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Convergent Strategy for the Synthesis of Oxa-, Thia-, and Selena[5]helicenes by Acetylene-Activated S_NAr Reactions

Samuel M. Hoenig, Youmian Yan, Emily A. Dougherty, Reuben Hudson, Sava Petovic, Christopher K. Lee, Yusheng Hu, Lucas S. Gomez, and Jeffrey L. Katz*

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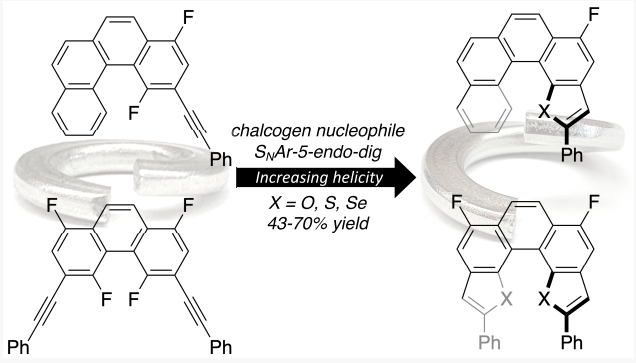
ABSTRACT: A tandem acetylene-activated S_NAr-anionic cyclization strategy is presented for the synthesis of chalcogen-containing hetero[5]helicenes. Oxa-, thia-, and selena[5]helicenes are accessed from common *ortho*-fluoro-ethynylarene precursors, allowing the heteroatoms to be installed at the 1-position or 1- and 12-positions of the hetero[5]helicene inner core surface.

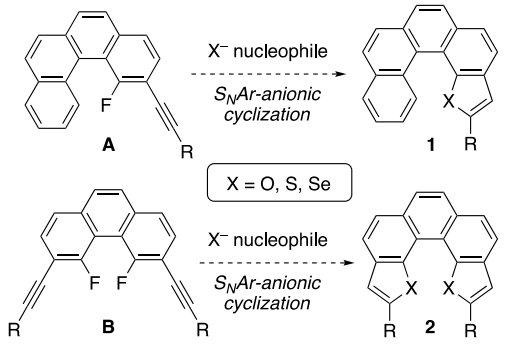


Helicenes are *ortho*-fused aromatic molecules that adopt sterically induced nonplanar helical topologies.[1] Owing to this three-dimensional geometry, carbohelicenes and their heteroaromatic variants, heterohelicenes, serve as unique scaffolds for molecular design.[2] In particular, helicenes bearing heteroatoms on the terminal positions of the helicene inner core surface are ideal candidates for chiral auxiliaries, organocatalysts, and as ligands for metals.[3] Although routes to a variety of heterohelicene structures have been reported, there remains a lack of general and efficient methods for the synthesis of heterohelicenes, especially those bearing heteroatoms on the inner core surface.

We recently studied the ability of ethynyl groups to successfully activate fluorobenzenes for nucleophilic aromatic substitution reactions, a reaction type we termed acetylene-activated S_NAr.[4] When applied to 2-fluoroethynylbenzenes, anilines, amides, and hydroxide were shown to readily undergo a cascade sequence of S_NAr followed by anionic cyclization onto the pendant alkyne, leading to indole and benzofuran products.[5] It was also shown by Li and coworkers that benzothiophenes could be accessed via a similar reaction manifold using sodium sulfide as the nucleophile.[6] These annulation processes have the advantages of proceeding without transition metal involvement and through displacement of a small and otherwise relatively inert fluorine atom.

Because fluorine atoms are readily installed in the sterically hindered bay regions of *ortho*-fused aromatics such as phenanthrenes,[7] we envisaged that acetylene-activated S_NAr-anionic cyclization cascades could provide a unique entry into helicene scaffolds containing heteroatoms on the inner core surface. As shown in Scheme 1, 1-fluoro-2-ethynylbenzo[*c*]-phenanthrenes **A** subjected to fluorine substitution and subsequent 5-endo-dig cyclization would furnish monohetero[5]helicenes **1**, while analogous reaction of 4,5-difluoro-3,6-bisethynylphenanthrenes **B** would allow access to dihetero[5]helicenes **2**. Not only would this strategy provide

Scheme 1. Strategy for the Synthesis of Monohetero[5]helicenes 1 and Dihetero[5]helicenes 2 by Acetylene-Activated S_NAr Reactions



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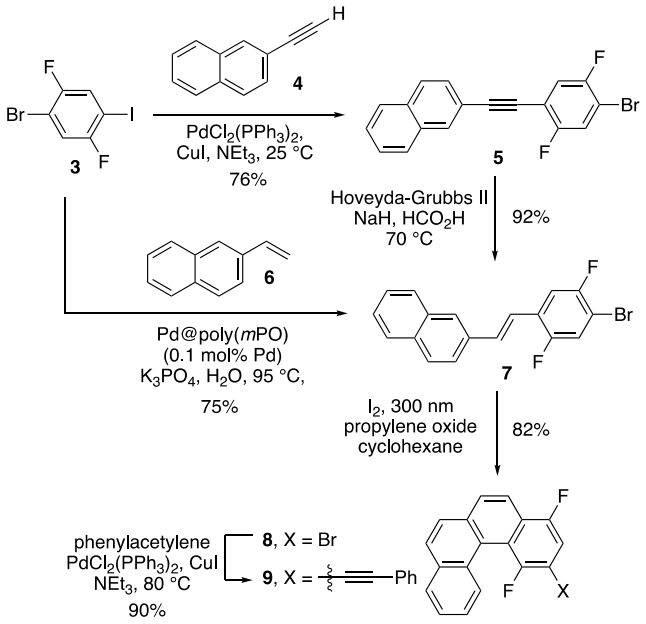
access to previously unknown heterohelicene motifs, but installation and variation of the heteroatom(s) from common synthetic precursors would be accomplished at the final stages of the synthetic sequence and simply by choice of nucleophile. Herein, we describe our synthetic efforts toward chalcogen-containing hetero[5]helicenes **1** and **2** using acetylene-activated S_NAr reactions.

Our initial strategy for the synthesis of hetero[5]helicenes **1** began with Sonogashira coupling of 1-bromo-2,5-difluoro-4-iodobenzene (**3**) with 2-ethynylnaphthalene[8] (**4**) ($PdCl_2(PPh_3)_2$, CuI, NEt_3, 25 °C, 8 h) to furnish diaryl acetylene **5** in 76% yield (Scheme 2). Subsequent reduction

Scheme 2. Synthesis of Common Cyclization Precursor 1,4-Difluoro-2-phenylethynyl-benzo[*c*]phenanthrene 9

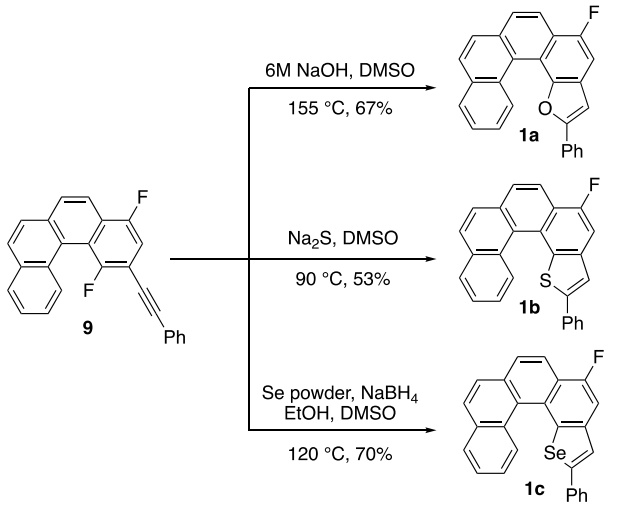


using the method of Grela[9] (2 mol % Hoveyda−Grubbs II, NaH, formic acid, 80 °C, 7 h, 92%) then provided access to stilbene derivative **7**. While this route was successful in producing the requisite photocyclization precursor **7**, a more efficient sequence using Mizoroki−Heck coupling was also investigated. Iodide **3** was successfully coupled to commercially available 2-vinylnaphthalene (**6**) under aqueous conditions using only 0.1 mol % Pd with our recently developed heterogeneous Pd@poly(*m*PO) catalyst[10] (Pd@poly(*m*PO), K_3PO_4, H_2O, 95 °C, 48 h, 75%), providing a single step entry for access to stilbene **7**.

Photocyclization[11] of **7** to the corresponding benzo[*c*]-phenanthrene **8** proceeded smoothly (I_2, cyclohexane, propylene oxide, 300 nm, 24 h, 82%),[12] as the fluorine atom in the 4-position of **7** ensured regioselective cyclization.[7c] Installation of the 2-ethynyl group to yield cyclization precursor **9** was then accomplished via Sonogashira coupling of phenylacetylene onto benzo[*c*]phenanthrene **8** ($PdCl_2(PPh_3)_2$, CuI, NEt_3, 80 °C, 18 h, 90%). While phenylacetylene was used exclusively in this initial study, it is notable that the ethynyl substituent provides an additional site for late-stage diversification, as a change of alkyne coupling partner in this penultimate step provides structural diversity at the 2-position on the target hetero[5]helicenes.

We then tested the reaction of 1-fluoro-2-ethynyl-benzo[*c*]-phenanthrene **9** with chalcogen nucleophiles for the synthesis of heterohelicene products **1** (Scheme 3). Benzo[*c*]-

Scheme 3. Synthesis of Monohetero[5]helicenes 1 from Common Precursor 9 via Acetylene-Activated S_NAr-Anionic Cyclization Reactions



phenanthrene **9** reacted more sluggishly with hydroxide in DMSO/H_2O than was observed with simple 2-fluoroethynyl benzenes,[5] perhaps due to the steric hindrance present in the bay region of **9**. Nonetheless, slow conversion to the corresponding oxa[5]helicene **1a** was observed at 155 °C (NaOH, DMSO/H_2O, 155 °C, 6 d, 67%). In contrast, sodium sulfide reacted with benzo[*c*]phenanthrene **9** in accord with literature precedent[6] ($Na_2S{\cdot}9H_2O$, DMSO, 90 °C, 18 h), furnishing thia[5]helicene **1b** in 53% yield. Finally, we attempted installation of a selenophene ring onto the [5]helicene scaffold, a previously unknown structural motif. NaSeH was generated *in situ* by $NaBH_4$ reduction of selenium powder in ethanol.[13] No reaction was observed after heating **9** at reflux in this ethanol solution for 24 h. However, benzo[*c*]phenanthrene **9** underwent efficient conversion to selena[5]helicene **1c** upon addition of DMSO and heating to 120 °C with removal of the ethanol by distillation, furnishing **1c** in 70% yield (Se powder, $NaBH_4$, EtOH, DMSO, 120 °C, 18 h).

With our convergent strategy to chalcogen-containing helicenes **1a**−**1c** validated, we turned to investigating the synthesis of helicene systems terminated on both ends with heterocyclic rings. As shown in Scheme 4, 3,6-dibromo-1,4,5,8-tetrafluorophenanthrene **11** was accessed in two steps beginning with the Stille coupling of 1-bromo-2,5-difluoro-4-iodobenzene (**3**) and 1,2-bis(tributylstannyl)ethene ($Pd(PPh_3)_4$, toluene, 110 °C, 12 h). This linchpin coupling proceeded efficiently to yield *trans*-stilbene **10**, although this material was difficult to completely separate from stannyl impurities. Photocyclization of stilbene **10** (I_2, propylene oxide, cyclohexane, 300 nm, 24 h) proceeded with high efficiency to furnish phenanthrene **11**. Impurities from the previous step were more easily separated from phenanthrene **11**, which was isolated in 80% overall yield from **3**. Sonogashira coupling ($PdCl_2(PPh_3)_2$, CuI, NEt_3, 80 °C, 18 h, 78%) then provided acetylene-substituted phenanthrene **12**, functionalized for entry into the S_NAr-anionic cyclization cascade.

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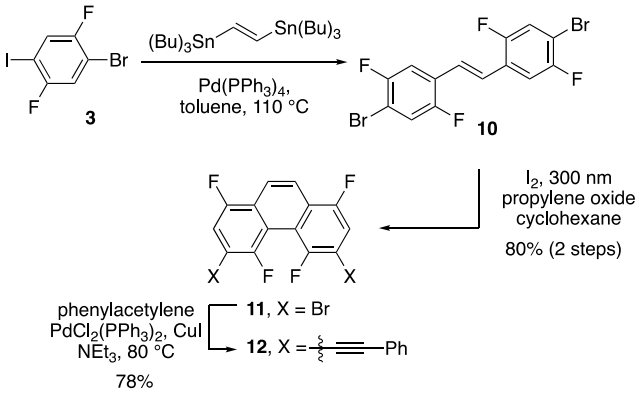
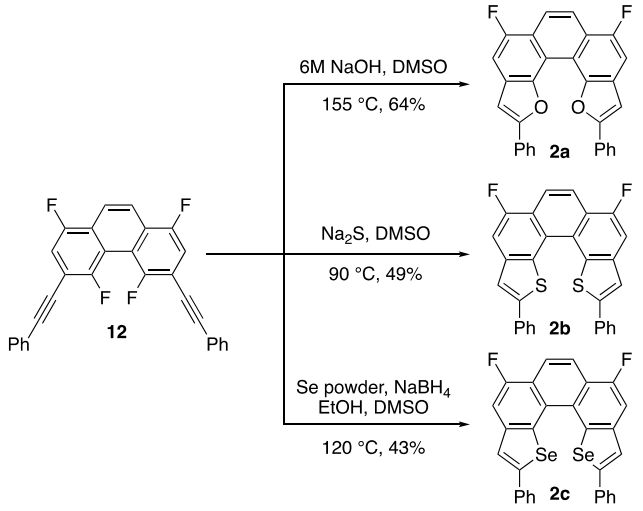
Scheme 4. Synthesis of Cyclization Precursor 4,5-Difluoro-3,6-bisethynylphenanthrene 12



As shown in Scheme 5, we were gratified to observe that each chalcogen nucleophile reacted smoothly with bis-

Scheme 5. Synthesis of Dihetero[5]helicenes 2 from Common Precursor 12



(phenylethynyl)phenathrene **12**, leading to dihetero[5]-helicenes **2** bearing heteroatoms at the 1- and 12-positions on the helicene inner core surface. Reaction of **12** with hydroxide furnished dioxa[5]helicene **2a** in 64% yield, while reaction with sulfide ion produced dithia[5]helicene **2b** in 49% yield. Finally, diselena[5]helicene **2c** was successfully formed by reaction of **12** with *in situ* generated NaSeH and isolated in 43% yield.

Single crystals of oxa[5]helicene **1a** and thia[5]helicene **1b** were obtained via vapor diffusion from chloroform-hexanes. The solid-state structures of both compounds are shown in Figure 1. As expected of [5]helicenes containing a five-membered heteroaromatic ring, each compound exhibits modest helical distortions from planarity. In the solid state, oxa[5]helicene **1a** adopts a shallow helical pitch with an interplanar angle of 34.01° and torsional angles of 1.24°, 21.34°, and 20.29°. The distance observed between the bay region oxygen and carbon atoms is 2.69 Å. Thia[5]helicene **1b** exhibits significantly greater distortion from planarity, with an interplanar angle of 49.82° and torsional angles of 9.12°, 27.24°, and 25.36°. The distance observed between the bay region sulfur and carbon atoms is 2.94 Å. In both **1a** and **1b**,

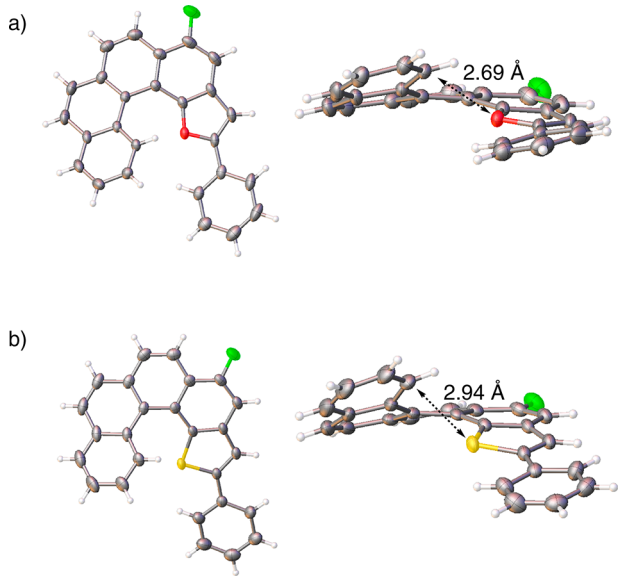


Figure 1. (a) Solid-state structure of oxa[5]helicene **1a**. (b) Solid-state structure of thia[5]helicene **1b**. Thermal ellipsoids drawn at the 50% probability level.

the smallest torsional angles were observed nearest to the heteroaromatic rings, and the sum of the torsional angles (**1a** = 42.87°, **1b** = 61.72°) were each less than that reported for carbo[5]helicene (65.94°).[14]

In conclusion, we have shown that acetylene-activated S_NAr-anionic cyclization reaction cascades are effective for the synthesis of helicene structures terminated with chalcogen-containing heteroaromatic rings. This strategy allows late-stage structural diversification of the helicene scaffold from common synthetic precursors, including choice of chalcogen atom(s). We continue to explore the synthesis of complex hetero-helicene systems by these S_NAr methods, including additional nucleophiles for the installation of alternative heteroaromatic systems, and those investigations will be reported in due course.

EXPERIMENTAL SECTION

General Information. Unless otherwise noted, all chemicals were obtained from commercial suppliers and were used without further purification. Triethylamine and toluene were distilled under an atmosphere of Ar prior to use. Tetrahydrofuran was passed through a PureSolv Solvent Purification System prior to use. Photochemistry was conducted in a Luzchem LZC-ORG photoreactor equipped with LZC-UVB lamps centered at 300 nm. Analytical thin-layer chromatography was performed with Sorbtech silica XHL TLC plates. Flash column chromatography was carried out with 200−400 mesh silica gel. NMR spectra were recorded on a Bruker Avance Neo 500 MHz spectrometer. Chemical shifts are expressed in parts per million (δ) using residual solvent peaks or tetramethylsilane (TMS) as internal references. Mass spectra were obtained using an Agilent 6230 TOF-HRMS spectrometer with an ESI interface. UV−vis spectra were taken on an Agilent 8453 spectrophotometer. Infrared spectra were obtained on a ThermoFisher Scientific Nicolet iS10 FT-IR spectrometer. Melting points are uncorrected and were obtained on an Optimelt MPA100 from Stanford Research Systems.

*2-((4-Bromo-2,5-difluorophenyl)ethynyl)naphthalene (**5**).* To a 25 mL Schlenk flask equipped with a stir bar under an Ar atmosphere was added 1-bromo-2,5-difluoro-4-iodobenzene (1.00 g, 3.14 mmol), bis(triphenylphosphine)palladium(II) chloride (0.066 g, 0.095 mmol), and copper(I) iodide (0.018 g, 0.095 mmol). The atmosphere was further purged by evacuating and backfilling with Ar three times.

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Triethylamine (10 mL) was then added via syringe, followed by 2-ethynylnaphthalene (0.525 g, 3.45 mmol). The solution was stirred at 25 °C for 8 h. The reaction mixture was then diluted with CH_2Cl_2 and poured into saturated ammonium chloride. The resulting mixture was separated, further extracted with CH_2Cl_2 (3 × 100 mL), and the combined organic layers dried over Na_2SO_4. Purification by silica gel column chromatography (loaded in minimum CH_2Cl_2, elution first with hexanes followed by 9:1 hexanes: CH_2Cl_2) afforded 0.824 g (2.40 mmol, 76%) of **5** as a white solid. Mp 119−121 °C; ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.09 (s, 1H), 7.78−7.88 (m, 3H), 7.58 (dd, J = 8.5, 1.6 Hz, 1H), 7.49−7.55 (m, 2H), 7.36 (dd, J = 8.0, 5.7 Hz, 1H), 7.31 (dd, J = 8.3, 5.9 Hz, 1H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 158.3 (dd, J = 252.1, 2.7 Hz), 155.1 (dd, J = 244.1, 2.8 Hz), 133.2, 132.9, 132.0, 128.2, 128.1, 127.9, 127.8, 127.1, 126.8, 120.4 (d, J = 25.9 Hz), 119.7 (dd, J = 25.9, 2.1 Hz), 119.4, 112.5 (dd, J = 18.5, 9.1 Hz), 109.5 (dd, J = 23.8, 9.5 Hz), 96.7 (d, J = 3.3 Hz), 81.3 (d, J = 2.6 Hz); IR (thin film): 3051, 2921, 2216, 1596, 1495, 1485, 1467, 1401, 1178, 902, 879, 820, 799, 741 cm^{-1}; TLC R_f = 0.23 (hexanes). HRMS (ESI) calcd for $[C_{18}H_8BrF_2]^-$ 340.9783, found 340.9742.

*2-(4-Bromo-2,5-difluorostyryl)naphthalene (**7**). Via Reduction of **5**.* To a 25 mL Schlenk flask equipped with a stir bar under an Ar atmosphere was added 2-((4-bromo-2,5-difluorophenyl)ethynyl)-naphthalene **5** (0.785 g, 2.29 mmol), followed by THF (11 mL) and stirred until homogeneous. Grubbs−Hoveyda II reagent (0.027 g, 0.043 mmol) was added, followed by sodium hydride (0.018 g, 0.45 mmol). The atmosphere was then purged by evacuating and backfilling with Ar three times. Formic acid (4.3 mL) was then added via syringe. The reaction mixture was heated to 80 °C for 7 h in an oil bath. The reaction was then cooled to room temperature and transferred to a 500 mL beaker where it was quenched by slow addition of saturated sodium bicarbonate. The resulting solution was extracted with CH_2Cl_2 (3 × 200 mL) and washed with brine (200 mL). The combined organic layers were dried over Na_2SO_4. Purification by silica gel column chromatography (CH_2Cl_2 load, elution with hexanes) afforded 0.726 g (2.10 mmol, 92%) of **7** as a white solid.

*2-(4-Bromo-2,5-difluorostyryl)naphthalene (**7**). Via Heck Coupling.* To a 10 mL microwave vial equipped with a stir bar under an Ar atmosphere was added 2-vinylnaphthalene (0.231 g, 1.5 mmol), 1-bromo-2,5-difluoro-4-iodobenzene **3** (0.319 g, 1.0 mmol), Pd@poly(*m*PO) catalyst[10] (0.015 g, 0.1 mol % Pd), and K_3PO_4 (0.415 g, 2.00 mmol). Degassed water (3.0 mL) was then added, and the reaction was sealed and heated to 95 °C for 48 h in an aluminum block. The reaction was cooled to room temperature and the seal removed. Water (5 mL) was added, and the product was collected by vacuum filtration. The precipitate was then dissolved in CH_2Cl_2, and dried over Na_2SO_4. After filtration and solvent removal *in vacuo*, purification by silica gel column chromatography (CH_2Cl_2 load, elution with hexanes) afforded 0.260 g (0.75 mmol, 75%) of **7** as a white solid. Mp 121.5−125 °C; ^{1}H NMR (500 MHz, $CDCl_3$), δ 7.81 (s, 1H), 7.78−7.74 (m, 3H), 7.66 (dd, J = 8.6, 1.8 Hz, 1H), 7.41 (m, 2H), 7.34 (dd, J = 9.1, 6.4 Hz, 1H), 7.26 (d, J = 16.4 Hz, 1H), 7.24 (dd, J = 9.5, 5.7 Hz, 1H), 7.19 (d, J = 16.4 Hz, 1H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 155.8 (dd, J = 249.9, 2.6 Hz), 155.8 (dd, J = 243.2, 2.7 Hz), 133.9, 133.5, 133.4, 132.5 (d, J = 4.6 Hz), 128.5, 128.2, 127.7, 127.6, 126.5, 126.4, 126.1 (dd, J = 14.3, 6.9 Hz), 123.2, 120.5 (d, J = 27.6 Hz), 119.2 (t, J = 2.7 Hz), 113.1 (dd, J = 25.2, 4.5 Hz), 107.4 (dd, J = 24.0, 10.4 Hz). IR (thin film): 3057, 1485, 1466, 1404, 1270, 1168, 956, 862, 843, 812, 742, 730 cm^{-1}. TLC R_f = 0.25 (hexanes). HRMS (ESI) calcd for $[C_{18}H_{11}BrF_2]^+$ 344.0012, found 344.0014.

*2-Bromo-1,4-difluorobenzo[c]phenanthrene (**8**).* To a large Kimax test tube equipped with a stir bar and a loose fitting polypropylene cap was added sequentially 2-(4-bromo-2,5-difluorostyryl)naphthalene **7** (0.070 g, 0.203 mmol), cyclohexane (45 mL), iodine (0.052 g, 0.205 mmol), and propylene oxide (3 mL). The resulting solution was stirred and irradiated at 300 nm (UVB) in a Luzchem photoreactor at room temperature for 24 h. The reaction tube was placed in a plastic rack at a distance of approximately 2 cm from the side lamps. The reaction mixture was then poured into a round-bottom flask and concentrated *in vacuo*. Purification by silica gel column chromatography (loaded with CH_2Cl_2, elution with hexanes) afforded 0.058 g (0.169 mmol, 82%) of **8** as a white solid. Mp 152−154 °C; ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.26 (ddd, J = 15.4, 6.8, 2.6 Hz, 1 H), 8.14 (dd, J = 8.5, 2.0 Hz, 1 H), 8.05 (d, J = 8.5 Hz, 1 H), 8.01 (dd, J = 6.7, 2.6 Hz, 1 H), 7.94 (d, J = 8.7 Hz, 1 H), 7.86 (d, J = 8.5 Hz, 1 H), 7.68 (m, 4 H), 7.57 (dd, J = 8.7, 4.9, 1 H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 154.2 (dd, J = 252.8, 2.8 Hz), 152.0 (dd, J = 250.6, 3.5 Hz), 133.0, 132.5, 129.6, 129.6, 129.4, 129.3, 128.5, 127.5, 126.5, 125.6, 125.5 (d, J = 3.0 Hz), 123.7 (dd, J = 4.1, 2.3 Hz), 123.4 (dd, J = 17.6, 4.5 Hz), 118.9 (dd, J = 6.8, 1.9 Hz), 114.7 (d, J = 25.8 Hz), 105.6 (dd, J = 26.5, 11.4 Hz); IR (thin film): 3050, 1601, 1416, 1357, 1283, 1236, 1179, 830, 816, 757 cm^{-1}; TLC R_f = 0.28 (hexanes). HRMS (ESI) calcd for $[C_{18}H_9BrF_2]^+$ 341.9856, found 341.9841.

*1,4-Difluoro-2-(phenylethynyl)benzo[c]phenanthrene (**9**).* In a 25 mL Schlenk flask equipped with a stir bar and a cold finger under an Ar atmosphere was added 2-bromo-1,4-difluorobenzo[*c*]-phenanthrene **8** (0.741 g, 2.160 mmol), bis(triphenylphosphine)-palladium(II) chloride (0.045 g, 0.065 mmol), and copper(I) iodide (0.012 g, 0.065 mmol). The atmosphere was then purged by evacuating and backfilling with Ar three times. Triethylamine (7.0 mL) and degassed phenylacetylene (261 μL, 2.38 mmol) were then added via syringe. The solution was stirred and heated to 80 °C for 18 h in an oil bath. The reaction mixture was then cooled to room temperature, transferred to a separatory funnel, diluted with CH_2Cl_2, and washed with saturated ammonium chloride. The aqueous layer was further extracted with CH_2Cl_2 (4 × 100 mL), and the combined organic layers were dried over Na_2SO_4. Following concentration *in vacuo*, the material was purified by silica gel column chromatography (loaded in CH_2Cl_2, elution with hexanes) to afford 0.712 g (1.95 mmol, 90%) of **9** as a white solid. Mp 150−167 °C (dec.); ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.31 (dd, J = 14.9, 7.9 Hz, 1H), 8.13 (dd, J = 8.4, 1.9 Hz, 1H), 8.03 (d, J = 8.5 Hz, 1H), 8.00 (d, J = 6.6 Hz, 1H), 7.91 (d, J = 8.7 Hz, 1 H), 7.84 (d, J = 8.5 Hz, 1 H), 7.70−7.61 (m, 4 H), 7.46 (dd, J = 9.6, 5.0, 1 H) 7.42−7.37 (m, 3 H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 156.1(dd, J = 256.9, 2.6 Hz), 154.1 (dd, J = 247.4, 2.7 Hz), 133.1, 132.4, 131.8, 129.7, 129.6, 129.4, 128.9, 128.8, 128.4, 127.5, 126.5, 125.7, 125.4 (d, J = 2.8 Hz), 124.3 (d, J = 4.9 Hz), 124.2 (d, J = 4.6 Hz), 122.8, 119.5 (dd, J = 14.6, 4.7 Hz), 119.0 (dd, J = 6.9, 2.0 Hz), 113.3 (dd, J = 24.1, 1.9 Hz), 108.3 (dd, J = 21.1, 11.0 Hz), 96.1 (d, J = 4.9 Hz), 83.2 (d, J = 2.6 Hz); IR (ATR): 3051, 2924, 2222, 1617, 1597, 1499, 1486, 1441, 1418, 1397, 1302, 1227, 1175, 1047, 1019, 907, 856, 830, 749, 688, 652 cm^{-1}; TLC R_f = 0.35 (hexanes). HRMS (ESI) calcd for $[C_{26}H_{14}F_2]^+$ 364.1064, found 364.1061.

*5-Fluoro-2-phenylbenzo[5,6]phenanthro[4,3-b]furan (**1a**).* To a 2 mL cone-shaped microwave vial equipped with a stir bar under an Ar atmosphere was added 1,4-difluoro-2-(phenylethynyl)benzo[*c*]-phenanthrene **9** (0.100 g, 0.274 mmol), followed by DMSO (500.0 μL), and 6.0 M KOH (91 μL, 0.546 mmol). The vial was sealed and heated to 155 °C for 6 d in an aluminum block. After cooling to room temperature, the seal was removed, and the reaction was diluted with $CHCl_3$ and poured into a separatory funnel. The reaction was partitioned between $CHCl_3$ and water (15 mL each), and the aqueous layer extracted twice with additional $CHCl_3$ (2 × 15 mL). The combined organics were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. Purification by silica gel column chromatography (dry loaded from $CHCl_3$, elution first with hexanes, followed by 95:5 hexanes:CH_2Cl_2) afforded 67 mg (0.18 mmol, 67%) of **1a** as a white solid. Mp 152−168 °C (dec.); ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.82 (d, J = 8.5 Hz, 1H), 8.26 (d, J = 8.6 Hz, 1H), 8.04 (dd, J = 8.1 Hz, 1H), 8.01 (d, J = 8.5 Hz, 1H), 7.86 (d, J = 8.5 Hz, 1H), 7.85 (d, J = 8.6 Hz, 1H), 7.78 (d, J = 7.1 Hz, 2H), 7.70 (dt, J = 7.4, 1.2 Hz, 1H), 7.58 (dt, J = 6.3, 1.5 Hz, 1H), 7.52 (d, J = 9.5 Hz, 1H), 7.39 (t, J = 7.9 Hz, 2H), 7.32 (tt, J = 7.3, 1.3 Hz, 1H), 7.20 (s, 1H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 155.7 (d, J = 244.5 Hz), 155.0, 146.8, 133.1, 132.4, 130.0, 129.9, 129.5, 128.8, 128.7, 128.6, 127.5, 126.5, 126.4, 126.3, 126.1 (d, J = 1.8 Hz), 124.7, 124.4 (d, J = 2.2 Hz), 124.3, 121.6 (d, J = 18.1 Hz), 120.3 (d, J = 8.7 Hz), 117.7 (d, J = 4.5 Hz), 103.4

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(d, J = 24.4 Hz), 102.3 (d, J = 4.2 Hz). IR (thin film): 3050, 1618, 1602, 1571, 1452, 1415, 1396, 1365, 1239, 1196, 1042, 1024, 932, 914, 835, 808, 795, 778, 753, 705 cm^{-1}; UV/vis λ_{max} ($CHCl_3$): 256, 269, 298, 309, 349, 362, 400 nm; TLC R_f = 0.60 (9:1 hexanes:CH_2Cl_2); HRMS (ESI) calcd for $[C_{26}H_{15}FO]^+$ 362.1107, found 362.1111.

*5-Fluoro-2-phenylbenzo[5,6]phenanthro[4,3-b]thiophene (**1b**).* To a 2 mL cone-shaped microwave vial equipped with a stir bar and under an Ar atmosphere was added sodium sulfide nonahydrate (0.138 g, 0.575 mmol) followed by DMSO (500.0 μL), and 1,4-difluoro-2-(phenylethynyl)benzo[c]phenanthrene **9** (0.100 g, 0.274 mmol). The vessel was sealed and heated to 90 °C for 18 h in an aluminum block. After cooling to room temperature, the seal was removed and the product precipitated from solution by the addition of water (5 mL). The precipitate was isolated by vacuum filtration, the solids dissolved in CH_2Cl_2, dried over Na_2SO_4, and concentrated *in vacuo*. Purification by silica gel column chromatography (dry loaded from $CHCl_3$, elution first with hexanes, and then with a step gradient of 5%, 10%, and then 15% CH_2Cl_2:hexanes) afforded 0.055 g (0.145 mmol, 53%) of **1b** as a light yellow solid. Mp 202−204 °C (melt/darken); ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.80 (d, J = 8.5 Hz, 1H), 8.21 (d, J = 8.5 Hz, 1H), 8.00 (d, J = 8.0 Hz, 1H), 7.94 (d, J = 8.4 Hz, 1H), 7.79 (d, J = 8.5 Hz, 1H), 7.78 (d, J = 8.6 Hz, 1H), 7.58−7.66 (m, 4H), 7.52 (s, 1H), 7.48 (dt, J = 7.6, 1.4 Hz, 1H), 7.36 (tt, J = 7.8, 1.6 Hz, 2H), 7.29 (tt, J = 7.3, 1.2 Hz, 1H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 157.2 (d, J = 246.9 Hz), 142.6, 140.0 (d, J = 10.4 Hz), 133.7, 133.0, 132.7 (d, J = 1.4 Hz), 132.5, 129.3, 128.9, 128.4, 128.3, 128.2, 127.9, 127.0, 126.7 (d, J = 4.6 Hz), 126.5, 126.2 (d, J = 2.4 Hz), 126.1 (d, J = 1.7 Hz), 126.0, 124.5, 122.1 (d, J = 17.3 Hz), 120.3 (d, J = 8.3 Hz), 119.1 (d, J = 4.4 Hz), 106.1 (d, J = 22.3 Hz); IR (thin film): 3053, 1612, 1489, 1388, 1263, 1221, 1128, 1073, 1046, 861, 834, 797, 738 cm^{-1}; UV/vis λ_{max} ($CHCl_3$): 271, 319, 361 nm; TLC R_f = 0.38 (9:1 hexanes:CH_2Cl_2). HRMS (ESI) calcd for $[C_{26}H_{15}FS]^+$ 378.0878, found 378.0882.

*5-Fluoro-2-phenylbenzo[5,6]phenanthro[4,3-b]selenophene (**1c**).* To a 10 mL round-bottom flask equipped with a stir bar and under an Ar atmosphere was added sodium borohydride (15.4 mg, 0.41 mmol), followed by anhydrous ethanol (1.0 mL). The reaction was cooled to 0 °C in an ice bath, selenium powder (25.1 mg, 0.32 mmol) was added, and the reaction was stirred at 0 °C for 40 min [**CAUTION**[15]]. 1,4-Difluoro-2-(phenylethynyl)benzo[c]-phenanthrene **9** (0.64 g, 0.175 mmol) was then added, followed by DMSO (3.0 mL). The flask was equipped with a short path condenser, and the solution was heated to 120 °C in an oil bath and held there for 18 h allowing the ethanol to distill out. The reaction was then cooled to room temperature, and nitrogen gas was actively bubbled through the solution for 20 min. The reaction was then diluted with CH_2Cl_2, and poured into a separatory funnel. The reaction was partitioned between CH_2Cl_2 and water (15 mL each), and the aqueous layer extracted once with additional CH_2Cl_2 (15 mL). The combined organics were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. Purification by silica gel column chromatography (dry loaded from $CHCl_3$, elution first with hexanes, and then with a step gradient of 5%, 10%, and then 15% CH_2Cl_2:hexanes) afforded 52 mg (0.12 mmol, 70%) of **1c** as a pale yellow solid. Mp 198−201 °C (melt/darken); ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.88 (d, J = 8.3 Hz, 1H), 8.22 (d, J = 8.6 Hz, 1H), 8.03 (d, J = 8.0 Hz, 1H), 7.96 (d, J = 8.5 Hz, 1H), 7.81 (d, J = 8.5 Hz, 1H), 7.80 (d, J = 8.6 Hz, 1H), 7.73 (s, 1H), 7.67 (d, 10.4 Hz, 1H), 7.55−7.60 (m, 2H), 7.51 (dt, 7.4, 1.4 Hz, 1H), 7.37 (dt, J = 7.7, 1.6 Hz, 2H), 7.31 (tt, J = 7.3, 1.2 Hz, 1H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 157.5 (d, J = 247.2 Hz), 146.1, 142.9 (d, J = 9.7 Hz), 135.6, 135.4 (d, J = 2.1 Hz), 133.0, 132.4, 129.3 (d, J = 4.2 Hz), 129.2, 129.0, 128.3, 128.1, 127.6, 126.8, 126.1 (d, J = 1.7 Hz), 126.0, 124.9, 122.6 (d, J = 4.1 Hz,) 122.0 (d, J = 16.8 Hz), 120.2 (d, J = 8.2 Hz), 107.8 (d, J = 21.8 Hz); IR (thin film): 3051, 2923, 2853, 1612, 1490, 1444, 1385, 1346, 1225, 1125, 1042, 864, 834, 778, 754, 736 cm^{-1}; UV/vis λ_{max} ($CHCl_3$): 273, 322, 366 nm; TLC R_f = 0.42 (9:1 hexanes:CH_2Cl_2); HRMS (ESI) calcd for $[C_{26}H_{15}FSe]^+$ 426.0323, found 426.0318.

*(E)-1,2-Bis(4-bromo-2,5-difluorophenyl)ethene (**10**).* In a 25 mL Schlenk flask equipped with a stir bar and a cold finger under an Ar atmosphere was added 1-bromo-2,5-difluoro-4-iodobenzene **3** (0.319 g, 1.0 mmol) and tetrakis(triphenylphosphine)palladium(0) (0.058g, 0.050 mmol). The atmosphere was then purged by evacuating and backfilling with Ar three times. Toluene (5.0 mL) followed by (*E*)-1,2-bis(tributylstannyl)ethene (0.303 g (268 μL), 0.50 mmol) were then added via syringe. The solution was stirred and heated to 110 °C for 18 h in an oil bath. The reaction mixture was then cooled to room temperature, diluted with CH_2Cl_2, filtered through a silica plug, and concentrated *in vacuo*. The material was purified by silica gel column chromatography (dry loaded from $CHCl_3$, elution with hexanes) to afford 0.415 g of **10** as a white solid contaminated with stannyl impurities. Mp 150−154 °C; ^{1}H NMR (500 MHz, $CDCl_3$), δ 7.35 (dd, J = 8.9, 6.3 Hz, 2H), 7.32 (dd, J = 9.4, 5.7 Hz, 2H), 7.18 (s, 2H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 155.9 (dd, J = 251.0, 2.7 Hz), 155.7 (dd, J = 244.0, 2.8 Hz), 125.1 (dd, J = 14.1, 6.9 Hz), 122.8 (m), 120.8 (d, J = 27.5 Hz), 113.4 (dd, J = 25.3, 3.9 Hz), 108.7 (dd, J = 23.9, 10.4 Hz); IR (thin film): 2954, 2921, 2853, 1491, 1406, 1261, 1171, 1077, 1012, 967, 872, 812 cm^{-1}; TLC R_f = 0.42 (hexanes). HRMS (ESI) calcd for $[C_{14}H_3Br_2F_4]^-$ 406.8694, found 406.8671.

*3,6-Dibromo-1,4,5,8-tetrafluorophenanthrene (**11**).* To a large Kimax test tube equipped with a stir bar and a loose fitting cap was added sequentially (*E*)-1,2-bis(4-bromo-2,5-difluorophenyl)ethene **10** (0.82 g, 0.20 mmol), cyclohexane (45 mL), iodine (0.51 g, 0.20 mmol), and propylene oxide (3 mL). The resulting solution was stirred and irradiated at 300 nm (UVB) in a Luzchem photoreactor at room temperature for 24 h. The reaction tube was placed in a plastic rack at a distance of approximately 2 cm from the side lamps. The reaction mixture was then poured into a round-bottom flask and concentrated *in vacuo*. Purification by silica gel column chromatography (dry loaded from $CHCl_3$, elution with hexanes) afforded 0.066 g (0.16 mmol, approximately 80% over 2 steps) **11** as a white solid. Mp 149−150 °C; ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.02 (s, 2H), 7.62 (dt, J = 8.4, 2.4 Hz, 2H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 153.7 (d, J = 251.3), 152.3 (m,[16] J = 254.5, 3.7 Hz), 123.0 (dt, J = 16.8, 2.3), 119.9 (dd, J = 7.6, 2.5), 117.6 (d, J = 25.7), 116.3 (m), 108.2 (q, J = 12.9); IR (thin film): 3050, 1602, 1425, 1292, 1185, 1056, 850, 824, 797 cm^{-1}; TLC R_f = 0.44 (hexanes); HRMS (ESI) calcd for $[C_{14}H_3Br_2F_4]^-$ 404.8538, found 404.8596.

*1,4,5,8-Tetrafluoro-3,6-bis(phenylethynyl)phenanthrene (**12**).* In a 25 mL Schlenk flask equipped with a stir bar and a cold finger under an Ar atmosphere was added 3,6-dibromo-1,4,5,8-tetrafluorophenanthrene **11** (0.954 g, 2.34 mmol), bis(triphenylphosphine)-palladium-(II) chloride (0.049 g, 0.070 mmol), and copper(I) iodide (0.013 g, 0.070 mmol). The atmosphere was then purged by evacuating and backfilling with Ar three times. Triethylamine (10.0 mL) and degassed phenylacetylene (564 μL, 5.14 mmol) were then added via syringe. The solution was heated to 80 °C for 18 h in an oil bath. The reaction was cooled to room temperature and transferred to a separatory funnel. The reaction mixture was diluted with CH_2Cl_2 and washed with saturated ammonium chloride. The aqueous layer was further extracted with CH_2Cl_2 (3 × 100 mL), and the combined organic layers were dried over Na_2SO_4. Following concentration *in vacuo*, the material was purified by silica gel column chromatography (dry loaded from CH_2Cl_2, elution first with hexanes, then 9:1 hexanes:CH_2Cl_2) to afford 0.822 g (1.82 mmol, 78%) of **12** as a yellow-orange solid. Mp 154−164 °C (dec.); ^{1}H NMR (500 MHz, $CDCl_3$), δ 7.98 (s, 2H), 7.58−7.65 (m, 4H), 7.47 (dt, J = 9.2, 2.3 Hz, 2H), 7.42−7.35 (m, 6H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 156.2 (m,[16] J = 259.7, 2.6 Hz), 153.7 (d, J = 247.6 Hz), 131.8, 129.0, 128.4, 123.6 (dt, J = 16.8, 2.7 Hz), 122.5, 120.2 (dd, J = 7.6, 2.4 Hz), 116.2 (m), 115.8 (d, J = 24.3 Hz), 110.8 (q, J = 11.1 Hz), 96.8 (t, J = 2.3 Hz), 82.7 (d, J = 2.8 Hz); IR (thin film): 3053, 2929, 2211, 1615, 1489, 1436, 1425, 100, 1319, 1185, 1089, 1005, 886, 860, 815, 751, 685 cm^{-1}; TLC R_f = 0.34 (9:1 hexanes:CH_2Cl_2); HRMS (ESI) calcd for $[C_{30}H_{14}F_4]^+$ 450.1032, found 450.1027.

*5,8-Difluoro-2,11-diphenylphenanthro[4,3-b:5,6-b′]difuran (**2a**).* To a 2 mL cone-shaped microwave vial equipped with a stir bar under an Ar atmosphere was added 1,4,5,8-tetrafluoro-3,6-bis-

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(phenylethynyl)phenanthrene **12** (0.100 g, 0.22 mmol) followed by DMSO (850 μL), and 6.0 M KOH (150 μL, 0.90 mmol). The vial was sealed and heated to 155 °C for 6 d in an aluminum block. After cooling to room temperature, the seal was removed, and the reaction was diluted with $CHCl_3$ and poured into a separatory funnel. The reaction was partitioned between $CHCl_3$ and water (15 mL each), and the aqueous layer extracted twice with additional $CHCl_3$ (2 × 15 mL). The combined organics were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. Purification by silica gel column chromatography (dry loaded from $CHCl_3$, elution with hexanes) afforded 63 mg (0.14 mmol, 64%) of **2a** as a white solid. Mp 200−209 °C (dec.); ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.14 (s, 2H), 7.87 (dt, *J* = 7.0, 1.5 Hz, 4H), 7.57 (d, *J* = 9.3 Hz, 4H), 7.20 (s, 2H), 7.19 (tt, *J* = 7.4, 1.3 Hz, 2H), 7.09 (tt, *J* = 7.5, 1.8 Hz, 4H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 156.8, 155.4 (d, *J* = 243.7 Hz), 147.3, 129.8, 128.6, 128.5, 127.3 (d, *J* = 1.6 Hz), 125.7, 120.8 (d, *J* = 18.3 Hz), 118.8 (dd, *J* = 9.2, 2.2 Hz), 114.7 (dd, *J* = 4.9, 2.8 Hz), 104.6 (d, *J* = 24.2 Hz), 102.5 (d, *J* = 4.2 Hz); IR (thin film): 3055, 1617, 1458, 1437, 1420, 1362, 1339, 1309, 1209, 1020, 848, 760 cm^{-1}; UV/vis λ_{max} ($CHCl_3$): 298, 310, 360, 376, 397 nm; TLC R_f = 0.31 (9:1 hexanes:CH_2Cl_2); HRMS (ESI) calcd for $[C_{30}H_{16}F_2O_2]^+$ 446.1118, found 446.1118.

*5,8-Difluoro-2,11-diphenylphenanthro[4,3-b:5,6-b′]dithiophene (**2b**).* To a 2 mL cone-shaped microwave vial equipped with a stir bar and under an Ar atmosphere was added sodium sulfide nonahydrate (0.205 g, 0.85 mmol), followed by DMSO (1.0 mL) and 1,4,5,8-tetrafluoro-3,6-bis(phenylethynyl)phenanthrene **12** (0.100 g, 0.22 mmol). The vessel was sealed and heated to 90 °C for 18 h in an aluminum block. After cooling to room temperature, the seal was removed and the product precipitated from solution by the addition of water (5 mL). The precipitate was isolated by vacuum filtration, the solids dissolved in CH_2Cl_2, dried over Na_2SO_4, and concentrated *in vacuo*. Purification by silica gel column chromatography (loaded in minimum CH_2Cl_2, elution with hexanes) afforded 52 mg (0.11 mmol, 49%) of **2b** as a yellow solid. Mp 231−239 °C (dec.); ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.19 (s, 2H), 7.74−7.82 (m, 4H), 7.71 (s, 2H), 7.43 (tt, *J* = 7.9, 2.1 Hz, 4H), 7.36 (tt, *J* = 7.5, 1.3 Hz, 2H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 156.9, (d, *J* = 247.5 Hz), 143.2, 140.6 (d, *J* = 10.2 Hz), 133.7, 130.0, 129.1, 128.5, 126.7, 125.5, 122.5 (d, *J* = 17.5 Hz), 119.3 (d, *J* = 5.0 Hz), 107.5 (d, *J* = 22.4 Hz); IR (thin film): 3057, 1616, 1558, 1540, 1447, 1395, 1237, 1207, 1057, 860, 756, 724 cm^{-1}; UV/vis λ_{max} ($CHCl_3$): 312, 324, 382 nm; TLC R_f = 0.30 (9:1 hexanes:CH_2Cl_2); HRMS (ESI) calcd for $[C_{30}H_{16}F_2S_2]^+$ 478.0661, found 478.0675.

*5,8-Difluoro-2,11-diphenylphenanthro[4,3-b:5,6-b′]diselenophene (**2c**).* To a 10 mL round-bottom flask equipped with a stir bar and under an Ar atmosphere was added sodium borohydride (27.5 mg, 0.73 mmol), followed by anhydrous ethanol (1.5 mL). The reaction was cooled to 0 °C in an ice bath; selenium powder (52 mg, 0.66 mmol) was added, and the reaction was stirred at 0 °C for 40 min [**CAUTION**[15]]. 1,4,5,8-Tetrafluoro-3,6-bis(phenylethynyl)-phenanthrene **12** (0.70 g, 0.155 mmol) was then added, followed by DMSO (3.0 mL). The flask was equipped with a short path condenser, and the solution was heated to 120 °C in an oil bath and held there for 18 h, allowing the ethanol to distill out. The reaction was then cooled to room temperature, and nitrogen gas was actively bubbled through the solution for 20 min. The reaction was then diluted with CH_2Cl_2, and poured into a separatory funnel. The reaction was partitioned between CH_2Cl_2 and water (15 mL each), and the aqueous layer extracted once with additional CH_2Cl_2 (15 mL). The combined organics were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. Purification by silica gel column chromatography (dry loaded from $CHCl_3$, elution first with hexanes, and then with a step gradient of 5%, 10%, and then 15% CH_2Cl_2:hexanes) afforded 38 mg (0.067 mmol, 43%) of **2c** as a yellow solid. Mp 256−279 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$), δ 8.15 (s, 2H), 7.88 (s, 2H), 7.81 (d, *J* = 10.1 Hz, 2H), 7.70 (dt, *J* = 7.0, 1.4 Hz, 4H), 7.43 (tt, *J* = 7.6, 1.4 Hz, 4H), 7.36 (tt, *J* = 7.4, 2.1 Hz, 2H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$), δ 157.1 (d, *J* = 247.0 Hz), 147.3, 143.7, 135.4, 130.9, 129.1, 128.8, 128.6, 127.0, 122.8 (d, *J* = 4.2 Hz), 122.5 (d, *J* = 17.0 Hz), 119.2 (d, *J* = 8.8 Hz), 109.3 (d, *J* = 21.9 Hz); IR (ATR): 3051, 3029, 2922, 2851, 1614, 1497, 1445, 1385, 1235, 1135, 1047, 1004, 865, 808, 754, 687, 636 cm^{-1}; UV/vis λ_{max} ($CHCl_3$): 307, 367 nm; TLC R_f = 0.28 (9:1 hexanes:CH_2Cl_2); HRMS (ESI) calcd for $[C_{30}H_{16}F_2Se_2]^+$ 573.9551, found 573.9539.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.joc.0c00052.

Crystallographic information for compounds **1a** and **1b**; NMR spectra for compounds **1a−c**, **2a−c**, **5**, and **7−12**; UV−vis spectra for compounds **1a−c** and **2a−c** (PDF)

X-ray crystallographic data for **1a** (CIF)

X-ray crystallographic data for **1b** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

Jeffrey L. Katz − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States;* orcid.org/0000-0001-6975-5880; Email: jlkatz@colby.edu

Authors

Samuel M. Hoenig − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Youmian Yan − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Emily A. Dougherty − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Reuben Hudson − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States;* orcid.org/0000-0001-9612-681X

Sava Petovic − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Christopher K. Lee − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Yusheng Hu − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Lucas S. Gomez − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.joc.0c00052

Notes

The authors declare no competing financial interest.

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