Tandem Intramolecular Silylformylation and Silicon-Assisted Cross-Coupling Reactions. Synthesis of Geometrically Defined α,β -Unsaturated Aldehydes

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General Experimental

All reactions were performed in oven-dried (140 °C) or flame-dried glassware under an inert atmosphere of dry Ar or N₂. The following reaction solvents were distilled from the indicated drying agents: diethyl ether (Na, benzophenone), THF (Na, benzophenone), CH₂Cl₂ (P₂O₅), benzene (Na), toluene (Na), methanol (Mg(OMe)₂), triethylamine (CaH₂). Brine refers to a saturated aqueous solution of NaCl. All reaction temperatures correspond to internal temperatures measured by Teflon-coated thermocouples unless otherwise noted.

Commercial reagents were purified by distillation or recrystallization prior to use. In our experience, the source of fluoride and palladium had a significant effect on the success of the coupling reactions. A 1.0 M solution of tetrabutylammonium fluoride in THF was prepared from solid tetrabutylammonium fluoride trihydrate (TBAF•3H₂O, Fluka) and distilled THF in a volumetric flask and was stored in a Schlenk bottle. Palladium bis(dibenzylideneacetone) (Pd(dba)₂) was purchased from Jansen and used without purification. Tris(dibenzylideneacetone)dipalladium chloroform (Pd₂(dba)₃•CHCl₃) was prepared by recrystallization of (Pd(dba)₂) from CHCl₃.¹ -Allylpalladium chloride dimer (APC, [allylPdCl]₂) was purchased from ACROS and used without purification.

Analytical thin-layer chromatography was performed on Merck silica or aluminum oxide, basic gel plates with QF-254 indicator. Visualization was accomplished with UV light and/or Iodide or KMnO₄ solution. Diethyl ether was of reagent grade and used as received; other solvents for chromatography and filtration were technical grade and distilled from the indicated drying agents: hexane and pentane (CaCl₂); ethyl acetate (K₂CO₃). Column chromatography was performed using EM Science 230-400-mesh silica gel or Aldrich 150-mesh aluminum oxide, activated, basic, Brockmann I.

¹H NMR spectra and ¹³C NMR spectra were recorded on 500 MHz, ¹H (126 MHz, ¹³C) spectrometers. Spectra are referenced to residual chloroform (7.26 ppm, ¹H; 77.0 ppm, ¹³C) and residual benzene (7.16 ppm, ¹H; 128.0 ppm, ¹³C). Chemical shifts are reported in ppm (); multiplicities are indicated by s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet) and br (broad). Coupling constants, *J*, are reported in Hertz. All ¹³C NMR and most ¹H NMR assignments are corroborated by 2-D experiments (HETCOR and COSY). Spectra available on request from denmark@scs.uiuc.edu.

Mass spectroscopy was performed by the University of Illinois Mass Spectrometer Center. Electron impact (EI) spectra were performed at 70 eV and chemical ionization (CI) spectra were obtained using methane as the carrier gas. Data are reported in the form of *m/z* (intensity relative to base peak = 100). Infrared spectra (IR) peaks are reported in cm⁻¹ with indicated relative intensities: s (strong, 67-100%); m (medium, 34-66%); w (weak, 0-33%). Elemental analyses were performed by the University of Illinois Microanalytical Service

Laboratory. Analytical high-pressure liquid chromatography (HPLC) was performed on a chromatograph with a built-in photometric detector ($\lambda = 254$ nm). Analytical capillary gas chromatography (GC) was performed using a gas chromatograph fitted with a flame ionization detector (H_2 carrier gas, 1 mL/min). The following columns were used: HP-5 50-m cross-linked 5%-phenyl methyl silicone gum phase or Ultra-2 50-m cross-linked 5%-Phenyl methyl silicone gum phase. The detector temperature was 300 °C. Both for HPLC and GC, retention times (t_R) and integrated ratios were obtained from reporting integrators. Bulb-to-bulb distillations were performed on a Kugelrohr; boiling points (bp) corresponding to uncorrected air-bath temperatures (ABT). Melting points (mp) were determined in sealed tubes and are corrected.

Literature Preparations

The following compounds were prepared by literature methods: diisopropyl-(3-pentynyloxy)silane (**2b**),² $[\text{Rh}(\text{CN-}t\text{-Bu})_4][\text{Co}(\text{CO})_4]$ (**6**).³

Experimental Procedures.

General Procedure for Preparation of Alkynylsilanes.

To a solution of alkynyl alcohol (1.0 equiv) and triethylamine (1.2 equiv) in hexane (20 mL/15.55 mmol of alkynyl alcohol) was added dropwise chloroisopropylsilane (1.1 equiv) at 0°C over 20 min. After stirring for 10 min at 0°C, the resulting white suspension was filtered through a glass fritte and filtrate was passed through short silica pad (3 g). The solvent was removed under reduced pressure to give the crude product. Kugelrohr distillation gave desired alkynyl silane.

Preparation of Diisopropyl-(3-butynyloxy)silane (**2a**)

Following the General Procedure, 3-butyn-1-ol (**1a**) (1.09 g, 15.55 mmol) was combined with chloroisopropylsilane (3.3 mL, 17.1 mmol, 1.1 equiv) in hexane (20 mL) in the presence of triethylamine (2.8 mL, 18.66 mmol, 1.2 equiv). The alkynylsilane **2a** (2.74 g, 96%) was obtained as a colorless oil. An analytical sample was obtained by further Kugelrohr distillation.

Data for **2a**:

bp: 100 °C (4.2 mmHg, ABT)

¹H NMR: (500 MHz, CDCl₃)

4.15 (t, *J* = 1.7, 1 H, HSi), 3.82 (t, *J* = 7.1, 2 H, H₂C(1)), 2.44 (td, *J* = 7.1, 2.8, 2 H, H₂C(2)), 1.97 (t, *J* = 2.8, 1 H, HC(4)), 1.08-0.95 (m, 14 H, HC(1'-3'))

¹³C NMR: (126 MHz, CDCl₃)

81.29 (C(3)), 69.38 (C(4)), 64.00 (C(1)), 22.55 (C(2)), 17.30 (2 x C(1')) 17.21 (2 x C(3')), 12.31 (C(2'))

IR: (CHCl₃)

3309 (m, HC(4)), 2947 (m), 2893 (w), 2866 (m), 2098 (m, SiH), 1464 (m), 1385 (w), 1217 (w), 1103 (m), 1061 (w), 1001 (m), 918 (w), 881 (m), 839 (m)

MS: (EI, 70 eV)

183 (M^+-1 , 1.34), 145 (11), 142 (18), 141 (100), 113 (59), 111 (34), 103 (25), 99 (63), 97 (14), 87 (11), 85 (19), 83 (56), 75 (16), 73 (14), 71 (13), 69 (22), 61 (30), 59 (34)

TLC: R_f 0.54 (hexane/EtOAc/Et₃N, 30/1/0.5) [silica gel, PMA]

GC: t_R 6.50 min (U-2, 150 °C, 15 psi)

Analysis: C₁₀H₂₀OSi (184.35)

Calcd: C, 65.15; H, 10.94%

Found: C, 65.08; H, 11.14%

Preparation of Diisopropyl-(4-pentynyloxy)silane (**2c**)

Following the General Procedure, 4-pentyn-1-ol (**1c**) (654.0 mg, 7.78 mmol) was combined with chloroisopropylsilane (1.5 mL, 8.55 mmol, 1.1 equiv) in hexane (20 mL) in the presence of triethylamine (1.4 mL, 9.33 mmol, 1.2 equiv). The alkynylsilane **2c** (1.47 g, 96%) was obtained as a colorless oil. An analytical sample was obtained by further Kugelrohr distillation.

Data for **2c**:

bp: 100-110 °C (3.0 mmHg, ABT)

¹H NMR: (500 MHz, CDCl₃)

4.14 (t, J = 1.7, 1 H, HSi), 3.78 (t, J = 6.0, 2 H, H₂C(1)), 2.44 (td, J = 7.1, 2.6, 2 H, H₂C(3)), 1.93 (t, J = 2.6, 1 H, HC(5)), 1.76 (tt, 2 H, J = 7.1, 6.0, 2 H, H₂C(2)), 1.08-0.94 (m, 14 H, HC(1'-3'))

¹³C NMR: (126 MHz, CDCl₃)

84.08 (C(4)), 68.29 (C(5)), 63.90 (C(1)), 31.32 (C(2)), 17.39 (2 x C(1')), 17.24 (2 x C(3')), 14.79 (C(3)), 12.34 (C(2'))

IR: (CHCl₃)

3307 (m, HC(5)), 3014 (w), 2947 (s), 2893 (m), 2866 (s), 2094 (m, SiH), 1462 (m), 1387 (w), 1230 (w), 1103 (s), 1070 (m), 1001 (m), 978 (w), 881 (m), 835 (s), 800 (m)

MS: (EI, 70 eV)

197 (M⁺-1, 0.6), 156 (12), 155 (62), 127 (42), 114 (16), 113 (100), 111 (13), 101 (17), 99 (13), 97 (18), 87 (25), 85 (14), 83 (12), 82 (11), 75 (12), 73 (11), 69 (15), 67 (16), 61 (57), 59 (18)

TLC: *R_f* 0.63 (hexane/EtOAc, 10/1) [silica gel, PMA]

GC: *t_R* 7.99 min (U-2, 150 °C, 15 psi)

Analysis: C₁₁H₂₂OSi (198.38)

Calcd: C, 66.60; H, 11.18%

Found: C, 66.34; H, 11.40%

General Procedure for Silylformylation of Alkynylsilanes

Toluene was pre-saturated with carbon monoxide prior to use with a gas dispersion tube. In a 100-mL, 2-necked round-bottomed flask was charged with [Rh(CN*t*-Bu)₄][Co(CO)₄] (**6**) (0.005 equiv) under a nitrogen atmosphere. Carbon monoxide was introduced into the flask to replace the nitrogen. The catalyst was dissolved with toluene (30 mL/6.67 mmol of alkynylsilane, pre-saturated with CO) under carbon monoxide atmosphere. To the solution of the catalyst was added via cannula a solution of alkynylsilane **2** (1.0 equiv) in toluene (10 mL/6.67 mmol of alkynylsilane, pre-saturated with CO). The flask was placed in a 300 mL stainless steel autoclave. The autoclave was evacuated and then carbon monoxide was introduced. The reaction was run at 70 °C and 150~750 psi of carbon monoxide. After stirring the mixture for 9~20 h, the solvent was removed under reduced pressure. The obtained residue was dissolved into 50 mL of hexane/EtOAc, 3/1 and then the solution was filtered through short silica pad (3 g). The solvent was removed again to give a crude material. Kugelrohr distillation of the residue gave the desired product **3** containing hydrosilane impurities. This distilled material was purified by column chromatography (10 g of Florisil was charged on a top of 70 g of silica gel using hexane/EtOAc as eluent) to give cyclic silyl ether **3** as a colorless oil.

Preparation of (Z)-2-(2,2-Diisopropyl-1-oxa-2-silacyclopent-3-ylidene)acetaldehyde (3a)

The silylformylation of **2a** (1.23 g, 6.67 mmol) was conducted in toluene (40 mL) in the presence of **6** (20 mg, 0.033 mmol, 0.005 equiv) at 70°C under carbon monoxide atmosphere (150 psi) for 9 h. Kugelrohr distillation of the crude material gave **3a** (1.02 g, 72%, containing hydrosilane) as a light yellow oil. Further purification by chromatography gave **3a** (965.1 g, 68%) as a colorless oil, diisopropyldisiloxane (**11**) (13.0 mg) as a colorless oil and unknown hydrosilane (33 mg) as a colorless oil. An analytical sample was obtained by further distillation of the chromatographed material using a diffusion pump.

Data for 3a:

bp: 70-80 °C (4.0 x 10⁻⁴ mmHg, ABT)

¹H NMR: (500 MHz, CDCl₃)

9.46 (d, *J* = 6.4, 1 H, CHO), 6.82 (dt, *J* = 6.4, 2.0, 1 H, HC(2)), 4.06 (t, *J* = 6.4, 2 H, H₂C(5')), 2.81 (td, *J* = 6.4, 2.0, 2 H, H₂C(4')), 1.23 (sept, *J* = 7.5, 2 H, HC(2')), 1.09 (d, *J* = 7.5, 6 H, HC(1')), 0.98 (d, *J* = 7.5, 6 H, HC(3'))

¹³C NMR: (126 MHz, CDCl₃)

192.22 (CHO), 170.90 (C(3')), 137.34 (C(2)), 65.63 (C(5')), 39.24 (C(4')), 17.52 (2 x C(1'')), 14.79 (2 x C(3'')), 12.34 (2 x C(2''))

IR: (CHCl₃)

3008 (w), 2949 (m), 2868 (m), 2731 (w), 1682 (s, CHO), 1591 (w), 1464 (w), 1414 (w), 1387 (w), 1360 (w), 1221 (w), 1146 (m), 1049 (m), 1030 (m), 995 (w), 926 (w), 881 (m)

MS: (EI, 70 eV)

212 (M⁺, 5), 170 (16), 169 (100), 141 (17), 139 (63), 127 (31), 111 (27),

TLC: *R_f* 0.38 (hexane/EtOAc, 7/1) [silica gel, PMA]

HPLC: *t_R* 7.81 min (SUPELCOSIL LC-SI, hexane/EtOAc, 95/5; 1.0 mL/min)

Analysis: C₁₁H₂₀O₂Si (212.36)

Calcd: C, 62.21; H, 9.49%

Found: C, 62.09; H, 9.75%

Data for 11:

4.26 (t, $J = 1.7$, 2 H, 2 x SiH), 1.03 (d, $J = 7.5$, 12 H, 4 x H₃C), 1.01 (d, $J = 7.5$, 12 H, 4 x H₃C), 0.98-0.86 (m, 4 H, 4 x HC)

Preparation of (Z)-2-(2,2-Diisopropyl-1-oxa-2-silacyclopent-3-ylidene)propanal (3b)

The silylformylation of **2b** (1.32 g, 6.67 mmol) in toluene (40 mL) in the presence of **6** (20 mg, 0.033 mmol, 0.005 equiv) at 70°C under carbon monoxide atmosphere (150 psi) for 9 h gave **3b** (1.08 g, 72%) as a colorless oil.

Data for 3b:

bp: 70-80 °C (2.0 x 10⁻⁴ mmHg, ABT)

¹H NMR: (500 MHz, CDCl₃)

9.38 (d, $J = 0.5$, 1 H, CHO), 4.10 (td, $J = 6.6$, 0.6, 2 H, H₂C(5')), 2.76 (tqd, $J = 6.6$, 1.5, 0.5, 2 H, H₂C(4')), 1.94 (t, $J = 1.5$, 3 H, H₃C(3)), 1.19 (sept, $J = 7.5$, 2 H, 2 x HC(2'')), 1.06 (d, $J = 7.5$, 6 H, HC(1'')), 0.96 (d, $J = 7.5$, 6 H, HC(3''))

¹³C NMR: (126 MHz, CDCl₃)

212.13 (CHO), 165.57 (C(3')), 144.80 (C(2)), 65.55 (C(5')), 36.28 (C(4')), 17.62 (2 x C(1'')), 17.26 (2 x C(3'')), 13.57 (2 x C(2'')), 12.93 (C(3))

IR: (CHCl₃)

3006 (w), 2947 (m), 2868 (m), 2721 (w), 1676 (s, CHO), 1597 (w), 1464 (w), 1373 (w), 1265 (w), 1236 (w), 1076 (w), 1038 (m), 993 (w), 931 (w), 881 (w)

MS: (EI, 70 eV)

226 (M⁺, 3.6), 184 (17), 183 (100), 154 (12), 153 (73), 141 (27), 125 (44), 79 (14)

HRMS: calcd for C₁₂H₂₂O₂Si (M⁺): 226.1389; found: 226.1391

TLC: R_f 0.38 (hexane/EtOAc, 7/1) [silica gel, PMA]

HPLC: t_R 6.94 min (SUPELCOSIL LC-SI, hexane/EtOAc, 95/5; 1.0 mL/min)

Preparation of (Z)-2-(2,2-Diisopropyl-1-oxa-2-silacyclohex-3-ylidene)acetaldehyde (3c**) and 4-Formyl-2,2-diisopropyl-1-oxa-2-silacyclohept-3-ene (**4c**)**

The silylformylation of **2c** (661.6 mg) in toluene (20 mL) in the presence of **6** (10 mg, 0.016 mmol, 0.005 equiv) at 70°C under carbon monoxide atmosphere (750 psi) for 20 h gave **3c** (137.5 mg, 18%) as a colorless oil and **4c** (13.0 mg, 2%) as a colorless oil.

Data for **3c**:

bp: 80-85 °C (4.0 x 10⁻⁴ mmHg, ABT)

¹H NMR: (500 MHz, CDCl₃)

9.58 (d, J = 8.1, 1 H, CHO), 6.48 (dt, J = 8.1, 1.7, 1 H, HC(2)), 4.07 (t, J = 5.4, 2 H, H₂C(6')), 2.71-2.65 (m, 2 H, H₂C(4')), 1.84-1.78 (m, 2 H, H₂C(5')), 1.17-0.93 (d, J = 7.5, 14 H, HC(1''-3''))

¹³C NMR: (126 MHz, CDCl₃)

192.50 (CHO), 169.07 (C(3')), 140.85 (C(2)), 65.81 (C(6')), 39.15 (C(4')), 28.88 (C(5')), 17.40 (2 x C(1'')), 17.18 (2 x C(3'')), 14.72 (2 x C(2''))

IR: (CHCl₃)

3010 (w), 2947 (m), 2868 (m), 2746 (w), 1678 (s, CHO), 1464 (w), 1232 (w), 1151 (w), 1105 (s), 993 (m), 881 (m)

MS: (EI, 70 eV)

227 ($M^+ + 1$, 81), 200 (11), 199 (65), 185 (15), 184 (18), 183 (100), 171 (22), 159 (12), 157 (19), 155 (42), 153 (37), 143 (10), 141 (22), 139 (39), 133 (12), 131 (30), 129 (20), 127 (46), 125 (21), 115 (10), 113 (31), 112 (12), 111 (34), 105 (38), 103 (40), 101 (21), 99 (18), 95 (23), 89 (14), 87 (14), 85 (16), 83 (13), 77 (99), 75 (46), 71 (16), 67 (23), 63 (15), 61 (46), 59 (11), 58 (16), 57 (12), 55 (16)

HRMS: calcd for $C_{12}H_{23}O_2Si$ ($M^+ + 1$): 227.1467; found: 227.1469

TLC: R_f 0.41 (hexane/EtOAc, 7/1) [silica gel, PMA]

HPLC: t_R 5.38 min (SUPELCOSIL LC-SI, hexane/EtOAc, 95/5; 1.0 mL/min)

Data for 4c:

bp: 60-65 °C (4.0×10^{-4} mmHg, ABT)

1H NMR: (500 MHz, $CDCl_3$)

9.48 (s, 1 H, CHO), 6.78 (t, $J = 0.86$, 1 H, HC(3)), 4.01-3.97 (m, 2 H, $H_2C(7)$), 2.63-2.59 (m, 2 H, $H_2C(5)$), 1.89-1.83 (m, 2 H, $H_2C(6)$), 1.15-0.98 (m, 14 H, HC(1'-3'))

^{13}C NMR: (126 MHz, $CDCl_3$)

194.72 (CHO), 158.91 (C(4)), 149.32 (C(3)), 65.94 (C(7)), 30.38 (C(6)), 25.32 (C(5)), 17.58 (2 x C(1')), 17.32 (2 x C(3')), 13.17 (2 x C(2'))

IR: ($CHCl_3$)

2945 (s), 2893 (w), 2868 (m), 1685 (s, CHO), 1464 (w), 1435 (w), 1365 (w), 1242 (w), 1213 (w), 1126 (m), 1051 (w), 995 (m), 960 (w), 883 (m), 825 (w)

MS: (CI)

227 (23), 226 (M^+ , 2), 185 (14), 184 (17), 183 (100), 131 (11), 59 (12)

HRMS: calcd for $C_{12}H_{23}O_2Si$ ($M^+ + 1$): 227.1467; found: 227.1462

TLC: R_f 0.44 (hexane/EtOAc, 7/1) [silica gel, PMA]

HPLC: t_R 4.51 min (SUPELCOSIL LC-SI, hexane/EtOAc, 95/5; 1.0 mL/min)

Analysis: $C_{11}H_{20}O_2Si$ (212.36)

Calcd: C, 63.66; H, 9.80%

Found: C, 63.34; H, 9.80%

Silicon Assisted Cross-coupling Reaction with CsF (Table 2 entry 6)

A 25-ml round-bottomed flask was charged with the cyclic silyl ether **3a** (Kugelrohr distilled material, 64.6 mg, 0.304 mmol, 1.2 equiv). A solution of 4-iodoacetophenone **7a** (62.3 mg, 0.253 mmol) in DMF (0.5 mL) and CuI (2.4 mg, 0.013 mmol, 0.05 equiv) was added to the reaction mixture successively under an argon atmosphere. The flask was carefully evacuated and argon was introduced into the flask again. [AllylPdCl]₂ (2.4 mg, 0.0063 mmol, 0.025 equiv) was added to the flask. The addition of [allylPdCl]₂ to the mixture caused the formation of a black precipitate immediately. After stirring the mixture for 7 min, CsF (76.9 mg, 0.506 mmol, 2.0 equiv) was added to the suspension and the mixture was stirred for 30 min at room temperature. The reaction mixture was filtered through short silica pad (3 g) and silica pad was washed with EtOAc (30 mL). The filtrate was washed with water (50 mL) and the aqueous layer was extracted with EtOAc (2 X 30 mL). The combined organic layers were washed with brine (30 mL), dried (Na₂SO₄). After evaporation of the solvent under reduced pressure, the residue was purified by silica gel column chromatography to afford the coupling product **8a**, homocoupling product **9a** and **10a** in 55%, 13% and 9% yields respectively.

Preparation of 2-Hydroxy-4-(4-acetylphenyl)-3,6-dihydro-2H-pyran (10a)

To the solution of **8a** (220 mg, 1.01 mmol) in DMF (3 mL) was added CsF (306.2 mg, 2.02 mmol, 2.0 equiv) at room temperature. After stirring the mixture for 1 h, water (30 mL) was added and the mixture was extracted with EtOAc (3 X 30 mL). The combined organic layers were washed with brine (30 mL), dried with Na₂SO₄. The solvent was removed under reduced pressure and the residue was purified by a column chromatography (silica gel, 35 g; hexane/EtOAc, 1/1) to give **10a** (176.0 mg, 80%) as colorless prisms. An analytical sample was obtained by recrystallization from EtOAc.

Data for 10a:

mp: 134-136°C (EtOAc)

¹H NMR: (500 MHz, CDCl₃)

7.93 (br d, *J* = 8.8, 2 H, 2 x HC(3')), 7.47 (br d, *J* = 8.8, 2 H, 2 x H₂C(2')), 6.28 (tt, *J* = 3.0, 1.5, 1 H, HC(5)), 5.37 (br t, *J* = 4.0, 1 H, HC(2)), 4.56 (dq, *J* = 17.4, 3.0, 1 H, HC(6)), 4.39 (dq, *J* = 17.4, 3.0, 1 H, HC(6)), 3.17 (br s, OH), 2.78 (br d, *J* = 16.7, 1 H, H₂C(3)), 2.60 (s, 3 H, H₃C(2'')), 2.54 (br d, *J* = 16.7, 1 H, H₃C(3)),

¹³C NMR: (126 MHz, CDCl₃)

197.68 (C(1'')), 144.17 (C(1')), 136.01 (C(4')), 130.93 (C(4)), 128.65 (C(3')), 124.87 (C(2')), 123.59 (C(5)), 91.69 (C(2)), 62.00 (C(6)), 32.83 (C(3)), 26.55 (C(2''))

IR: (CHCl₃)

3595 (w, OH), 3423 (w, OH), 3026 (w), 3012 (w), 2941 (w), 2866 (w), 1680 (s, Ac), 1604 (m), 1562 (w), 1409 (m), 1361 (m), 1311 (w), 1271 (s), 1242 (m), 1190 (w), 1108 (m), 1072 (m), 1024 (m), 958 (m), 889 (w), 848 (w)

MS: (EI, 70 eV)

218 (M^+ , 83), 206 (32), 203 (26), 200 (30), 199 (11), 189 (22), 185 (23), 178 (37), 175 (30), 159 (11), 158 (26), 157 (72), 131 (24), 130 (17), 129 (100), 128 (48), 127 (21), 116(12), 115 (34), 103 (10), 102 (13), 101 (11), 91 (14), 89 (10), 78 (10), 77 (26), 76 (13), 75 (14), 65 (11), 64 (12), 63 (13).

TLC: R_f 0.44 (EtOAc) [silica gel, PMA]

HPLC: t_R 5.70 min (SUPELCOSIL LC-SI, hexane/EtOAc, 70/30; 1.0 mL/min)

Analysis: $C_{13}H_{14}O_3$ (218.25)

Calcd: C, 71.54; H, 6.47%

Found: C, 71.47; H, 6.46%

Preparation of 5-Iodo-1-phenylsulfonyl-1*H*-indole (**7h**)

A solution of 5-iodoindole (241 mg, 0.994 mmol) in DMF (2 mL) was treated with NaH (59.7 mg, 1.49 mmol, 0.5 equiv, 60% suspension in mineral oil) at room temperature under a nitrogen atmosphere. To the suspension was added a solution of benzenesulfonyl chloride (210.7 mg, 1.193 mmol, 1.2 equiv) in DMF (1 mL). After stirring the mixture for 30 min, water (30 mL) was added and the mixture was extracted with EtOAc (3 X 30 mL). The combined organic layers were washed with brine (30 mL) and dried (Na_2SO_4). The solvent was removed under reduced pressure to give crude material (424.0 mg) as a colorless oil. Purification of the oil by column chromatography (silica gel, 35g; hexane/EtOAc, 3/1) gave **7h** (372.6 mg, 98%) as colorless crystals. An analytical sample was obtained by recrystallization from hexane.

Data for 7h:

mp: 84-85°C (hexane)

¹H NMR: (500 MHz, CDCl₃)

7.88 (d, *J* = 1.5, 1 H, HC(4)), 7.85 (br d, *J* = 7.5, 2 H, 2 x HC(2')), 7.76 (d, *J* = 8.8, 1 H, HC(7)), 7.58 (dd, *J* = 8.8, 1.7, 1 H, HC(6)), 7.56 (br t, *J* = 7.5, 1 H, HC(4')), 7.53 (d, *J* = 3.6, 1 H, HC(2)), 7.45 (br t, *J* = 7.5, 2 H, HC(3')), 6.59 (d, *J* = 3.6, 1 H, HC(3)),

¹³C NMR: (126 MHz, CDCl₃)

138.00 (aryl), 134.13 (aryl), 134.08 (C(4')), 133.15 (C(6)), 133.40 (aryl), 130.31 (C(4)), 129.39 (C(3')), 127.15 (C(2)), 126.74 (C(2')), 115.33 (C(7)), 108.21 (C(3)), 87.54 (aryl)

IR: (CHCl₃)

3145 (w), 3116 (w), 3068 (w), 3030 (w), 1730 (w), 1439 (w), 1377 (m), 1335 (w), 1284 (w), 1196 (m), 1173 (s), 1132 (s), 1093 (w), 993 (w), 804 (w)

MS: (EI, 70 eV)

383 (M⁺, 100), 243 (17), 242 (25), 141 (16), 115 (17), 77 (13)

TLC: *R_f* 0.31 (hexane/EtOAc, 4/1) [silica gel, PMA]

HPLC: *t_R* 5.56 min (SUPELCOSIL LC-SI, hexane/EtOAc, 85/15; 1.0 mL/min)

Analysis: C₁₄H₁₀INO₂S (383.21)

Calcd: C, 43.88; H, 2.63; N, 3.66; I, 33.12%

Found: C, 43.73; H, 2.42; N, 3.57; I, 33.12%

General Procedure for the Silicon Assisted Cross-coupling Reaction

A 25 mL-round-bottomed flask was charged with the cyclic silyl ether **3** (1.316 mmol, 1.3 equiv). To this solution was added a solution of methylhydrocyclosiloxane (**14**) (6.1 mg, 0.0253 mmol, 0.025 equiv) at room temperature under an argon atmosphere. A solution of aryl iodide **7** (1.012 mmol) in DMF (2 mL) and CuI (19.2 mg, 0.101 mmol, 0.1 equiv) was added to the reaction mixture successively. The flask was carefully evacuated and argon was introduced into the flask again. A solution of [allylPdCl]₂ (18.5 mg, 0.0506 mmol, 0.05 equiv) in DMF (5 mL) was added to the flask. The addition of [allylPdCl]₂ to the mixture caused the formation of a black precipitate immediately. After stirring for 7 min, KF•2H₂O (190.5 mg, 2.02 mmol, 2.0 equiv) was added to the suspension and the mixture was stirred for 2-7 h at room temperature.

After the reaction was complete, the reaction mixture was filtered through short silica pad (3 g) and the silica pad was washed with EtOAc (30 mL). The filtrate was washed with water (50 mL) and the aqueous layer was extracted with EtOAc (2 X 30 mL). The combined organic layers were washed with brine (30 mL) and dried (Na_2SO_4), filtered and the solvent was removed under reduced pressure. Purification of the residue by silica gel column chromatography as specified afforded the coupling product **8**.

Preparation of (2Z)-3-(4-Acetylphenyl)-5-hydroxy-2-pental (8a)

The coupling reaction of **3a** (279.5 mg, 1.32 mmol, 1.3 equiv with 4-iodoacetophenone (**7a**) (249.0 mg, 1.01 mmol) was complete in 2 h. Purification by column chromatography (silica gel, 35 g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded **8a** (200.5 mg, 91%) as yellow crystals and 4,4-diacetylbiphenyl (**9a**)⁴ (8.0 mg, 7%) as colorless crystals. An analytical sample of **8a** was obtained by a recrystallization from $\text{CH}_2\text{Cl}_2/\text{Et}_2\text{O}$.

Data for **8a**:

mp: 55-56°C ($\text{CH}_2\text{Cl}_2/\text{Et}_2\text{O}$)

¹H NMR: (500 MHz, CDCl_3)

9.43 (d, $J = 8.1$, 1 H, HC(1)), 8.01 (br d, $J = 8.3$, 2 H, 2 x HC(3')), 7.42 (br d, $J = 8.3$, 2 H, 2 x HC(2')), 6.22 (dt, $J = 8.1, 1.1$, 1 H, HC(6)), 3.75 (br t, $J = 6.2$, 2 H, $\text{H}_2\text{C}(5)$), 2.85 (td, $J = 6.2$, 2 H, $\text{H}_2\text{C}(4)$), 2.64 (s, 3 H, $\text{H}_3\text{C}(2')$), 1.60 (br s, 1 H, OH)

¹³C NMR: (126 MHz, CDCl_3)

197.34 (C(1'')), 192.54 (C(1)), 161.30 (C(3)), 141.96 (C(4' or 1')), 137.41 (C(4' or 1')), 130.53 (C(2)), 128.90 (2xC(2')), 128.49 (2xC(3')), 59.94 (C(5)), 42.20 (C(4)), 26.65 (C(2''))

IR: (CHCl_3)

3622 (w, OH), 3026 (w), 3014 (w), 1680 (s, CHO and Ac), 1604 (m), 1400 (w), 1360 (w), 1267 (m), 1132 (w), 1041 (w), 847 (w), 752 (w)

MS: (EI, 70 eV)

218 (M^+ , 100), 203 (42), 200 (25), 190 (36), 187 (17), 185 (35), 175 (41), 173 (40), 158 (20), 157 (36), 145 (45), 129 (43), 128 (27), 115 (51), 102 (11), 91 (19), 77 (16), 63 (13)

TLC: R_f 0.35 (EtOAc) [silica gel, PMA]

HPLC: t_R 8.50 min (SUPELCOSIL LC-SI, EtOAc/hexane, 70/30; 1.0 mL/min)

Analysis: $C_{13}H_{14}O_3$ (218.25)
 Calcd: C, 71.54; H, 6.47%
 Found: C, 71.18; H, 6.46%

Data for 9a:

1H NMR: (500 MHz, $CDCl_3$)
 8.04 (br d, $J = 8.6$, 4 H, HC(3, 3', 5, 5')), 7.72 (br d, $J = 8.6$, 4 H, HC(2, 2', 6, 6')), 2.65 (s, 6 H, 2 x H_3C)

Preparation of (2Z)-3-(4-Ethoxycarbonylphenyl)-5-hydroxy-2-pentalenal (8b)

The coupling reaction of **3a** (279.5 mg, 1.32 mmol, 1.3 equiv) with ethyl 4-iodobenzoate (**7b**) (279.4 mg, 1.01 mmol) was complete in 2 h. Purification by column chromatography (silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded **8b** (231.1 mg, 92%) as a light yellow oil and 4,4-bis(ethoxycarbonyl)biphenyl (**9b**)⁵ (7.9 mg, 5%) as yellow crystals.

Data for 8b:

1H NMR: (500 MHz, $CDCl_3$)
 9.43 (dd, $J = 7.9, 0.6$, 1 H, HC(1)), 8.10 (br d, $J = 8.1$, 2 H, 2 x HC(3')), 7.38 (br d, $J = 8.1$, 2 H, 2 x HC(2')), 6.22 (dt, $J = 7.9, 1.1$, 1 H, HC(2)), 4.41 (q, $J = 7.3$, 2 H, $H_2C(2'')$), 3.75 (t, $J = 6.2$, 2 H, $H_2C(5)$), 2.85 (br t, $J = 6.2$, 2 H, $H_2C(4)$), 1.47 (br s, 1 H, OH), 1.41 (t, $J = 7.3$, 3 H, $H_3C(3'')$)

¹³C NMR: (126 MHz, CDCl₃)
192.61 (C(1)), 165.89 (C(3 or 1'')), 161.36 (C(3 or 1'')), 141.65 (C(1')),
131.18(C(4')), 130.49 (C(2)), 129.75 (2xC(3')), 128.61 (2xC(2')), 61.30 (C(2)),
59.97 (C(5)), 42.25 (C(4)), 14.27 (C(3'))

IR: (CHCl₃)
3620 (w, OH), 3450 (w, OH), 3028 (w), 3014 (w), 1714 (s, CO₂Et), 1672 (s,
CHO), 1606 (m), 1398 (w), 1369 (w), 1279 (s), 1227 (w), 1180 (w), 1107 (m),
1020 (m), 864 (m)

MS: (EI, 70 eV)
249 (33), 248 (M⁺, 40), 231 (45), 220 (39), 219 (100), 204 (10), 203 (65), 201
(20), 189 (21), 185 (15), 175 (56), 158 (15), 157 (51), 147 (23), 145 (42), 144
(17), 131 (22), 130 (13), 129 (49), 128 (24), 127 (10), 117 (25), 116 (19), 115
(72), 105 (10), 91 (23), 91 (23), 77 (14)

TLC: *R_f* 0.18 (EtOAc) [silica gel, PMA]

HPLC: *t_R* 6.17 min (SUPELCOSIL LC-SI, EtOAc/hexane, 70/30; 1.0 mL/min)

Analysis: C₁₄H₁₆NO₄ (248.27)
Calcd: C, 67.73; H, 6.50%
Found: C, 67.44; H, 6.44%

Data for 9b:

¹H NMR: (400 MHz, CDCl₃)
8.14 (br d, *J* = 8.5, 4 H, HC(3, 3', 5, 5')), 7.69 (br d, *J* = 8.5, 4 H, HC(2, 2', 6, 6')),
4.41 (q, *J* = 7.1, 4 H, 2 x H₂C), 1.42 (t, *J* = 7.1, 6 H, 2 x H₃C)

Preparation of (2Z)-3-(4-Nitrophenyl)-5-hydroxy-2-pentalenal (8c)

The coupling reaction of **3a** (279.5 mg, 1.32 mmol, 1.3 equiv) with 4-iodonitrobenzene (**7c**) (252.0 mg, 1.01 mmol) was complete in 1 h. $^1\text{H-NMR}$ analysis of the crude mixture showed 13% of the homocoupling product **9c**. Purification by column chromatography (silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded **8c** (185.7 mg, 83%) as brown crystals and 4,4-dinitrobiphenyl (**9c**)⁶ (15.6 mg, 13%) as colorless crystals. An analytical sample of **8c** was obtained by a recrystallization from $\text{CH}_2\text{Cl}_2/\text{Et}_2\text{O}$.

Data for 8c:

mp: 60–61°C ($\text{CH}_2\text{Cl}_2/\text{Et}_2\text{O}$)

$^1\text{H NMR}$: (500 MHz, CDCl_3)

9.41 (d, $J = 8.1$, 1 H, HC(1)), 8.30 (br d, $J = 8.8$, 2 H, 2 x HC(3')), 7.51 (br d, $J = 8.8$, 2 H, 2 x HC(2')), 6.27 (dt, $J = 8.1$, 1.1, 1 H, HC(2)), 3.77 (t, $J = 6.2$, 2 H, $\text{H}_2\text{C}(5)$), 2.85 (td, $J = 6.4$, 1.1, 2 H, $\text{H}_2\text{C}(4)$), 1.62 (br s, 1 H, OH),

$^{13}\text{C NMR}$: (126 MHz, CDCl_3)

191.83 (C(1)), 159.99 (C(3)), 148.12 (C(4')), 143.95 (C(1')), 131.01 (C(2)), 129.56 (2xC(2')), 123.79 (2xC(3')), 59.74 (C(5)), 42.05 (C(4))

IR: (CHCl_3)

3624 (w, OH), 3450 (w, OH), 3024 (w), 2953 (w), 2953 (w), 2852 (w), 1678 (s, CHO), 1597 (m), 1525 (s, NO_2), 1350 (s, NO_2), 1130 (w), 1039 (w), 858 (m)

MS: (EI, 70 eV)

221 (M^+ , 15), 204 (40), 203 (23), 202 (21), 193 (37), 186 (20), 178 (29), 176 (50), 175 (13), 174 (73), 163 (27), 158 (13), 157 (31), 156 (34), 151 (11), 146 (11), 145 (16), 144 (48), 131 (11), 130 (17), 129 (36), 128 (56), 127 (16), 117 (19), 116 (50), 115 (100), 103 (14), 102 (20), 91 (26), 90 (21), 78 (11), 77 (26), 76 (14), 75 (16), 74 (10), 65 (15), 63 (23)

TLC: R_f 0.31 (EtOAc) [silica gel, PMA]

HPLC: t_R 8.02 min (SUPELCOSIL LC-SI, EtOAc/hexane, 70/30; 1.0 mL/min)

Analysis: $C_{11}H_{11}NO_4$ (221.21)

Calcd: C, 59.73; H, 5.01; N, 6.33%

Found: C, 59.45; H, 4.91; N, 6.29%

Data for 9c:

¹H NMR: (500 MHz, $CDCl_3$)

8.36 (br d, $J = 8.8$, 4 H, HC(3, 3', 5, 5')), 7.79 (br d, $J = 8.8$, 4 H, HC(2, 2', 6, 6'))

Preparation of (2Z)-3-Phenyl-5-hydroxy-2-pental (8d)

The coupling reaction of **3a** (279.5 mg, 1.32 mmol, 1.3 equiv) with iodobenzene (**7d**) (206.5 mg, 1.01 mmol) was complete in 2 h. ¹H-NMR analysis of the crude mixture showed 4% of the homocoupling product **9d**.^{4c} Purification by column chromatography (silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded **8d** (163.0 mg, 93%) as a colorless oil.

Data for 8d:

¹H NMR: (500 MHz, $CDCl_3$)

9.46 (dd, $J = 7.9, 0.9$, 1 H, HC(1)), 7.45-7.40 (m, 3 H, aryl), 7.33-7.28 (m, 2 H, aryl), 6.18 (dt, $J = 7.9, 1.1$, 1 H, HC(2)), 3.75 (td, $J = 6.4, 0.6$, 2 H, $H_2C(5)$), 2.85 (br t, $J = 6.4$, 2 H, $H_2C(4)$), 1.48 (br s, 1 H, OH)

¹³C NMR: (126 MHz, $CDCl_3$)

193.48 (C(1)), 162.89 (C(2)), 137.08 (C(3)), 129.86 (C(4')), 129.21 (C(1')), 128.61 (2xC(2' or 3')), 128.52 (2xC(2' or 3')), 60.08 (C(5)), 42.46 (C(4))

IR: ($CHCl_3$)

3622 (w, OH), 3442 (w, OH), 3026 (w), 3012 (w), 2958 (w), 2888 (w), 1668 (s, CHO), 1616 (w), 1396 (w), 1230 (w), 1200 (w), 1132 (w), 1038 (m)

MS: (EI, 70 eV)

176 (M^+ , 12), 175 (11), 158 (21), 148 (29), 145 (34), 133 (15), 132 (11), 131 (85), 130 (16), 129 (37), 128 (11), 118 (10), 117 (27), 116 (13), 115 (41), 103 (41), 91 (21), 88 (13), 86 (65), 84 (100), 78 (16), 77 (19)

HRMS: calcd for $C_{11}H_{12}O_2$ (M^+): 176.0837; found: 176.0840

TLC: R_f 0.46 (EtOAc) [silica gel, PMA]

HPLC: t_R 5.71 min (SUPELCOSIL LC-SI, EtOAc/hexane, 70/30; 1.0 mL/min)

Preparation of (2Z)-3-(4-Methoxyphenyl)-5-hydroxy-2-pental (8e)

The coupling reaction of **3a** (279.5 mg, 1.32 mmol, 1.3 equiv) with 4-iodoanisole (**7e**) (236.8 mg, 1.01 mmol) was complete in 2 h. Purification by column chromatography (silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded **8e** (181.2 mg, 87%) as a yellow oil and 4,4-dimethoxybiphenyl (**9e**)^{4b,c} (5.7 mg, 5%) as yellow crystals. An analytical sample of **8e** was obtained by Kugelrohr distillation by diffusion pump.

Data for 8e:

bp: 130-135°C (7x10⁻⁵ mmHg, ABT)

¹H NMR: (500 MHz, CDCl₃)

9.49 (d, J = 8.1, 1 H, HC(1)), 7.25 (br d, J = 8.8, 2 H, 2 x HC(2')), 6.94 (br d, J = 8.8, 2 H, HC(3')), 6.15 (dt, J = 8.0, 1.1, 1 H, HC(2)), 3.85 (s, 3 H, OMe), 3.73 (t, J = 6.2, 2 H, H₂C(5)), 2.84 (td, J = 6.2, 1.1, 2 H, H₂C(4)), 1.45 (br s, 1 H, OH),

¹³C NMR: (126 MHz, CDCl₃)

193.46 (C(1)), 162.15 (C(3)), 160.65 (C(4')), 130.33 (2 x C(2')), 129.53 (C(2)), 129.21 (C(1')), 114.00 (2 x C(3')), 60.54 (C(5)), 55.38 (OMe), 42.33 (C(4))

IR: (CHCl_3)

3622 (w, OH), 3477 (w, OH), 3012 (w), 2960 (w), 2840 (w), 1666 (s, CHO), 1606 (m), 1512 (m), 1464 (w), 1396 (m), 1294 (m), 1254 (s), 1180 (m), 1132 (w), 1034 (m), 839 (m)

MS: (EI, 70 eV)

206 (M^+ , 73), 205 (20), 189 (23), 188 (64), 187 (42), 178 (15), 175 (35), 173 (13), 163 (47), 162 (16), 161 (100), 160 (20), 159 (31), 157 (23), 148 (10), 147 (33), 146 (10), 145 (40), 144 (12), 135 (27), 133 (32), 132 (17), 131 (15), 129 (19), 121 (17), 117 (21), 116 (11), 115 (32), 108 (30), 105 (11), 103 (22), 91 (27), 89 (17), 78 (17), 77 (25), 65 (12), 63 (15)

TLC: R_f 0.13 (hexane/EtOAc, 1/1) [silica gel, PMA]

HPLC: t_R 6.52 min (SUPELCOSIL LC-SI, EtOAc/hexane/, 70/30; 1.0 mL/min)

Analysis: $\text{C}_{12}\text{H}_{14}\text{O}_3$ (206.24)
 Calcd: C, 69.88; H, 6.84%
 Found: C, 69.80; H, 6.99%

Data for 9e:

^1H NMR: (500 MHz, CDCl_3)
 7.48 (br d, $J = 8.6$, 4 H, HC(2, 2', 6, 6')), 6.96 (br d, $J = 8.5$, 4 H, HC(3, 3', 5, 5')),
 3.85 (s, 6 H, 2 x H_3CO)

Preparation of (2Z)-3-(2-Methylphenyl)-5-hydroxy-2-pental (8f)

The coupling reaction of **3a** (322.4 mg, 1.52 mmol, 1.5 equiv) with 2-iodotoluene (**7f**) (220.7 mg, 1.01 mmol) was complete in 4 h. ^1H -NMR of crude mixture showed 18% of the homocoupling product **9f**.^{4c} Purification by column chromatography (silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded **8f** (152.9 mg, 79%) as a colorless oil.

Data for 8f:¹H NMR: (500 MHz, CDCl₃)

9.25 (d, $J = 8.1$, 1 H, HC(1)), 7.30-7.20 (m, 3 H, ArylH), 7.10 (dd, $J = 7.5$, 1.3, 1 H, ArylH), 6.20 (dt, $J = 8.1$, 1.3, 1 H, HC(2)), 3.79 (dt, $J = 10.9$, 6.0, 1 H, one of H₂C(5)), 3.75 (dt, $J = 10.9$, 6.0, 1 H, one of H₂C(5)), 2.78 (dtd, $J = 14.8$, 6.0, 1.3, 1 H, one of H₂C(4)), 2.72 (dtd, $J = 14.8$, 6.0, 1.3, 1 H, one of H₂C(4)), 2.27 (s, 3 H, H₃C(5')), 1.55 (br s, 1 H, OH)

¹³C NMR: (126 MHz, CDCl₃)

193.34 (C(1)), 163.35 (C(3)), 136.91 (C(2')), 134.86 (C(1')), 130.55 (aryl), 130.22 (C(2)), 128.55 (aryl), 128.37 (aryl), 125.81 (C(5)), 59.72 (C(5)), 42.42 (C(4)), 19.60 (C(5'))

IR: (CHCl₃)

3622 (w, OH), 3480 (w, OH), 3016 (w), 2956 (w), 2866 (w), 1674 (s, CHO), 1394 (w), 1228 (w), 1188 (w), 1140 (w), 1039 (w)

MS: (EI, 70 eV)

191 (42), 190 (M⁺, 4), 189 (13), 176 (12), 175 (100), 173 (54), 157 (15), 145 (42), 143 (11), 129 (16), 128 (14), 115 (17), 91 (11)

HRMS: calcd for C₁₂H₁₄O₂ (M⁺): 190.0994; found: 190.0990TLC: R_f 0.31 (hexane/EtOAc, 1/2) [silica gel, PMA]HPLC: t_R 5.22 min (SUPELCOSIL LC-SI, EtOAc/hexane, 70/30; 1.0 mL/min)**Preparation of (2Z)-3-(2-Thienyl)-5-hydroxy-2-pentalenal (8g)**

The coupling reaction of **3a** (279.5 mg, 1.32 mmol, 1.3 equiv) with 2-iodothiophene (**7g**) (212.6 mg, 1.01 mmol) was worked up at 3 h. ¹H-NMR analysis of the crude mixture showed 5% of the **7g** and 7% of the homocoupling product **9g**.⁷ Purification by column chromatography

(silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded desired coupling product **8g** (143.0 mg, 78%) as a yellow oil.

Data for **8g**:

¹H NMR: (500 MHz, CDCl₃)

9.82 (d, *J* = 7.7, 1 H, HC(1)), 7.52 (dd, *J* = 5.1, 1.1, 1 H, HC(5')), 7.20 (dd, *J* = 3.6, 1.1, 1 H, HC(3')), 7.11 (dd, *J* = 5.1, 3.6, 1 H, HC(4')), 6.19 (dt, *J* = 7.7, 1.1, 1 H, HC(2)), 3.82 (t, *J* = 6.4, 2 H, H₂C(5)), 2.87 (td, *J* = 6.4, 1.1, 2 H, H₂C(4)), 1.52 (br s, 1 H, OH)

¹³C NMR: (126 MHz, CDCl₃)

192.49 (C(1)), 152.96 (C(3)), 138.70 (C(2')), 130.68 (C(3')), 130.19 (C(2)), 128.95 (C(5')), 127.69 (C(4')), 60.79 (C(5)), 43.24 (C(4))

IR: (CHCl₃)

3618 (w, OH), 3452 (w, OH), 3010 (w), 2958 (w), 2887 (w), 2866 (w), 1664 (s, CHO), 1599 (w), 1431 (w), 1392 (w), 1317 (w), 1234 (w), 1120 (w), 1039 (w), 854 (w)

MS: (EI, 70 eV)

182 (M⁺, 38), 164 (18), 163 (15), 154 (23), 151 (11), 139 (18), 138 (10), 137 (100), 136 (17), 135 (31), 125 (11), 123 (27), 121 (11), 111 (16), 109 (20), 97 (17), 91 (16), 85 (55), 84 (22), 83 (77), 79 (11), 77 (12), 69 (11), 67 (13), 65 (11)

TLC: *R_f* 0.46 (EtOAc) [silica gel, PMA]

HPLC: *t_R* 5.80 min (SUPELCOSIL LC-SI, EtOAc/hexane, 70/30; 1.0 mL/min)

Analysis: C₉H₁₀O₂S (182.24)

Calcd: C, 59.32; H, 5.53%

Found: C, 59.27; H, 5.62%

Preparation of (2Z)-5-Hydroxy-3-(1-phenylsulfonyl-1H-indol-5-yl)-2-pentenal (8h)

The coupling reaction of **3a** (279.5 mg, 1.32 mmol, 1.3 equiv) with 5-iodo-1-phenylsulfonyl-1*H*-indole (**7h**) (350.6 mg, 1.01mmol) was complete in 2 h. ¹H-NMR analysis of the crude mixture showed 8% of 1,1'-bis(benzenesulfonyl)-1*H*,1'*H*-[5,5']biindolyl (**9h**). Purification by column chromatography (silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded desired coupling product **8h** (285.6 mg, 88%) as a yellow oil.

Data for 8h:

¹H NMR: (500 MHz, CDCl₃)

9.38 (d, *J* = 8.1, 1 H, HC(1)), 8.02 (br d, *J* = 8.6, 1 H, HC(7')), 7.91 (br d, *J* = 8.6, 2 H, 2xHC(2'')), 7.64 (d, *J* = 3.6, 1 H, HC(2')), 7.57 (br t, *J* = 8.6, 1 H, HC(4'')), 7.48 (br t, *J* = 8.6, 2 H, 2xHC(3'')), 7.48 (d, *J* = 1.7, 1 H, HC(4')), 7.25 (dd, *J* = 8.8, 1.7, 1H, HC(6')), 6.68 (dd, *J* = 3.6, 0.6, 1H, HC(3')), 6.19 (dt, *J* = 7.9, 1.1, 1 H, HC(2)), 3.70 (t, *J* = 6.4, 2 H, H₂C(5)), 2.86 (td, *J* = 6.4, 1.1, 2 H, H₂C(4)), 1.72 (br s, 1 H, OH)

¹³C NMR: (126 MHz, CDCl₃)

193.48 (C(1)), 162.73 (C(3)), 138.00 (aryl), 134.94 (aryl), 134.14 (C(4'')), 132.27 (aryl), 130.65 (aryl), 130.00 (C(2)), 129.45 (2xC(3'')), 127.48 (C(2')), 126.80 (2xC(2'')), 125.05 (C(6')), 122.01 (C(7')), 133.44 (C(7')), 108.95 (C(3')), 60.21 (C(5)), 42.66 (C(4))

IR: (CHCl₃)

3020 (w, OH), 2401 (w), 2360 (w), 2341 (w), 1670 (m, CHO), 1377 (w), 1211 (s), 1174 (m), 1136 (m)

MS: (EI, 70 eV)

355 (M⁺, 13), 214 (11), 196 (13), 168 (14), 141 (12), 87 (12), 85 (12), .85 (67), 83 (100), 77 (26)

HRMS: Calcd for $C_{19}H_{17}NO_4S$ (M^+): 355.0878; found 355.0874

TLC: R_f 0.35 (EtOAc) [silica gel, PMA]

HPLC: t_R 7.63 min (SUPELCOSIL LC-SI, EtOAc/hexane, 70/30; 1.0 mL/min)

Preparation of (2Z)-3-(4-Acetylphenyl)-5-hydroxy-2-methyl-2-pentalenal (8i)

The coupling reaction of **3b** (297.9 mg, 1.32 mmol, 1.3 equiv) with 4-iodoacetophenone (**7a**) (249.0 mg, 1.01 mmol) was complete in 7 h. 1H -NMR analysis of the crude mixture showed 14% of the homocoupling product **9i** (=9a). Purification by column chromatography (silica gel, 35g; hexane/EtOAc, 7/1 to 3/1 to 1/1 to 0/1) afforded desired coupling product **8i** (194.7 mg, 83%) as a light yellow.

Data for 8i:

1H NMR: (500 MHz, $CDCl_3$)

9.39 (s, 1 H, HC(1)), 7.97 (br d, $J = 8.6$, 2 H, 2 x HC (3')), 7.42 (br d, $J = 8.6$, 2 H, HC(2')), 3.67 (t, $J = 6.6$, 2 H, $H_2C(5)$), 2.92 (t, $J = 6.6$, 2 H, $H_2C(4)$), 2.63 (s, 3 H, $H_3C(2'')$), 1.98 (s, 3 H, $H_3C(1''')$), 1.57 (br s, 1 H, OH),

^{13}C NMR: (126 MHz, $CDCl_3$)

197.46 (C(1'')), 193.15 (C(1)), 156.42 (C(3)), 143.54 (C(2 or 4' or 1')), 136.81 (C(2 or 4' or 1')), 136.71 (C(2 or 4' or 1')), 129.48 (2xC(2')), 128.32 (2xC(3')), 59.98 (C(5)), 39.22 (C(4)), 26.63 (C(2'')), 11.23 (C(1'''))

IR: ($CHCl_3$)

3622 (w, OH), 3026 (w), 3014 (w), 1680 (s, CHO and Ac), 1604 (m), 1400 (w), 1360 (w), 1267 (m), 1132 (w), 1041 (w), 847 (w)

MS: (EI, 70 eV)

232 (M^+ , 20), 217 (45), 215 (13), 214 (12), 119 (16), 187 (13), 172 (13), 171 (16), 159 (28), 143 (18), 129 (12), 128 (21), 115 (19), 87 (12), 85 (66), 84 (13), 83 (100)

HRMS: Calcd for $C_{14}H_{16}O_3$ (M^+): 232.1099; found 232.1099

TLC: R_f 0.38 (EtOAc) [silica gel, PMA]

HPLC: t_R 6.67 min (SUPELCOSIL LC-SI, EtOAc/hexane/, 70/30; 1.0 mL/min)

Preparation of 1,1'-Bis(phenylsulfonyl)-1*H*,1'*H*-[5,5']biindolyl (**9h**)

The 25-mL, round-bottomed flask was charged with 5-iodo-1-phenylsulfonyl-1*H*-indole (**7h**) (429.0 mg, 1.12 mmol), 1,4-hydroquinone (61.6 mg, 0.56 mmol, 0.5 equiv) and $CsCO_3$ (364.6 mg, 1.12 mmol, 1.0 equiv). To the mixture was added a solution of $Pd(OAc)_2$ (12.6 mg, 0.056 mmol, 0.05 equiv) and (*o*-tol) $_3P$ (17.0 mg, 0.056 mmol, 0.05 equiv) in DMF (5 mL) under an argon atmosphere. After stirring the mixture for 3 h at 75°C, EtOAc (50 mL) was added to the mixture and the mixture was filtered through short silica pad (3 g). The solvent was removed from filtrate under reduced pressure and the residue was purified by successive recrystallization from CH_2Cl_2 to give **9h** (34.2 mg, 12%) as light pink crystals. An analytical sample of **9h** was obtained by a recrystallization from CH_2Cl_2 - Et_2O .

Data for **9h**:

mp: 293-294°C (dec, $CHCl_3$ - Et_2O)

1H NMR: (500 MHz, DMSO)

7.99 (br d, $J = 7.3$, 4 H, 4 x HC(2')), 7.99 (d, $J = 8.8$, 2 H, 2 x HC(7)), 7.85 (d, $J = 2.1$, 2 H, 2 x HC(4)), 7.84 (d, $J = 3.9$, 2 H, 2 x HC(2)), 7.69 (br t, $J = 7.3$, 2 H, 2 x HC(4')), 7.62 (dd, $J = 8.8$, 2 H, 2 x HC(6)), 7.59 (br t, $J = 7.3$, 4 H, 4 x HC(3')), 6.80 (dd, $J = 3.9$, 0.6, 2 H, 2 x HC(3))

^{13}C NMR: (126 MHz, DMSO)

137.09 (2 x C(aryl)), 136.00 (2 x C(aryl)), 134.73 (2 x C(4')), 133.45 (2 x C(aryl)), 131.18 (2 x C(aryl)), 129.92 (4 x C(3')), 127.67 (2 x C(2)), 126.69 (4 x C(2')), 124.13 (2 x C(6)), 119.92 (2 x C(4)), 113.44 (2 x C(7)), 109.90 (2 x C(3))

IR: (KBr)

3134 (w), 3089 (w), 3066 (w), 1892 (w), 1581 (w), 1566 (w), 1479 (w), 1446 (s),
1367 (s), 1257 (m), 1194 (m), 1169 (s), 1122 (s), 1092 (m), 1022 (w), 987 (m),
887 (w), 866 (w), 802 (m)

MS: (EI, 70 eV)

514 (17), 513 (35), 512 (M^+ , 100), 447 (10), 446 (29), 373 (12), 372 (41), 371
(71), 359 (11), 232 (13), 230 (63), 230 (63), 229 (16), 77 (18)

HRMS: Calcd for $C_{28}H_{20}N_2O_4S_2$ (M^+): 512.0862; found 512.0865

TLC: R_f 0.38 (hexane/EtOAc, 1/1) [silica gel, PMA]

HPLC: t_R 4.43 min (SUPELCOSIL LC-SI, EtOAc/hexane/, 50/50; 1.0 mL/min)

Results of nOe Experiments of the Cyclic Silyl Ethers 3.

Table 1, entry 2.

Table 1, entry 3.

Table 1, entry 5.

[$\Rightarrow$ indicates proton(s) irradiated.]

Results of nOe Experiments of the Cross-coupling Products 8.

Table 10, entry 1.

Table 10, entry 2.

Table 10, entry 3.

Table 10, entry 4.

Table 10, entry 5.

Table 10, entry 7.

Table 10, entry 8.

Table 10, entry 9.

Table 10, entry 11.

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