Cross-Coupling Reaction of Phenols. *Angew. Chem. Int. Ed.* **2014**, *53*, 5210–5213.

(8) Selected recent emxamples: Natural products; (a) Xiao, Z.; Li, Y.; Gao, S. Total Synthesis and Structural Determination of the Dimeric Tetrahydroxanthone Ascherxanthone A. *Org. Lett.* **2017**, *19*, 1834–1837. (b) Richieu, A.; Peixoto, P. A.; Pouysegu, L.; Deffieux, D.; Quideau, S. Bioinspired Total Synthesis of (–)-Vescalin: A Nonahydroxytriphenoylated *C*-Glucosidic Ellagitannin. *Angew. Chem. Int. Ed.* **2017**, *56*, 13833–13837. Chiral reagents; (c) Zhang, Z. P.; Chen, C. Y.; Wang, Q.; Han, Z. Y.; Dong, X. Q.; Zhang, X. M. New Tetraphosphite Ligands for Regioselective Linear Hydroformylation of Terminal and Internal Olefins. *Rsc Adv.* **2016**, *6*, 14559–14562. (d) Zhuang, Y.; He, Y.; Zhou, Z.; Xia, W.; Cheng, C.; Wang, M.; Chen, B.; Zhou, Z.; Pang, J.; Qiu, L. Synthesis of a Class of Chiral-Bridged Phosphoramidite Ligands and Their Applications in the First Iridium-Catalyzed Asymmetric Addition of Arylboronic Acids to Isatins. *J. Org. Chem.* **2015**, *80*, 6968–6975. Functional materials; (e) Chen, E.; Chen, X.; Yuan, X.; Wei, S.; Zhou, L.; Zhou, J.; Shen, J. One-pot Method to Prepare a Theranostic Nanosystem with Magnetic Resonance Imaging Function and Anticancer Activity through Multiple Mechanisms. *Dalton Trans.* **2017**, *46*, 5151–5158. (f) Li, J.; Zhang, J.; Yang, S.; Jiang, C.; Zhang, D.; Jin, Q.; Wang, Q.; Wang, C.; Ni, Y.; Yin, Z.; Song, S. Synthesis and Preclinical Evaluation of Radioiodinated Hypericin Dicarboxylic Acid as a Necrosis Avid Agent in Rat Models of Induced Hepatic, Muscular, and Myocardial Necroses. *Mol. Pharmaceutics* **2016**, *13*, 232–240.

(9) (a) Kang, H.; Torruellas, C.; Liu, J.; Kozlowski, M. C. Total Synthesis of Chaetoglobin A via Catalytic, Atroposelective Oxidative Phenol Coupling. *Org. Lett.* **2018**, *20*, 5554–5558. (b) Kang, H.; Lee, Y. E.; Reddy, P. V. G.; Dey, S.; Allen, S. E.; Niederer, K. A.; Sung, P.; Hewitt, K.; Torruellas, C.; Herling, M. R.; Kozlowski, M. C. Asymmetric Oxidative Coupling of Phenols and Hydroxycarbazoles. *Org. Lett.* **2017**, *19*, 5505–5508. (c) Kang, H.; Herling, M. R.; Niederer, K. A.; Lee, Y. E.; Reddy, P. V. G.; Dey, S.; Allen, S. E.; Hewitt, P. S. K.; Torruellas, C.; Kim, G. J.; Kozlowski, M. C. Enantioselective Vanadium-Catalyzed Oxidative Coupling: Development and Mechanistic Insights. *J. Org. Chem.* DOI: 10.1021/acs.joc.8b02083.

(10) (a) Kim, H. Y.; Takizawa, S.; Sasai, H.; Oh, K. Reversal of Enantioselectivity Approach to BINOLs via Single and Dual 2-Naphthol Activation Modes. *Org. Lett.* **2017**, *19*, 3867–3870. (b) Sako, M.; Takeuchi, Y.; Tsujihara, T.; Kodera, J.; Kawano, T.; Takizawa, S.; Sasai, H. Efficient Enantioselective Synthesis of Oxahelicenes Using Redox/Acid Cooperative Catalysts. *J. Am. Chem. Soc.* **2016**, *138*, 11481–11484. (c) Takizawa, S.; Gröger, H.; Sasai, H. Vanadium in Asymmetric Synthesis: Emerging Concepts in Catalyst Design and Applications. *Chem. Eur. J.* **2015**, *21*, 8992–8997.

(11) Halogenated BINOL catalysts exhibit better catalytic activity and asymmetric induction than unsubstitued BINOLs, see (a) Huang, J.; Wei, S.; Wang, L.; Zhang, C.; Li, S.; Liu, P.; Du, X.; Wang, Q. Highly Enantioselective Catalytic Methyl Propiolate Addition to both Aromatic and Aliphatic Aldehydes. *Tetrahedron: Asymmetry* **2016**, *27*, 428–435. (b) Gou, S.; Ye, Z.; Shi, L.; Qing, D.; Zhang, W.; Wang, Y. Copper-catalyzed Asymmetric 1,4-Conjugate Addition of Dialkylzinc to Enones. *Appl. Organometal. Chem.* **2010**, *24*, 517–522. (c) Hashimoto, T.; Omote, M.; Hato, Y.; Kano, T.; Maruoka, K. Asymmetric 1,3-Dipolar Cycloadditions of *N*-Benzyl and *N*-Diphenylmethyl Nitrones and α,β-Unsaturated Aldehydes Catalyzed by Bis-Titanium Chiral Lewis Acids. *Chem. Asian. J.* **2008**, *3*, 407–412. (d) Bao, H.; Zhou, J.; Wang, Z.; Guo, Y.; You, T.; Ding, K. Insight into the Mechanism of the Asymmetric Ring-Opening Aminolysis of 4,4-Dimethyl-3,5,8-trioxabicyclo[5.1.0]octane Catalyzed by Titanium/BINOLate/Water System: Evidence for the Ti(BINOLate)$_2$-Bearing Active Catalyst Entities and the Role of Water. *J. Am. Chem. Soc.* **2008**, *130*, 10116–10127. (e) Chen, Z.; Morimoto, H.; Matsunaga, S.; Shibasaki, M. Catalytic Asymmetric Epoxidation of α-Methyl α,β-Unsaturated Anilides as Ester Surrogates. *Synlett* **2006**, 3529–3532.

(12) El-Deeb, I. Y.; Funakoshi, T.; Shimomoto, Y.; Matsubara, R.; Hayashi, M. Dehydrogenative Formation of Resorcinol Derivatives Using Pd/C–Ethylene Catalytic System. *J. Org. Chem.* **2017**, *82*, 2630–2640.

(13) Uchida, K.; Yoshida, S.; Hosoya, T. Controlled Generation of 3-Trifluoxyarynes. *Synthesis* **2016**, *48*, 4099–4109.

(14) Dol, G. C.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. Synthesis of 5-Substituted Resorcinol Derivatives via Cross-Coupling Reactions. *Eur. J. Org. Chem.* **1998**, 359–364.

(15) Percec, V.; Holerca, M. N.; Nummelin, S.; Morrison, J. J.; Glodde, M.; Smidrkal, J.; Peterca, M.; Rosen, B. M.; Uchida, S.; Balagurusamy, V. S.; Sienkowska, M. J.; Heiney, P. A. Exploring and Expanding the Structural Diversity of Self-Assembling Dendrons through Combinations of AB, Constitutional Isomeric AB$_2$, and AB$_3$ Biphenyl-4-Methyl Ether Building Blocks. *Chem. Eur. J.* **2006**, *12*, 6216–6241.

(16) Li, L.; Qiu, D.; Shi, J.; Li, Y. Vicinal Diamination of Arenes with Domino Aryne Precursors. *Org. Lett.* **2016**, *18*, 3726–3729.

(17) Deng, L.; Sundriyal, S.; Rubio, V.; Shi, Z.; Song, Y. Coordination Chemistry Based Approach to Lipophilic Inhibitors of 1-Deoxy-d-xylulose-5-phosphate Reductoisomerase. *J. Med. Chem.* **2009**, 52, 6539–6542.