Palladium-catalyzed enol/enolate directed oxidative annulation: functionalized naphthofuroquinones synthesis and bioactivity evaluation

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1. General Information

Chemicals and solvents were purchased from commercial suppliers and used as received. $^1$H and $^{13}$C NMR spectra were recorded on Inova 400 or Bruker VNMRS 600 spectrometer. Chemical shifts were reported in parts per million (ppm), and the residual solvent peak was used as an internal reference: proton (chloroform $\delta$ 7.26), carbon (chloroform $\delta$ 77.0) or tetramethylsilane (TMS $\delta$ 0.00) was used as a reference. Multiplicity was indicated as follows: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), dd (doublet of doublet), bs (broad singlet). Coupling constants were reported in Hertz (Hz). All high-resolution mass spectra were obtained on a a ThermoFisher Scientific LTQ-Orbitrap XL. For thin layer chromatography (TLC), Merck pre-coated TLC plates (Merck 60 F254) were used, and compounds were visualized with a UV light at 254 nm. Further visualization was achieved by staining with iodine. Flash chromatography separations were performed on Merck 60 (0.040-0.063 mm) mesh silica gel.

2. Preparation of Starting Materials

2-Hydroxy-1,4-naphthoquinone 1a and diphenylacetylene 2a were commercially available. Others 2-hydroxy-1,4-naphthoquinones$^1$ and alkynes$^2,3$ were prepared according to literature, respectively.

3. Optimization of reaction conditions

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>Catalyst</th>
<th>Additives</th>
<th>Temp/$^\circ$C</th>
<th>Yield/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MeCN</td>
<td>Pd(OAc)$_2$</td>
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<td>42 %</td>
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<tr>
<td>2</td>
<td>MeCN</td>
<td>Pd(OAc)$_2$</td>
<td>Oxone/C$_2$CO$_3$</td>
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<td>No reaction</td>
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<tr>
<td>3</td>
<td>IPA</td>
<td>Pd(OAc)$_2$</td>
<td>Oxone</td>
<td>100</td>
<td>No reaction</td>
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<tr>
<td></td>
<td>solvent</td>
<td>Pd(OAc)$_2$</td>
<td>Oxone</td>
<td></td>
<td></td>
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<tr>
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<td>----------------</td>
<td>--------------</td>
<td>-------</td>
<td>-----</td>
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</tr>
</tbody>
</table>
| 4 | MeOH           | Pd(OAc)$_2$ | Oxone | 100 | 17 %  
| 5 | Diethyl ether  | Pd(OAc)$_2$ | Oxone |  80 | No reaction  
| 6 | CHCl$_3$       | Pd(OAc)$_2$ | Oxone |  80 | 14 %  
| 7 | DCE            | Pd(OAc)$_2$ | Oxone | 100 | 22 %  
| 8 | Toluene        | Pd(OAc)$_2$ | Oxone | 100 | 21 %  
| 9 | 1,4-Dioxane    | Pd(OAc)$_2$ | Oxone | 100 | No reaction  
|10 | THF            | Pd(OAc)$_2$ | Oxone |  80 | No reaction  
|11 | DMF            | Pd(OAc)$_2$ | Oxone | 100 | No reaction  
|12 | DMA            | Pd(OAc)$_2$ | Oxone | 100 | No reaction  
|13 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone | 100 | 61 %  
|14 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ | 100 | 71 %  
|15 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/DDQ | 100 | No reaction  
|16 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/PPPh$_3$ | 100 | 69 %  
|17 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/CuCl$_2$ | 100 | No reaction  
|18 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/CuOAc | 100 | No reaction  
|19 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/AgOAc | 100 | No reaction  
|20 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/PCy$_3$ | 100 | <10 %  
|21 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/dppe | 100 | No reaction  
|22 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ | 100 | 77 %  
|23 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ | 120 | 75 %  
|24 | MeCN/HOAc (v/v = 1:1) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ | 100 | 50 %  
|25 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ/N$_2$ | 100 | 64 %  
|26 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ |  60 | 55 %  
|27 | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ |  80 | 59 %  
|28 | MeCN/HOAc (v/v = 1:2) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ | 100 | 61 %  
|29[a] | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ | 100 | 52 %  
|30[b] | MeCN/HOAc (v/v = 3:1) | Pd(OAc)$_2$ | Oxone/BQ/O$_2$ | 100 | 68 %  

Reaction condition: HOAc/MeCN (1:3, v/v) 2 mL, 2-hydroxy-1,4-naphthoquinone 1a (0.2 mmol, 1 equiv.).
diphenylacetylene 2a (1.0 mmol, 3 equiv.), Pd(OAc)$_2$ 10 mol%, Oxone 2 equiv., BQ 1 equiv., O$_2$ 1 atm, reaction time 24 hours; [a] BQ 2 equiv.; [b] Oxone 4 equiv.

### Reaction Condition

Solvent 2 mL, 2-hydroxy-1,4-naphthoquinone 1a (0.2 mmol, 1 equiv.), diphenylacetylene 2a (1.0 mmol, 5 equiv.), Pd(OAc)$_2$ 10 mol%, CuCl$_2$ 2 equiv., N$_2$ 1 atm, reaction time 24-40 hours. [a] Pd(OAc)$_2$ 5 mol%. [b] CuCl$_2$ 4 equiv.

### Table

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>Catalyst</th>
<th>Additives</th>
<th>Temp/°C</th>
<th>Yield/%</th>
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<td>CuCl$_2$</td>
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<td>Trace product</td>
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<td>CuCl$_2$</td>
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<td>Cu(OAc)$_2$</td>
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<td>Cu(ClO$_4$)$_2$/O$_2$</td>
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<td>Trace product</td>
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</tbody>
</table>
4. Representative Procedure for Palladium-Catalyzed Oxidative Annulation Reaction

a) Procedure for palladium-catalyzed 1,2-naphthofuroquinone synthesis (Typical Procedure A)

\[
\begin{align*}
\text{Pd(OAc)}_2 (10 \text{ mol}\%), \text{ Oxone (2 equiv)} \\
\text{BQ (1 equiv), } \text{O}_2 (1 \text{ atm}) \\
\text{HOAc/MecN(1:3 v/v)} \\
24 \text{ h, } 100^\circ\text{C}
\end{align*}
\]

To a solution of diphenylacetylene 2a (178.0 mg, 1.0 mmol) and 2-hydroxy-1,4-naphthoquinone 1a (34.8 mg, 0.2 mmol) in 2.0 ml MeCN/HOAc (v/v = 3:1), palladium acetate (4.5 mg, 0.02 mmol) as catalyst, oxone (245.6 mg, 0.4 mmol) and benzoquinone (21.7 mg, 0.2 mmol) as an oxidant were added. The reaction was refluxed at 100 °C for 24 h under O\(_2\). The reaction mixture was cooled to room temperature and the solvent was removed by evaporation and the residue was directly purified by silica gel flash chromatography, eluted by hexane/EtOAc=25:1 then 10:1 to afford 51.8 mg (74 % yield) of the desired product 3a as dark red solid.

b) Procedure for palladium-catalyzed cyclobutene fused 1,4-naphthofuroquinone synthesis (Typical Procedure B)

\[
\begin{align*}
\text{Pd(OAc)}_2 (10 \text{ mol}\%), \text{ CuCl}_2 (2 \text{ equiv}) \\
\text{DMA, } 100^\circ\text{C} \\
24 \text{ h, } \text{N}_2 (1 \text{ atm})
\end{align*}
\]

To a solution of diphenylacetylene 2a (178.0 mg, 1.0 mmol) and 2-hydroxy-1,4-naphthoquinone 1a (34.8 mg, 0.2 mmol) in 2.0 ml DMA, palladium acetate (4.5 mg, 0.02 mmol) as catalyst and copper (II) chloride (57.2 mg, 0.4 mmol) as an oxidant were added. The reaction was refluxed at 100 °C for 24 h under N\(_2\). The reaction mixture was cooled to room temperature and the solvent was removed by evaporation and the residue was directly purified by silica gel flash chromatography, eluted by hexane/EtOAc=25:1 then 10:1 to afford 71.8 mg (68 % yield) of the desired product 8 as pale yellow solid.
c) Procedure for palladium-catalyzed late-stage functionalization (Typical Procedure C)

To a solution of N-protected efavirenz (197.4 mg, 3.0 mmol) and 2-hydroxy-1,4-naphthoquinone 1a (34.8 mg, 0.2 mmol) in 2.0 ml MeCN/HOAc (v/v = 3:1), palladium acetate (4.5 mg, 0.02 mmol) as catalyst, oxone (245.6 mg, 0.4 mmol) and benzoquinone (21.7 mg, 0.2 mmol) as an oxidant were added. The reaction was refluxed at 100 °C for 24 h under O₂. The reaction mixture was cooled to room temperature and the solvent was removed by evaporation and the residue was directly purified by silica gel flash chromatography, eluted by hexane/EtOAc=10:1 then 4:1 to afford 47.6 mg (45 % yield) of the desired product 5a as pale-yellow solid.

2,3-Diphenylnaphtho[1,2-b]furan-4,5-dione (3a)

Following the procedure A, 3a was obtained as a dark red solid (53.9 mg, 77%).

Melting Point: 199-201°C.

^1H NMR (500 MHz, CDCl₃): δ = 8.09 (d, J = 7.6 Hz, 1H), 7.86 (d, J = 7.6 Hz, 1H), 7.70 (t, J = 7.6 Hz, 1H), 7.51 – 7.41 (m, 7H), 7.33 – 7.32 (m, 3H), 6.85 – 6.83 (m, 1H).

^13C NMR (125 MHz, CDCl₃): δ = 181.04, 174.94, 159.65, 152.01, 135.90, 131.89, 130.89, 130.66, 130.61, 130.40, 129.56, 129.42, 129.39, 129.08, 129.02, 128.91, 127.08, 127.04, 122.87, 122.31, 122.25.

7-Methyl-2,3-diphenynaphtho[1,2-b]furan-4,5-dione (3b)

Following the procedure A, 3b was obtained as a dark red solid (57.5 mg, 79%).

Melting Point: 206-208°C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 7.90$ (s, 1H), 7.74 (d, $J = 7.8$ Hz, 1H), 7.51 – 7.49 (m, 2H), 7.44 – 7.40 (m, 4H), 7.32 – 7.30 (m, 2H), 6.87 – 6.81 (m, 2H), 2.44 (s, 3H);

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta = 181.36$, 175.04, 160.22, 151.61, 141.41, 136.48, 131.91, 131.53, 130.75, 130.43, 129.69, 129.42, 129.26, 129.06, 128.99, 128.85, 127.05, 126.50, 126.66, 122.92, 122.23, 121.59, 21.94;

HRMS (ESI): calcd for C$_{25}$H$_{17}$O$_3$ [M+H]$^+$ 365.1172, found 365.1178.

7-Methoxy-2,3-diphenynaphtho[1,2-b]furan-4,5-dione (3c)

Following the procedure A, 3c was obtained as a dark red solid (61.6 mg, 81%).

Melting Point: 218-220°C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 7.77$ (d, $J = 8.5$ Hz, 1H), 7.59 (d, $J = 2.6$ Hz, 1H), 7.50 – 7.48 (m, 2H), 7.45 – 7.43 (m, 2H), 7.42 – 7.40 (m, 2H), 7.31 – 7.30 (m, 3H), 7.19 (dd, $J = 8.5$, 2.6 Hz, 1H), 6.85 – 6.83 (m, 2H), 3.91 (s, 3H);

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta = 181.16$, 174.96, 161.96, 160.65, 151.19, 131.91, 131.14, 130.79, 130.41, 129.72, 129.16, 129.04, 128.97, 128.82, 127.04, 126.97, 125.66, 124.65, 122.36, 122.11, 122.08, 120.43, 115.10,
56.36;

HRMS (ESI): calcd for C_{25}H_{17}O_{4} [M+H]^+ 381.1121, found 381.1122.

[7,8-\textit{d}] [1,3] dioxole-2,3-diphenynaphtho[1,2-\textit{b}]furan-4,5-dione (3d)

\[
\begin{array}{c}
\text{O} \\
\text{O} \\
\text{3d}
\end{array}
\]

Following the procedure \textit{A}, 3d was obtained as a dark red solid (55.9 mg, 71%).

\textbf{Melting Point:} 237-239°C.

\textit{1H NMR (500 MHz, CDCl}_3\textit{):} \(\delta = 7.46 - 7.42 \) (m, 7H), 7.36 - 7.28 (m, 5H), 6.15 (s, 2H).

\textit{13C NMR (125 MHz, CDCl}_3\textit{):} \(\delta = 179.29, 174.97, 159.63, 154.15, 151.43, 150.01, 130.64, 130.43, 130.39, 129.62, 129.26, 129.07, 129.02, 128.99, 128.88, 126.99, 126.13, 125.27, 123.47, 122.31, 110.73, 103.16, 103.01.

HRMS (ESI): calcd for C_{25}H_{15}O_{5} [M+H]^+ 395.0914, found 395.0906.

7,8-Dimethoxy-2,3-diphenynaphtho[1,2-\textit{b}]furan-4,5-dione (3e)

\[
\begin{array}{c}
\text{MeO} \\
\text{MeO} \\
\text{3e} \\
\text{Ph}
\end{array}
\]

Following the procedure \textit{A}, 3e was obtained as a dark red solid (59.1 mg, 72%).

\textbf{Melting Point:} 228-230°C.

\textit{1H NMR (500 MHz, CDCl}_3\textit{):} \(\delta = 7.55 \) (s, 1H), 7.50 - 7.48 (m, 2H), 7.45 - 7.42 (m, 2H), 7.41 - 7.38 (m, 3H), 7.33 - 7.31 (m, 3H), 7.22 (s, 1H), 4.09 (s, 3H), 3.98 (s, 3H).

\textit{13C NMR (125 MHz, CDCl}_3\textit{):} \(\delta = 179.78, 175.35, 159.96, 155.57, 151.35, 151.01, 130.65, 130.41, 129.70, 129.22, 129.04, 128.94, 128.83, 127.12, 124.10, 123.29, 122.41, 120.76, 112.93, 104.89, 57.13, 56.88.

**HRMS (ESI):** calcd for C_{26}H_{19}O_{5} [M+H]^+ 411.1227, found 411.1230.

**7,9-Dimethyl-2,3-diphenylnaptho[1,2-b]furan-4,5-dione (3f)**

![Chemical Structure 3f](image)

Following the procedure A, 3f was obtained as a dark red solid (38.6 mg, 51%).

**Melting Point:** 239-241°C.

**^1H NMR (500 MHz, CDCl₃):** \(\delta = 7.79 \text{ (s, } 1\text{H}), 7.48 - 7.41 \text{ (m, } 7\text{H}), 7.32 - 7.30 \text{ (m, } 4\text{H}), 2.80 \text{ (s, } 3\text{H}), 2.38 \text{ (s, } 3\text{H}).

**^13C NMR (125 MHz, CDCl₃):** \(\delta = 181.79, 175.31, 161.48, 151.22, 140.74, 139.89, 135.71, 130.85, 130.40, 130.21, 129.68, 129.11, 129.08, 129.00, 128.83, 126.58, 124.60, 122.02, 121.80, 22.31, 21.63.

**HRMS (ESI):** calcd for C_{26}H_{19}O_{5} [M+H]^+ 379.1329, found 379.1332.

**9-Methoxy-2,3-diphenylnaptho[1,2-b]furan-4,5-dione (3g)**

![Chemical Structure 3g](image)

Following the procedure A, 3g was obtained as a dark red solid (44.1 mg, 58%).

**Melting Point:** 220-222°C.

**^1H NMR (500 MHz, CDCl₃):** \(\delta = 7.70 \text{ (dd, } J = 7.6, 0.9 \text{ Hz, } 1\text{H}), 7.51 - 7.49 \text{ (m, } 2\text{H}), 7.45 - 7.38 \text{ (m, } 6\text{H}), 7.31 - 7.28 \text{ (m, } 3\text{H}), 7.26 - 7.23 \text{ (m, } 1\text{H}), 4.09 \text{ (s, } 3\text{H}).

**^13C NMR (125 MHz, CDCl₃):** \(\delta = 181.38, 175.04, 159.31, 156.21, 151.30, 151.52, 131.50, 130.91, 130.44, 129.83, 128.98, 128.94, 128.75, 126.62, 123.63, 122.36, 121.56, 119.42, 117.20, 57.04.

**HRMS (ESI):** calcd for C_{25}H_{17}O_{4} [M+H]^+ 381.1121, found 381.1125.
7-Fluoro-2,3-diphenylnaphtho[1,2-b]furan-4,5-dione (3h)

Following the procedure A, 3h was obtained as a dark red solid (36.8 mg, 50%).

**Melting Point:** 224-226°C.

**1H NMR (400 MHz, CDCl₃):** \( \delta = 7.87 \) (dd, \( J = 8.5, 4.9 \) Hz, 1H), 7.77 (dd, \( J = 8.3, 2.6 \) Hz, 1H), 7.51 – 7.48 (m, 2H), 7.43 – 7.40 (m, 6H), 7.34 – 7.31 (m, 3H).

**13C NMR (101 MHz, CDCl₃):** \( \delta = 180.05, 174.52, 165.49, 162.96, 159.12, 151.98, 131.51 \) (d, \( J_{C,F} = 6.6 \) Hz), 130.42, 130.35, 129.45, 129.40, 129.11, 129.05, 128.99, 127.06, 125.55 (d, \( J_{C,F} = 4.6 \) Hz), 125.06 (d, \( J_{C,F} = 8.0 \) Hz), 123.12, 122.89, 122.21, 121.53, 121.51, 118.14, 117.90.

**19F NMR (376 MHz, CDCl₃):** \( \delta = -107.36 \) (s, F) ppm.

**HRMS (ESI):** calcd for \( C_{24}H_{14}O_3F \) [M+H]^+ 369.0922, found 369.0923.

7-Chloro-2,3-diphenylnaphtho[1,2-b]furan-4,5-dione (3i)

Following the procedure A, 3i was obtained as a dark red solid (42.3 mg, 55%).

**Melting Point:** 232-234°C.

**1H NMR (500 MHz, CDCl₃):** \( \delta = 8.07 \) (d, \( J = 2.1 \) Hz, 1H), 7.83 (d, \( J = 8.2 \) Hz, 1H), 7.69 (dd, \( J = 8.2, 2.1 \) Hz, 1H), 7.53 – 7.51 (m, 2H), 7.47 – 7.43 (m, 4H), 7.35 – 7.34 (m, 3H), 7.21 – 7.20 (m, 1H).

**13C NMR (125 MHz, CDCl₃):** \( \delta = 180.07, 174.21, 158.77, 152.32, 137.26, 135.80, 130.89, 130.49, 130.39, 130.35, 130.30, 129.54, 129.33, 129.12, 129.06, 129.02, 128.76, 127.31, 127.09, 124.15, 122.38, 122.25.

**HRMS (ESI):** calcd for \( C_{24}H_{14}O_3Cl \) [M+H]^+ 385.0626, found 385.0628.
7-Bromo-2,3-diphenyl-naphtho[1,2-b]furan-4,5-dione (3j)

Following the procedure A, 3j was obtained as a dark red solid (48.8 mg, 57%).

Melting Point: 245-247°C.

$^1$H NMR (500 MHz, CDCl$_3$): δ = 8.20 (d, $J = 2.0$ Hz, 1H), 8.16 (dd, $J = 8.4$, 1.5 Hz, 1H), 7.99 (d, $J = 8.0$ Hz, 1H), 7.50 – 7.46 (m, 2H), 7.45 – 7.41 (m, 4H), 7.33 – 7.29 (m, 3H), 7.19 – 7.17 (m, 2H).

$^{13}$C NMR (125 MHz, CDCl$_3$): δ = 180.06, 174.14, 158.82, 152.44, 138.74, 133.83, 130.50, 130.43, 130.37, 130.32, 129.57, 129.38, 129.13, 129.08, 129.04, 128.77, 127.73, 127.13, 125.25, 124.23, 122.48.


2,3,7-Triphenyl-naphtho[1,2-b]furan-4,5-dione (3k)

Following the procedure A, 3k was obtained as a dark red solid (45.2 mg, 53%).

Melting Point: 269-271°C.

$^1$H NMR (500 MHz, CDCl$_3$): δ = 8.34 (s, 1H), 7.93 (s, 2H), 7.68 (d, $J = 7.7$ Hz, 2H), 7.52 – 7.41 (m, 10H), 7.34 – 7.32 (m, 3H);

$^{13}$C NMR (125 MHz, CDCl$_3$): δ = 181.12, 174.95, 159.72, 152.03, 143.56, 139.13, 134.00, 130.60, 130.42, 129.81, 129.62, 129.57, 129.41, 129.39, 129.11, 129.09, 129.02, 128.92, 127.55, 127.35, 127.10, 123.46, 122.38, 122.14.
HRMS (ESI): calcd for C_{30}H_{18}NaO_{3} [M+Na]^+ 449.1148, found 449.1164.

8-Chloro-2,3-diphenylnaphtho[1,2-b]furan-4,5-dione (3l)

\[
\begin{array}{c}
\text{O} \\
\text{Cl} \\
\text{3l}
\end{array}
\]

Following the procedure A, 3l was obtained as a dark red solid (36.9 mg, 48%).

Melting Point: 223-225°C.

\(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta = 8.02 \, (d, \, J = 8.3 \, Hz, \, 1H), \, 7.83 \, (d, \, J = 1.9 \, Hz, \, 1H), \, 7.52 - 7.50 \, (m, \, 2H), \, 7.45 - 7.42 \, (m, \, 6H), \, 7.35 - 7.32 \, (m, \, 3H)\).

\(^{13}\)C NMR (125 MHz, CDCl\(_3\)): \(\delta = 179.95, 174.50, 157.95, 152.64, 142.85, 132.32, 130.53, 130.35, 130.32, 130.29, 129.63, 129.25, 129.14, 129.07, 129.04, 127.46, 127.13, 123.02, 122.89, 122.47\).

HRMS (ESI): calcd for C_{24}H_{14}O_{3}Cl [M+H]^+ 385.0626, found 385.0629.

8-Chloro-2,3-diphenylnaphtho[1,2-b]furan-4,5-dione (3m)

\[
\begin{array}{c}
\text{O} \\
\text{Br} \\
\text{Ph} \\
\text{3m}
\end{array}
\]

Following the procedure A, 3m was obtained as a dark red solid (51.4 mg, 46%).

Melting Point: 233-235°C.

\(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta = 8.10 \, (dd, \, J = 7.6, 1.2 \, Hz, \, 1H), \, 7.91 \, (dd, \, J = 8.1, 1.2 \, Hz, \, 1H), \, 7.59 - 7.57 \, (m, \, 2H), \, 7.44 \, (s, \, 5H), \, 7.33 - 7.28 \, (m, \, 4H)\).

\(^{13}\)C NMR (125 MHz, CDCl\(_3\)): \(\delta = 180.42, 174.66, 157.18, 152.22, 142.10, 132.03, 130.70, 130.60, 130.57, 130.36, 129.47, 129.29, 129.14, 129.05, 128.23, 126.82, 124.00, 121.96, 118.23\).
HRMS (ESI): calcd for C_{24}H_{14}O_{3}Br [M+H]^+ 429.0120, found 429.0126.

2,3-Diphenylanthra[1,2-b]furan-4,5-dione (3n)

Following the procedure A, 3n was obtained as a dark red solid (49.6 mg, 62%).

Melting Point: 267-269°C.

^1H NMR (500 MHz, CDCl₃): δ = 9.41 (d, J = 8.7 Hz, 1H), 8.16 (d, J = 8.4 Hz, 1H), 7.99 (d, J = 8.4 Hz, 1H), 7.84 (d, J = 8.1 Hz, 1H), 7.71 – 7.68 (m, 1H), 7.56 – 7.42 (m, 8H), 7.35 – 7.34 (m, 3H).

^13C NMR (125 MHz, CDCl₃): δ = 183.69, 175.26, 160.26, 152.47, 137.66, 132.85, 131.56, 130.59, 130.53, 130.37, 129.63, 129.46, 129.12, 129.06, 128.99, 128.10, 127.17, 127.14, 123.56, 122.63, 121.62, 119.68.

HRMS (ESI): calcd for C_{28}H_{17}O_{3} [M+H]^+ 401.1172, found 401.1168.

6-Methyl-1,2-diphenylphenanthro[1,2-b]furan-10,11-dione (3o)

Following the procedure A, 3o was obtained as a dark red solid (43.9 mg, 53%).

Melting Point: 258-260°C.

^1H NMR (500 MHz, CDCl₃): δ = 9.20 (s, 1H), 8.09 (d, J = 8.4 Hz, 1H), 7.88 (d, J = 8.4 Hz, 1H), 7.71 – 7.62 (m, 1H), 7.55 – 7.42 (m, 7H), 7.39 – 7.29 (m, 4H), 2.54 (s, 3H).

^13C NMR (125 MHz, CDCl₃): δ = 183.71, 175.35, 160.39, 152.25, 142.19, 137.34, 133.35, 133.08, 130.57, 130.49, 130.35, 130.25, 129.63, 129.42, 129.38, 129.09, 129.03, 128.93, 127.10, 126.08, 122.88, 122.50, 121.44,
118.78, 22.99.

HRMS (ESI): calcd for C_{29}H_{19}O_{3} [M+H]' 415.1328, found 415.1331.

2,3-Bis(4-methoxyphenyl)naphtho[1,2-b]furan-4,5-dione (3p)

Following the procedure A, 3p was obtained as a dark red solid (63.1 mg, 77%).

Melting Point: 212-214°C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ = 8.06 (d, $J$ = 7.6 Hz, 1H), 7.81 (d, $J$ = 7.6 Hz, 1H), 7.68 – 7.65 (m, 1H), 7.46 – 7.44 (m, 3H), 7.37 – 7.36 (m, 2H), 6.94 – 6.93 (m, 2H), 6.86 – 6.84 (m, 2H), 3.86 (s, 3H), 3.82 (s, 3H);

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ = 181.23, 175.09, 160.48, 160.03, 159.23, 152.02, 135.83, 131.72, 130.79, 130.37, 129.30, 129.23, 128.60, 122.86, 122.69, 122.33, 120.56, 114.57, 114.46, 55.79, 55.73;

HRMS (ESI): calcd for C_{26}H_{19}O_{5} [M+H]' 411.1227, found 411.1232.

2,3-Bis(4-fluorophenyl)naphtho[1,2-b]furan-4,5-dione (3q)

Following the procedure A, 3q was obtained as a dark red solid (47.9 mg, 62%).

Melting Point: 231-233°C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ = 8.09 (d, $J$ = 7.6 Hz, 1H), 7.84 (d, $J$ = 7.6 Hz, 1H), 7.70 (t, $J$ = 7.5 Hz, 1H), 7.48 – 7.39 (m, 5H), 7.13 – 7.02 (m, 4H).
$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ = 180.85, 174.96, 164.40, 162.32, 159.76, 151.26, 135.96, 132.27, 132.20, 130.99, 130.85, 129.37, 129.13 (d, $J_{C,F}$ = 6.6 Hz), 128.80, 126.29, 125.57, 122.87, 122.01, 121.00, 116.51, 116.33, 116.18; HRMS (ESI): calcd for C$_{24}$H$_{13}$F$_2$O$_3$ [M+H]$^+$ 387.0627, found 387.0629.

2,3-Bis(4-chlorophenyl)naphtho[1,2-b]furan-4,5-dione (3r)

![Structure of 3r]

Following the procedure A, 3r was obtained as a dark red solid (49.3 mg, 59%).

Melting Point: 237-239°C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ = 8.10 (d, $J$ = 7.6 Hz, 1H), 8.03 (d, $J$ = 8.5 Hz, 1H), 7.85 (d, $J$ = 7.5 Hz, 1H), 7.73 – 7.70 (m, 1H), 7.51 (t, $J$ = 7.6 Hz, 1H), 7.46 – 7.31 (m, 7H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ = 180.73, 174.88, 160.01, 151.09, 135.99, 135.63, 135.17, 132.06, 131.74, 131.04, 131.01, 129.55, 129.47, 129.42, 129.38, 128.76, 128.67, 128.35, 127.70, 122.95, 121.89, 121.52.

HRMS (ESI): calcd for C$_{24}$H$_{12}$Cl$_2$NaO$_3$ [M+Na]$^+$ 441.0056, found 441.0055.

2,3-Di(naphthalen-2-yl)naphtho[1,2-b]furan-4,5-dione (3s)

![Structure of 3s]

Following the procedure A, 3s was obtained as a dark red solid (61.2 mg, 68%).

Melting Point: 258-260°C.
$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ = 8.12 (d, $J$ = 8.0 Hz, 2H), 8.04 (s, 1H), 7.96 (d, $J$ = 7.6 Hz, 1H), 7.89 (t, $J$ = 8.0 Hz, 2H), 7.81 (d, $J$ = 8.0 Hz, 1H), 7.78 – 7.72 (m, 3H), 7.68 (d, $J$ = 8.7 Hz, 1H), 7.55 – 7.46 (m, 7H);

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ = 181.07, 175.00, 159.99, 152.35, 135.93, 133.86, 133.74, 133.69, 133.57, 132.92, 130.93, 130.76, 130.02, 129.51, 129.05, 128.92, 128.83, 128.76, 128.61, 128.29, 128.23, 128.13, 127.97, 127.47, 127.19, 126.98, 126.73, 126.71, 124.40, 123.03, 122.67, 122.39, 112.66.

HRMS (ESI): calcd for C$_{32}$H$_{18}$NaO$_3$ [M+Na]$^+$ 473.1148, found 473.1157.

2-(Naphthalen-2-yl)-3-phenylnaphtho[1,2-b]furan-4,5-dione (3t)

Following the procedure A, 3t was obtained as a dark red solid (48.0 mg, 60%), regioisomer ratio $\approx$ 1:1.

Melting Point: 241-243°C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ = 8.11 (d, $J$ = 7.7 Hz, 1H), 8.07 (s, 1H), 7.94 (d, $J$ = 7.6 Hz, 1H), 7.93 – 7.87 (m, 1H), 7.80 – 7.71 (m, 4H), 7.54 – 7.48 (m, 5H), 7.44 – 7.42 (m, 2H), 7.31 – 7.29 (m, 1H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ = 181.06, 174.97, 159.84, 152.14, 135.91, 133.65, 133.54, 130.93, 130.72, 130.64, 130.54, 129.83, 129.48, 129.14, 129.04, 129.02, 128.89, 128.79, 128.71, 128.63, 128.23, 128.04, 127.44, 127.18, 126.98, 126.66, 124.33, 122.98, 122.71, 122.35.

3-Phenyl-2-(4-(trimethylsilyl)phenyl)naphtho[1,2-b]furan-4,5-dione (3u)

Following the procedure A, 3u obtained as a dark red solid (67.5 mg, 80%), regioisomer ratio $\approx 5:3$.

Melting Point: 207-209°C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 8.09$ (d, $J = 7.5$ Hz, 2H), 7.86 (d, $J = 7.7$ Hz, 2H), 7.72 – 7.68 (m, 2H), 7.56 – 7.50 (m, 16H), 7.35 – 7.33 (m, 4H), 0.31 (s, 9H), 0.26 (s, 9H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta = 181.07, 174.99, 159.74, 152.07, 142.36, 141.23, 135.90, 133.99, 133.91, 130.90, 130.87, 130.80, 130.69, 130.66, 130.40, 129.65, 129.54, 129.46, 129.39, 129.10, 129.07, 129.04, 128.92, 127.20, 126.01, 122.87, -0.59, -0.77.

HRMS (ESI): calcd for C$_{27}$H$_{23}$O$_3$Si [M+H]$^+$ 423.0907, found 423.0909.

2-(4-Fluorophenyl)-3-phenylnaphtho[1,2-b]furan-4,5-dione (3v).

Following the procedure A, 3v obtained as a dark red solid (46.6 mg, 63%), regioisomer ratio $\approx 3:2$.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 8.09$ (d, $J = 7.6$ Hz, 1H), 7.85 (t, $J = 7.0$ Hz, 1H), 7.70 (t, $J = 7.6$ Hz, 1H), 7.49 – 7.47 (m, 3H), 7.44 – 7.40 (m, 4H), 7.35 – 7.33 (m, 1H), 7.11 (t, $J = 8.6$ Hz, 1H), 7.02 (t, $J = 8.6$ Hz, 1H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta = 180.96, 174.91, 162.35, 159.63, 151.18, 135.92$ (d, $J_{C-F} = 4.2$ Hz), 132.28 (d, $J_{C-F} = 6.6$ Hz), 130.94, 130.78, 130.73, 130.43, 130.36, 129.55, 129.42, 129.18, 129.09 (d, $J_{C-F} = 6.6$ Hz), 129.02,

HRMS(ESI): calcd for C_{24}H_{13}FO_3 [M+H]^+ 369.0921, found 369.0931.

\(N, N\text{-Dimethyl-4,5-dioxo-2-phenyl-4,5-dihydronaphtho[1,2-b]furan-3-carboxamide (3w)}\)

\[
\begin{align*}
\text{O} & \quad \text{O} \\
\text{Ph} \quad \text{N} & \quad \text{3w}
\end{align*}
\]

Following the procedure A, 3w was obtained as a red solid (28.3 mg, 41%).

**Melting Point:** 284 – 286°C.

\(^1\text{H NMR (500 MHz, CDCl}_3\): \(\delta = 8.26 - 8.24\) (m, 1H), \(8.17 - 8.15\) (m, 1H), \(7.90 - 7.87\) (m, 2H), \(7.79 - 7.76\) (m, 2H), \(7.49 - 7.47\) (m, 3H), 3.28 (s, 3H), 2.95 (s, 3H).

\(^{13}\text{C NMR (125 MHz, CDCl}_3\): \(\delta = 180.73, 173.57, 163.90, 155.73, 151.13, 134.68, 134.48, 133.38, 132.99, 131.19, 129.85, 129.72, 128.19, 127.51, 127.43, 126.80, 115.46, 38.55, 35.59.}

HRMS (ESI): calcd for C_{21}H_{16}O_4N \([\text{M+H}]^+ 346.1073\), found 346.1076.

\(\text{Ethyl 4,5-dioxo-3-phenyl-4,5-dihydronaphtho[1,2-b]furan-2-carboxylate (3x)}\)

\[
\begin{align*}
\text{O} & \quad \text{O} \\
\text{CO}_2\text{Et} \quad \text{Ph} & \quad \text{3x}
\end{align*}
\]

Following the procedure A, 3x was obtained as a yellow solid (24.6 mg, 37%).

**Melting Point:** 196 – 198°C.

\(^1\text{H NMR (500 MHz, CDCl}_3\): \(\delta = 8.13\) (d, \(J = 7.7\) Hz, 1H), \(7.90 - 7.88\) (m, 3H), \(7.84 - 7.69\) (d, \(J = 7.6\) Hz, 1H), \(7.54 - 7.49\) (m, 4H), 4.45 (q, \(J = 7.1\) Hz, 2H), 1.41 (t, \(J = 7.1\) Hz, 3H).

\(^{13}\text{C NMR (125 MHz, CDCl}_3\): \(\delta = 180.46, 173.76, 163.43, 159.31, 156.67, 135.98, 131.23, 131.17, 130.87, 129.56, 129.26, 128.39, 128.35, 127.84, 123.14, 121.44, 113.86, 62.65, 14.42.\)
**HRMS (ESI):** calcd for C_{21}H_{15}O_{5} [M+H]^+ 347.0495, found 347.0500.

3-Methyl-2-phenylnaphtho[1,2-b]furan-4,5-dione (3y)

![Chemical structure of 3y](image)

Following the procedure A, 3y was obtained as a yellow solid (20.0 mg, 33%).

**Melting Point:** 123 – 125°C.

**{H NMR (500 MHz, CDCl₃):** δ = 8.06 (d, J = 7.6 Hz, 1H), 7.77 (d, J = 7.6 Hz, 1H), 7.71 (d, J = 7.6 Hz, 2H), 7.65 (t, J = 7.6 Hz, 1H), 7.51 – 7.39 (m, 4H), 2.54 (s, 3H).

**{C NMR (125 MHz, CDCl₃):** δ = 181.25, 176.21, 159.30, 152.20, 135.88, 130.91, 130.42, 130.13, 129.38, 129.32, 129.08, 128.98, 128.88, 126.64, 123.35, 122.67, 117.50, 10.58.

**HRMS (ESI):** calcd for C_{19}H_{13}O_{3} [M+H]^+ 289.0859, found 289.0857.

2,3-Diphenyl-2,3-dihyronaphtho[1,2-b]furan-4,5-dione (3z)

![Chemical structure of 3z](image)

Following the procedure A, 3z was obtained as a pale-yellow solid (21.8 mg, 31%).

**Melting Point:** 163 – 165°C.

**{H NMR (500 MHz, CDCl₃):** δ = 8.16 (dd, J = 6.6, 2.3 Hz, 1H), 8.01 – 7.99 (m, 1H), 7.72 – 7.70 (m, 2H), 7.42 – 7.29 (m, 10H), 5.83 (d, J = 6.6 Hz, 1H), 4.70 (d, J = 6.6 Hz, 1H).

**{C NMR (125 MHz, CDCl₃):** δ = 182.04, 178.63, 160.09, 140.76, 139.73, 134.84, 133.61, 133.55, 132.16, 129.67, 129.47, 129.44, 128.31, 127.98, 126.84, 126.75, 126.38, 125.96, 95.25, 55.93.

**HRMS (ESI):** calcd for C_{24}H_{17}O_{3} [M+H]^+ 353.1172, found 353.1176.
1,2,2a,9b-Tetraphenylicyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4a)

Following the procedure B, 4a was prepared according to the general procedure. The product was obtained as a pale-yellow solid (71.8 mg, 68%).

**Melting Point:** 281-283°C.

**1H NMR (500 MHz, CDCl₃):** δ = 8.20 – 8.18 (m, 1H), 8.10 (dd, J = 7.5, 1.5 Hz, 1H), 8.02 – 8.01 (m, 2H), 7.75 – 7.71 (m, 3H), 7.33 – 7.28 (m, 8H), 7.10 – 7.09 (m, 3H), 7.03 – 6.99 (m, 4H), 6.88 – 6.86 (m, 2H).

**13C NMR (125 MHz, CDCl₃):** δ = 182.12, 179.19, 163.30, 148.98, 138.65, 135.44, 134.76, 134.68, 133.69, 133.46, 132.99, 132.61, 132.20, 132.04, 131.91, 130.33, 130.08, 129.35, 129.11, 129.00, 128.98, 128.77, 128.68, 128.64, 128.59, 128.23, 128.19, 127.53, 127.40, 127.16, 127.05, 126.69, 125.66, 100.30, 69.30.

**HRMS (ESI):** calcd for C₅₈H₃₃O₃ [M+H]+ 529.1747, found 529.1752.

6-Methyl-1,2,2a,9b-tetraphenylicyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4b)

Following the procedure B, 4b was obtained as a pale-yellow solid (76.9 mg, 71%).

**Melting Point:** 293-295°C.

**1H NMR (500 MHz, CDCl₃):** δ = 8.07 – 8.05 (m, 2H), 8.01 – 7.99 (m, 2H), 7.76 – 7.74 (m, 2H), 7.54 (d, J = 8.0 Hz, 1H), 7.41 – 7.30 (m, 8H), 7.12 – 7.11 (m, 3H), 7.04 – 7.02 (m, 4H), 6.91 – 6.30 (m, 1H), 2.51 (s, 3H).

**13C NMR (125 MHz, CDCl₃):** δ = 182.08, 179.42, 163.17, 148.99, 144.42, 138.55, 135.48, 135.30, 134.72,
132.59, 132.20, 131.89, 131.37, 129.28, 128.52, 128.12, 127.44, 127.26, 127.07, 127.02, 125.63, 100.17, 69.29, 22.06.

**HRMS (ESI):** calcd for C_{39}H_{27}O_3 [M+H]^+ 543.1955, found 543.1980.

**6-Methoxy-1,2,2a,9b-tetraphenylcyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4c)**

![4c](image)

Following the procedure B, 4c obtained as a pale-yellow solid (87.1 mg, 78%).

**Melting Point:** >300°C.

**1H NMR (500 MHz, CDCl₃):** δ = 8.04 – 8.02 (m, 2H), 7.72 – 7.70 (m, 2H), 7.63 (d, J = 2.6 Hz, 1H), 7.39 – 7.28 (m, 7H), 7.20 (dd, J = 8.6, 2.6 Hz, 1H), 7.11 – 7.09 (m, 2H), 7.03 – 6.97 (m, 4H), 6.88 – 6.86 (m, 4H), 3.97 (s, 3H);

**13C NMR (125 MHz, CDCl₃):** δ = 181.60, 179.24, 164.00, 163.07, 149.03, 141.10, 140.79, 138.55, 135.56, 134.79, 133.87, 132.65, 132.25, 131.90, 130.03, 129.41, 129.30, 129.09, 129.01, 128.96, 128.64, 128.59, 128.21, 128.15, 127.47, 127.40, 127.05, 127.00, 125.66, 110.56, 100.17, 69.36, 56.46.

**HRMS (ESI):** calcd for C_{39}H_{27}O_4 [M+H]^+ 559.1904, found 559.1910.

**6-Tert-butyl-1,2,2a,9b-tetraphenylcyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4d)**

![4d](image)

Following the procedure B, 4d was obtained as a pale-yellow solid (87.1 mg, 78%).

**Melting Point:** 275-277 °C.

**1H NMR (500 MHz, CDCl₃):** δ = 8.18 (d, J = 2.0 Hz, 1H), 8.01 – 7.97 (m, 3H), 7.74 (dd, J = 8.1, 2.0 Hz, 1H),
7.69 – 7.67 (m, 2H), 7.35 – 7.28 (m, 6H), 7.26 – 7.24 (m, 2H), 7.07 – 7.06 (m, 3H), 7.00 – 6.94 (m, 5H), 1.38 (s, 9H).

$^1{\text{H}}$ NMR (500 MHz, CDCl$_3$): $\delta =$ 8.02 – 8.00 (m, 2H), 7.72 – 7.70 (m, 2H), 7.57 (s, 1H), 7.49 (s, 1H), 7.38 – 7.27 (m, 6H), 7.10 – 6.97 (m, 6H), 6.88 – 6.86 (m, 2H), 6.14 (d, $J =$ 8.2 Hz, 2H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta =$ 181.17, 178.02, 163.22, 153.13, 151.97, 149.00, 141.09, 140.78, 138.53, 135.50, 134.71, 132.61, 132.23, 131.90, 131.05, 130.04, 129.31, 129.09, 128.97, 128.62, 128.57, 128.48, 128.20, 128.16, 127.62, 127.49, 127.38, 127.04, 125.65, 107.16, 106.28, 103.14, 100.42, 69.27.

HRMS (ESI): calcd for C$_{39}$H$_{25}$O$_5$ [M+H]$^+$ 573.1697, found 573.1719.

6,7-Dimethoxy-1,2,2a,9b-tetraphenylcyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4f)

Following the procedure B, 4e was obtained as a pale-yellow solid (78.9 mg, 69%).

Melting Point: >300°C.

$^1{\text{H}}$ NMR (500 MHz, CDCl$_3$): $\delta =$ 8.02 – 8.00 (m, 2H), 7.72 – 7.70 (m, 2H), 7.57 (s, 1H), 7.49 (s, 1H), 7.38 – 7.27 (m, 6H), 7.10 – 6.97 (m, 6H), 6.88 – 6.86 (m, 2H), 6.14 (d, $J =$ 8.2 Hz, 2H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta =$ 181.17, 178.02, 163.22, 153.13, 151.97, 149.00, 141.09, 140.78, 138.53, 135.50, 134.71, 132.61, 132.23, 131.90, 131.05, 130.04, 129.31, 129.09, 128.97, 128.62, 128.57, 128.48, 128.20, 128.16, 127.62, 127.49, 127.38, 127.04, 125.65, 107.16, 106.28, 103.14, 100.42, 69.27.

HRMS (ESI): calcd for C$_{42}$H$_{33}$O$_3$ [M+H]$^+$ 585.2424, found 585.2431.
Following the procedure B, 4f was obtained as a pale-yellow solid (76.4 mg, 65%).

**Melting Point:** >300°C.

\(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta = 7.99\ (dd, \(J = 6.5, 3.2\ Hz, 2H\)), 7.70 – 7.67 (m, 2H), 7.57 (s, 1H), 7.52 (s, 1H), 7.37 – 7.33 (m, 3H), 7.32 – 7.28 (m, 3H), 7.27 – 7.24 (m, 2H), 7.07 – 7.06 (m, 3H), 7.01 – 6.94 (m, 5H), 4.03 (s, 3H), 3.99 (s, 3H).

\(^{13}\)C NMR (125 MHz, CDCl\(_3\)): \(\delta = 181.89, 178.60, 163.36, 154.14, 152.93, 148.97, 138.46, 135.55, 134.72, 132.60, 132.24, 130.01, 129.30, 129.08, 128.96, 128.62, 128.57, 128.55, 128.19, 128.13, 127.44, 127.38, 126.20, 109.06, 108.34, 100.28, 69.22, 57.07, 56.93.


6,8-Dimethyl-1,2,2a,9b-tetraphenylcyclobuta\([d]\)naphtho[2,3-\(b\)]furan-4,9(2a\(H\),9b\(H\))-dione (4g).

Following the procedure B, 4g was obtained as a pale-yellow solid (67.8 mg, 61%).

**Melting Point:** 284-286 °C.

\(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta = 8.03\ (dd, \(J = 6.5, 3.0\ Hz, 2H\)), 7.94 (d, \(J = 1.3\ Hz, 1H\)), 7.70 (dd, \(J = 6.7, 3.0\ Hz, 2H\)), 7.39 – 7.27 (m, 9H), 7.10 – 6.97 (m, 8H), 2.68 (s, 3H), 2.46 (s, 3H).

\(^{13}\)C NMR (125 MHz, CDCl\(_3\)): \(\delta = 184.51, 179.72, 161.77, 148.86, 143.21, 142.08, 139.84, 135.74, 134.86, 132.63, 132.38, 129.94, 129.26, 129.06, 129.01, 128.91, 128.63, 128.59, 128.53, 128.15, 128.13, 127.42, 127.36, 126.37, 99.94, 69.79, 23.60, 21.84.

**HRMS (ESI):** calcd for C\(_{40}\)H\(_{29}\)O\(_3\) [M+H]\(^+\) 557.2111, found 557.2119.

8-Methoxy-1,2,2a,9b-tetraphenylcyclobuta\([d]\)naphtho[2,3-\(b\)]furan-4,9(2a\(H\),9b\(H\))-dione (4h)
Following the procedure B, 4h was obtained as a pale-yellow solid (61.4 mg, 55%).

**Melting Point:** >300 °C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 8.04 – 8.01$ (m, 2H), 7.84 (dd, $J = 7.6$, 1.0 Hz, 1H), 7.69 – 7.61 (m, 3H), 7.36 – 7.27 (m, 7H), 7.25 – 7.22 (m, 2H), 7.06 – 7.04 (m, 3H), 6.97 – 6.94 (m, 5H), 3.93 (s, 3H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta =$ 181.88, 179.31, 161.13, 160.33, 148.88, 138.54, 135.68, 134.88, 134.45, 134.40, 132.71, 132.30, 130.20, 129.92, 129.21, 129.15, 129.06, 128.91, 128.63, 128.56, 128.51, 128.13, 128.08, 127.38, 127.22, 120.59, 119.69, 99.84, 69.88, 56.89.

HRMS (ESI): calcd for C$_{39}$H$_{27}$O$_4$ [M+H]$^+$ 559.1903, found 559.1912.

**6-Fluoro-1,2,2a,9b-tetraphenylcyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4i)**

Following the procedure B, 4i was obtained as a pale-yellow solid (54.6 mg, 50%).

**Melting Point:** >300 °C.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 8.10 (dd, $J = 8.6$, 5.2 Hz, 1H), 7.99 – 7.97 (m, 2H), 7.81 (dd, $J = 8.4$, 2.6 Hz, 1H), 7.70 – 7.67 (m, 2H), 7.40 – 7.30 (m, 7H), 7.25 – 7.23 (m, 2H), 7.09 – 7.07 (m, 3H), 7.03 – 7.00 (m, 3H), 6.98 – 6.94 (m, 2H).

$^{13}$C NMR (101 MHz, CDCl$_3$): $\delta =$ 180.95, 178.09, 167.41, 164.87, 163.28, 148.85, 138.69, 135.28, 134.50, 134.39, 132.50, 132.10, 130.18, 130.14, 130.09, 129.41, 129.13, 128.97 (d, $J_{C-F} = 3.2$ Hz), 128.87, 128.74, 128.61, 128.55, 128.23 (d, $J_{C-F} = 3.2$Hz), 127.60, 127.36, 121.49 (d, $J_{C-F} = 22.2$ Hz), 113.56 (d, $J_{C-F} = 24.2$ Hz), 100.48,
69.21.

\(^{19}\text{F NMR (376 MHz, CDCl}_3\):} \, \delta = -103.68 \, (s, \, \text{F}) \, \text{ppm.}\n
\text{HRMS (ESI):} \, \text{calcd for C}_{38}\text{H}_{24}\text{O}_3\text{F} \, [\text{M+H}]^+ \, 547.1704, \, \text{found} \, 547.1712.

**6-Chloro-1,2,2a,9b-tetraphenylcyclobuta[d]naptho[2,3-b]furan-4,9(2aH,9bH)-dione (4j).**

![Chemical structure of 4j](image)

Following the procedure B, 4j was obtained as a pale-yellow solid (58.5 mg, 52%).

\text{Melting Point:} >300 \, ^\circ\text{C.}

\(^1\text{H NMR (500 MHz, CDCl}_3\):} \, \delta = 8.12 \, (d, \, J = 2.1 \, \text{Hz, 1H}), \, 8.02 – 7.96 \, (m, \, 3H), \, 7.70 – 7.66 \, (m, \, 3H), \, 7.36 – 7.30 \, (m, \, 6H), \, 7.26 – 7.20 \, (m, \, 2H), \, 7.08 – 7.06 \, (m, \, 2H), \, 7.02 – 7.00 \, (m, \, 3H), \, 6.96 – 6.94 \, (m, \, 2H).

\(^{13}\text{C NMR (125 MHz, CDCl}_3\):} \, \delta = 181.13, \, 178.12, \, 163.09, \, 148.81, \, 140.39, \, 138.67, \, 135.20, \, 134.56, \, 134.43, \, 133.11, \, 132.45, \, 132.06, \, 131.81, \, 130.16, \, 129.43, \, 129.14, \, 129.00, \, 128.93, \, 128.81, \, 128.75, \, 128.59, \, 128.52, \, 128.26, \, 128.23, \, 127.62, \, 127.34, \, 126.64, \, 100.49, \, 69.16.

\text{HRMS (ESI):} \, \text{calcd for C}_{38}\text{H}_{24}\text{O}_3\text{Cl} \, [\text{M+H}]^+ \, 563.1408, \, \text{found} \, 563.1416.

**1,2,2a,6,9b-Pentaphenylcyclobuta[d]naptho[2,3-b]furan-4,9(2aH,9bH)-dione (4k)**

![Chemical structure of 4k](image)

Following the procedure B, 4k was obtained as a pale-yellow solid (70.1 mg, 58%).

\text{Melting Point:} >300 \, ^\circ\text{C.}

\(^1\text{H NMR (500 MHz, CDCl}_3\):} \, \delta = 8.41 \, (s, \, 1H), \, 8.00 – 7.93 \, (m, \, 3H), \, 7.73 – 7.67 \, (m, \, 3H), \, 7.51 \, (t, \, J = 7.5 \, \text{Hz, 1H}), \, 7.44 \, (t, \, J = 7.3 \, \text{Hz, 1H}), \, 7.35 – 7.34 \, (m, \, 4H), \, 7.28 – 7.26 \, (m, \, 2H), \, 7.12 – 7.10 \, (m, \, 2H), \, 7.00 \, (s, \, 4H), \, 6.85 – 6.82 \, (m,
$\text{1}^3\text{C NMR (125 MHz, CDCl}_3): \delta = 181.37, 175.48, 172.70, 150.28, 145.62, 141.08, 140.77, 139.11, 137.95, 135.03, 134.79, 133.24, 132.87, 132.08, 131.89, 131.82, 130.17, 129.66, 129.35, 129.25, 129.14, 129.10, 129.05, 128.80, 128.60, 128.42, 128.34, 128.17, 127.58, 127.46, 127.42, 127.04, 126.01, 125.65, 120.33, 101.73, 68.29.$

HRMS (ESI): calcd for C$_{44}$H$_{29}$O$_3$ [M+H]$^+$ 605.2111, found 605.2124.

**7-Chloro-1,2,2a,9b-tetraphenylcyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4l)**

![Image of 7-Chloro-1,2,2a,9b-tetraphenylcyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4l)]

Following the procedure B, 4l was obtained as a pale-yellow solid (53.9 mg, 48%).

**Melting Point:** $>300$ °C.

$^1\text{H NMR (500 MHz, CDCl}_3): \delta = 8.10 (d, J = 8.3 \text{ Hz, 1H}), 8.03 (d, J = 2.1 \text{ Hz, 1H}), 7.98 – 7.96 (m, 2H), 7.70 – 7.64 (m, 3H), 7.36 – 7.30 (m, 6H), 7.26 – 7.23 (m, 2H), 7.09 – 7.07 (m, 3H), 7.03 – 7.00 (m, 3H), 6.97 – 6.94 (m, 2H).

$^{13}\text{C NMR (125 MHz, CDCl}_3): \delta = 180.89, 178.17, 163.40, 148.81, 141.88, 138.62, 135.12, 134.91, 134.39, 133.39, 132.44, 132.00, 130.19, 130.17, 129.41, 129.13, 129.00, 128.91, 128.76, 128.65, 128.58, 128.50, 128.29, 128.25, 128.23, 127.64, 127.39, 127.35, 100.56, 69.10.$

HRMS (ESI): calcd for C$_{38}$H$_{24}$O$_3$Cl [M+H]$^+$ 563.1408, found 563.1420.

**1,2,2a,11b-Tetraphenylanthra[2,3-b]cyclobuta[d]furan-4,11(2aH,11bH)-dione (4m)**

![Image of 1,2,2a,11b-Tetraphenylanthra[2,3-b]cyclobuta[d]furan-4,11(2aH,11bH)-dione (4m)]
Following the procedure B, 4m was obtained as a pale-yellow solid (69.4 mg, 60%).

**Melting Point:** >300 °C.

**1H NMR (500 MHz, CDCl3):** δ = 8.24 (d, J = 8.5 Hz, 1H), 8.18 (d, J = 8.5 Hz, 1H), 8.06 – 8.04 (m, 1H), 7.92 – 7.87 (m, 2H), 7.77 – 7.75 (m, 2H), 7.64 (t, J = 7.5 Hz, 1H), 7.47 – 7.44 (m, 1H), 7.40 – 7.32 (m, 7H), 7.23 – 7.19 (m, 4H), 7.13 – 7.10 (m, 2H), 7.06 – 7.02 (m, 3H), 6.89 – 6.86 (m, 1H).

**13C NMR (125 MHz, CDCl3):** δ = 182.50, 181.91, 163.99, 149.06, 145.04, 138.46, 136.88, 136.69, 136.08, 135.74, 135.38, 134.75, 134.44, 133.45, 132.66, 132.22, 131.90, 130.50, 130.31, 129.33, 129.22, 129.12, 129.01, 128.98, 128.84, 128.76, 128.65, 128.63, 128.24, 128.20, 128.02, 127.54, 127.43, 127.04, 125.60, 122.99, 100.45, 69.22.


**1,2,2a,9b-Tetrap-tolylcyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4n).**

Following the procedure B, 4n was obtained as a pale-yellow solid (89.9 mg, 77%).

**Melting Point:** 276-278 °C.

**1H NMR (500 MHz, CDCl3):** δ = 8.14 (dd, J = 7.3, 1.5 Hz, 1H), 8.06 (dd, J = 7.3, 1.4 Hz, 1H), 7.88 (d, J = 8.1 Hz, 2H), 7.76 (d, J = 8.1 Hz, 1H), 7.71 – 7.65 (m, 2H), 7.58 (d, J = 8.0 Hz, 2H), 7.15 – 7.16 (m, 6H), 6.99 (d, J = 8.0 Hz, 1H), 6.90 – 6.81 (m, 4H), 2.35 (s, 3H), 2.33 (s, 3H), 2.16 (s, 3H), 2.15 (s, 3H).

**13C NMR (125 MHz, CDCl3):** δ = 180.15, 177.30, 161.14, 146.17, 142.10, 142.06, 137.92, 137.03, 136.13, 135.94, 134.84, 132.62, 131.30, 130.59, 129.92, 128.67, 128.11, 128.04, 127.81, 127.67, 127.58, 127.54, 127.43, 126.96, 126.91, 126.89, 126.52, 126.46, 125.33, 125.07, 124.56, 98.43, 66.75, 19.98, 19.90, 19.58, 19.52.

**HRMS (ESI):** calcd for C42H33O3 [M+H]+ 585.2424, found 585.2448.
1,2,2a,9b-tetram-tolylcyclobuta[d]naptho[2,3-b]furan-4,9(2aH,9bH)-dione (4o)

Following the procedure B, 4o was obtained as a pale-yellow solid (83.1 mg, 71%).

**Melting Point:** 269-271 °C.

**1H NMR (500 MHz, CDCl₃):** δ = 8.20 – 8.19 (m, 1H), 8.12 – 8.10 (m, 1H), 7.90 (s, 1H), 7.83 (d, J = 7.8 Hz, 1H), 7.75 – 7.70 (m, 2H), 7.56 – 7.52 (m, 2H), 7.29 – 7.18 (m, 4H), 7.14 (d, J = 7.6 Hz, 1H), 7.09 – 7.03 (m, 2H), 6.97 – 6.89 (m, 3H), 6.84 – 6.77 (m, 2H), 2.35 (s, 3H), 2.32 (s, 3H), 2.18 (s, 3H), 2.12 (s, 3H);

**13C NMR (125 MHz, CDCl₃):** δ = 182.02, 179.31, 163.18, 148.86, 138.62, 138.57, 138.35, 137.54, 137.37, 135.49, 134.68, 134.62, 133.73, 133.33, 132.71, 132.28, 132.00, 130.73, 130.03, 129.40, 129.25, 129.22, 129.05, 128.87, 128.82, 128.80, 128.17, 127.99, 127.82, 127.46, 127.10, 126.59, 126.27, 125.83, 125.71, 124.41, 100.41, 69.16, 21.89, 21.87, 21.77, 21.72.

**HRMS (ESI):** calcd for C₄₂H₃₃O₃ [M+H]+ 585.2424, found 585.2425.

1,2,2a,9b-Tetrakis(4-fluorophenyl)cyclobuta[d]naptho[2,3-b]furan-4,9(2aH,9bH)-dione (4p).

Following the procedure B, 4p was prepared according to the general procedure. The product was obtained as a pale-yellow solid (72.0 mg, 60%).

**Melting Point:** >300 °C.

**1H NMR (500 MHz, CDCl₃):** δ = 8.16 (dd, J = 7.3, 1.6 Hz, 1H), 8.08 – 8.06 (m, 1H), 7.95 – 7.92 (m, 2H), 7.75 –
7.70 (m, 2H), 7.64 – 7.61 (m, 2H), 7.21 – 7.19 (m, 2H), 7.06 – 7.00 (m, 4H), 6.92 – 6.89 (m, 2H), 6.82 – 6.73 (m, 4H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ = 182.20, 178.93, 164.90, 164.34, 164.14, 163.36, 163.12, 162.90, 162.35, 162.17, 161.38, 147.52, 136.77, 134.99, 133.75, 133.43, 131.90, 131.03, 130.97, 130.93, 130.91, 130.49, 130.43, 130.16, 130.13, 130.05, 129.99, 129.17, 129.10, 129.07, 128.24, 128.22, 128.06, 127.78 (d, $J_{C,F}$ = 3.2 Hz), 127.18, 126.83, 116.60, 116.43, 116.27, 115.71, 115.61, 115.54, 115.44, 99.61, 68.57.

HRMS (ESI): calcd for C$_{38}$H$_{21}$F$_4$O$_3$ [M+H]$^+$ 601.1421, found 601.1442.

1,2,2a,9b-Tetra(naphthalen-2-yl)cyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione (4q)

Following the procedure B, 4q was obtained as a pale-yellow solid (84.1 mg, 58%).

Melting Point: >300 °C.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ = 8.67 (s, 1H), 8.25 – 8.20 (m, 2H), 8.13 – 8.11 (m, 1H), 8.05 (s, 1H), 7.91 (d, $J$ = 8.6 Hz, 1H), 7.87 – 7.80 (m, 4H), 7.77 – 7.70 (m, 5H), 7.57 – 7.28 (m, 16H), 7.18 (d, $J$ = 8.6 Hz, 1H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ = 182.21, 179.36, 163.34, 149.42, 139.51, 134.83, 134.29, 133.88, 133.69, 133.51, 133.38, 133.27, 133.09, 132.85, 132.30, 132.09, 130.14, 129.76, 129.62, 129.06, 128.79, 128.71, 128.50, 128.42, 128.27, 128.18, 128.11, 128.03, 127.94, 127.60, 127.24, 126.98, 126.90, 126.76, 126.63, 126.39, 126.25, 126.15, 126.01, 125.87, 124.61, 100.75, 69.78.

HRMS (ESI): calcd for C$_{54}$H$_{33}$O$_3$ [M+H]$^+$ 729.2274, found 729.2286.

2,2a-Diphenyl-1,9b-bis(4-(trimethylsilyl)phenyl)cyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione

and 1,2a-Diphenyl-2,9b-bis(4-(trimethylsilyl)phenyl)cyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione

and 2,9b-Diphenyl-1,2a-bis(4-(trimethylsilyl)phenyl)cyclobuta[d]naphtho[2,3-b]furan-4,9(2aH,9bH)-dione

and 1,9b-Diphenyl-2,2a-bis(4-(trimethylsilyl)phenyl)cyclobuta[d]naphtho[2,3-
Following the procedure B, 4r was obtained as a pale-yellow solid (105.8 mg, 79%), regioisomer ratio ≈ 5:5:7:8.

**Melting Point:** no determined.

Regioisomer mixture A

**$^1$H NMR (500 MHz, CDCl$_3$):** δ = 8.19 (d, $J = 7.0$ Hz, 2H), 8.11 (d, $J = 7.2$ Hz, 2H), 8.03 – 7.98 (m, 5H), 7.76 – 7.67 (m, 10H), 7.55 – 7.53 (m, 3H), 7.48 (d, $J = 7.7$ Hz, 2H), 7.40 – 7.33 (m, 9H), 7.29 – 7.27 (m, 4H), 7.25 – 7.19 (m, 6H), 7.17 – 7.13 (m, 4H), 7.08 – 6.91 (m, 12H), 0.29 (m, 9H), 0.28 (s, 6H), 0.15 – 0.15 (m, 6H), 0.14 (s, 5H), 0.13 (m, 6H).

**$^{13}$C NMR (125 MHz, CDCl$_3$):** δ = 182.23, 182.07, 179.18, 163.38, 163.31, 149.23, 148.86, 143.12, 142.23, 140.96, 139.35, 138.96, 138.53, 135.88, 135.79, 135.42, 134.97, 134.71, 134.00, 133.88, 133.66, 133.45, 133.09, 133.06, 132.97, 132.87, 132.41, 132.34, 132.00, 130.02, 129.29, 129.09, 129.07, 128.99, 128.78, 128.69, 128.65, 128.56, 128.50, 128.16, 128.11, 127.93, 127.81, 127.74, 127.62, 127.36, 127.31, 127.28, 127.15, 126.67, 126.56, 126.51, 100.45, 100.28, 69.37, 69.28, 69.26, -0.75, -0.82.

**HRMS (ESI):** calcd for C$_{44}$H$_{41}$O$_3$Si$_2$ [M+H]$^+$ 673.2589, found 673.2617.

Regioisomer mixture B

**$^1$H NMR (500 MHz, CDCl$_3$):** δ = 8.15 (d, $J = 7.6$ Hz, 2H), 7.98 (dd, $J = 7.5$, 2.1 Hz, 2H), 7.93 – 7.91 (m, 4H), 7.72 – 7.70 (m, 5H), 7.67 – 7.61 (m, 4H), 7.49 – 7.46 (m, 4H), 7.37 – 7.32 (m, 7H), 7.22 – 7.15 (m, 8H), 7.09 – 7.07 (m, 5H), 6.97 (s, 5H), 6.89 (d, $J = 8.1$ Hz, 2H), 0.26 (s, 8H), 0.24 (s, 10H), 0.13 (s, 8H), 0.09 (s, 7H).

**$^{13}$C NMR (125 MHz, CDCl$_3$):** δ = 181.28, 175.51, 175.39, 172.66, 172.53, 150.52, 150.09, 143.27, 142.11, 141.22, 139.24, 138.32, 137.94, 135.48, 135.23, 135.20, 135.04, 135.02, 134.82, 134.01, 133.99, 133.22, 133.16, 133.08, 133.02, 132.95, 132.57, 132.07, 131.95, 131.66, 130.12, 130.06, 129.97, 129.17, 129.13, 129.10, 129.06.
Following the procedure B, 4s was prepared according to the general procedure. The product was obtained as a pale-yellow solid (36.4 mg, 34%), regioisomer ratio \( \approx 8:7:4:1 \).

**Melting Point:** no determined.

Regioisomer mixture

\[ ^1H \text{ NMR (600 MHz, CDCl}_3\]: } \delta = 7.88 (dd, \( J = 8.4, 1.1 \text{ Hz, 1H} \)), 7.59 – 7.28 (m, 8H), 7.27 – 7.07 (m, 3H), 4.21 – 4.10 (m, 2H), 4.03 – 3.93 (m, 2H), 1.06 (t, \( J = 7.2 \text{ Hz, 2H} \)), 0.97 (t, \( J = 7.1 \text{ Hz, 2H} \)), 0.91 (t, \( J = 7.1 \text{ Hz, 2H} \)), 0.84 (t, \( J = 3.5 \text{ Hz, 1H} \)).

\[ ^13C \text{ NMR (151 MHz, CDCl}_3\]: } \delta = 193.09, 191.73, 165.48, 165.39, 164.87, 163.21, 154.76, 149.09, 140.71, 137.66, 133.90, 133.74, 133.58, 133.56, 130.02, 129.98, 129.79, 129.71, 129.56, 129.40, 129.30, 129.17, 129.10, 129.00, 128.89, 128.88, 128.86, 128.84, 128.81, 128.66, 128.46, 128.39, 128.26, 128.22, 128.19, 128.10, 115.08, 82.13, 63.04, 62.81, 61.85, 61.14, 14.16, 14.03, 14.03, 14.02.

**HRMS (ESI):** calcd for \( C_{32}H_{24}O_7Na \ [M+Na]^- \) 543.1414, found 543.1423.

Regioisomer mixture

\[ ^1H \text{ NMR (500 MHz, CDCl}_3\]: } \delta = 7.91 – 7.87 (m, 1H), 7.74 – 7.30 (m, 11H), 7.25 – 7.22 (m, 2H), 4.43 – 4.30 (m,
1H), 4.04 – 3.85 (m, 3H), 1.38 (t, \( J = 7.1 \) Hz, 1H), 1.06 (t, \( J = 7.1 \) Hz, 1H), 0.92 (t, \( J = 7.1 \) Hz, 2H), 0.80 (t, \( J = 7.1 \) Hz, 2H).

\(^{13}\)C NMR (125 MHz, CDCl\(_3\)): \( \delta = 192.84, 167.54, 163.08, 161.66, 154.85, 153.17, 142.59, 142.12, 136.91, 134.38, 133.24, 132.69, 129.36, 129.30, 129.16, 128.82, 128.80, 128.58, 128.52, 128.41, 121.92, 70.33, 62.52, 61.73, 61.39, 14.69, 14.03, 13.79.

HRMS (ESI): calcd for C\(_{32}\)H\(_{24}\)O\(_7\)Na [M+Na]\(^+\) 543.1414, found 543.1424.

\((R)-3-(6-chloro-1-methyl-2-oxo-4-(trifluoromethyl)-2,4-dihydro-1H-benzo[d][1,3]oxazin-4-yl)-4-cyclopropyl-1H-benzo[g]chromene-2,5,10-trione (5a)\)

\[
\text{Melting Point: 285-287 °C.}
\]

\(^1\)H NMR (600 MHz, CDCl\(_3\)): \( \delta = 8.20 – 8.14 \) (m, 2H), 7.87 – 7.79 (m, 2H), 7.52 (d, \( J = 2.1 \) Hz, 1H), 7.46 (dd, \( J = 8.8, 2.3 \) Hz, 1H), 6.96 (d, \( J = 8.8 \) Hz, 1H), 3.49 (s, 3H), 2.77 (ddd, \( J = 15.3, 8.8, 6.5 \) Hz, 1H), 0.99 (tt, \( J = 9.3, 5.6 \) Hz, 1H), 0.63 (tt, \( J = 8.8, 5.6 \) Hz, 1H), 0.10 (dt, \( J = 17.0, 6.5 \) Hz, 1H), -0.42 (td, \( J = 11.3, 6.5 \) Hz, 1H).

\(^{13}\)C NMR (151 MHz, CDCl\(_3\)): \( \delta = 180.60, 175.96, 162.18, 156.97, 153.35, 148.59, 136.51, 135.92, 134.73, 133.21, 132.25, 132.20, 130.45, 130.02, 127.85, 127.64, 127.24, 123.85 (q, \( J_{C-F} = 289.9 \) Hz), 122.50, 117.45, 115.25, 85.58 (q, \( J_{C-F} = 31.8 \) Hz), 32.34, 18.58, 10.28, 10.19.

HRMS (ESI): calcd for C\(_{26}\)H\(_{15}\)O\(_6\)NClF\(_3\)Na [M+Na]\(^+\) 552.0432, found 552.0438.

\((R)-3-(6-Chloro-1-methyl-2-oxo-4-(trifluoromethyl)-2,4-dihydro-1H-benzo[d][1,3]oxazin-4-yl)-4-cyclopropyl-7,8-dimethoxy-1H-benzo[g]chromene-2,5,10-trione (5b)\).

\[
\text{Following the procedure C, 5a was prepared according to the general procedure. The product was obtained as a pale-yellow solid (47.6 mg, 45%).}
\]

\[
\text{Melting Point: 285-287 °C.}
\]

\(^1\)H NMR (600 MHz, CDCl\(_3\)): \( \delta = 8.20 – 8.14 \) (m, 2H), 7.87 – 7.79 (m, 2H), 7.52 (d, \( J = 2.1 \) Hz, 1H), 7.46 (dd, \( J = 8.8, 2.3 \) Hz, 1H), 6.96 (d, \( J = 8.8 \) Hz, 1H), 3.49 (s, 3H), 2.77 (ddd, \( J = 15.3, 8.8, 6.5 \) Hz, 1H), 0.99 (tt, \( J = 9.3, 5.6 \) Hz, 1H), 0.63 (tt, \( J = 8.8, 5.6 \) Hz, 1H), 0.10 (dt, \( J = 17.0, 6.5 \) Hz, 1H), -0.42 (td, \( J = 11.3, 6.5 \) Hz, 1H).

\(^{13}\)C NMR (151 MHz, CDCl\(_3\)): \( \delta = 180.60, 175.96, 162.18, 156.97, 153.35, 148.59, 136.51, 135.92, 134.73, 133.21, 132.25, 132.20, 130.45, 130.02, 127.85, 127.64, 127.24, 123.85 (q, \( J_{C-F} = 289.9 \) Hz), 122.50, 117.45, 115.25, 85.58 (q, \( J_{C-F} = 31.8 \) Hz), 32.34, 18.58, 10.28, 10.19.

HRMS (ESI): calcd for C\(_{26}\)H\(_{15}\)O\(_6\)NClF\(_3\)Na [M+Na]\(^+\) 552.0432, found 552.0438.
Following the procedure C, 5b was obtained as a pale-yellow solid (60.1 mg, 51%).

**Melting Point:** 288-290 °C.

$^1$H NMR (600 MHz, CDCl$_3$): $\delta = 7.56 - 7.53$ (m, 3H), 7.46 (dd, $J = 8.8$, 2.2 Hz, 1H), 6.96 (d, $J = 8.8$ Hz, 1H), 4.06 (s, 3H), 4.05 (s, 3H), 2.79 - 2.71 (m, 1H), 0.97 (ddd, $J = 14.8$, 9.1, 5.5 Hz, 1H), 0.62 (ddd, $J = 13.9$, 8.8, 5.5 Hz, 1H), 0.11 (td, $J = 11.6$, 5.9 Hz, 1H), -0.43 (dt, $J = 11.2$, 5.9 Hz, 1H).

$^{13}$C NMR (151 MHz, CDCl$_3$): $\delta =$ 180.05, 175.16, 162.32, 157.17, 155.35, 154.19, 153.62, 148.68, 136.47, 132.21, 131.55, 130.02, 128.11, 127.69, 125.06, 123.83 (q, $J_{C,F} = 289.9$ Hz), 121.87, 117.59, 115.22, 109.17, 108.17, 85.61 (q, $J_{C,F} = 31.8$ Hz), 57.21, 32.33, 18.60, 10.38, 10.17, 0.48.

**HRMS (ESI):** calcd for C$_{28}$H$_{19}$O$_8$NClF$_3$Na [M+Na]$^+$ 612.0644, found 612.0653.

(R)-10-(6-Chloro-1-methyl-2-oxo-4-(trifluoromethyl)-2,4-dihydro-1H-benzo[d][1,3]oxazin-4-yl)-11-cyclopropyl-4-methyl-1H-naphtho[1,2-g]chromene-7,9,12-trione.

Following the procedure C, 5c was obtained as a pale-yellow solid (49.8 mg, 42%).

**Melting Point:** 294-296 °C.

$^1$H NMR (600 MHz, CDCl$_3$): $\delta =$ 9.37 (s, 1H), 8.24 (d, $J = 8.5$ Hz, 1H), 8.15 (d, $J = 8.5$ Hz, 1H), 7.87 (d, $J = 8.4$ Hz, 1H), 7.58 - 7.56 (m, 2H), 7.49 (dd, $J = 8.8$, 2.3 Hz, 1H), 6.99 (d, $J = 8.8$ Hz, 1H), 3.52 (s, 3H), 2.80 (ddd, $J = 16.3$, 7.4, 5.6 Hz, 1H), 2.66 (s, 3H), 1.04 (ddd, $J = 11.4$, 7.4, 4.5 Hz, 1H), 0.67 (ddd, $J = 14.1$, 8.8, 5.6 Hz, 1H), 0.16
(td, $J = 11.4, 6.0$ Hz, 1H), -0.38 (td, $J = 11.4, 6.0$ Hz, 1H).

$^{13}$C NMR (151 MHz, CDCl$_3$): $\delta =$ 181.57, 177.92, 161.75, 157.35, 153.70, 148.66, 142.55, 137.07, 136.51, 135.22, 134.18, 132.22, 131.97, 131.35, 130.45, 130.01, 129.24, 127.72, 127.00, 125.14, 123.89 (q, $J_{C-F} = 289.9$ Hz), 122.05, 120.50, 117.62, 115.22, 85.60 (q, $J_{C-F} = 33.2$ Hz), 32.34, 23.06, 18.31, 10.35, 10.09.

HRMS (ESI): calcd for C$_{31}$H$_{19}$O$_6$NClF$_3$Na [M+Na]$^+$ 616.0745, found 616.0750.

(R)-3-(6-chloro-1-methyl-2-oxo-4-(trifluoromethyl)-2,4-dihydro-1H-benzo[d][1,3]oxazin-4-yl)-4-cycloproplyphenyl[3,2-c]chromene-2,5-dione (6).

Following the procedure C (4-hydroxycoumarin as starting material), 5a was obtained as a pale-yellow solid (56.7 mg, 55%).

Melting Point: 285-287 °C.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 8.12 (d, $J = 8.0$ Hz, 1H), 7.71 (dd, $J = 11.4, 4.3$ Hz, 1H), 7.54 (d, $J = 2.1$ Hz, 1H), 7.47 – 7.39 (m, 3H), 6.96 (d, $J = 8.8$ Hz, 1H), 3.49 (s, 3H), 2.69 – 2.61 (m, 1H), 1.18 – 1.10 (m, 1H), 0.68 – 0.61 (m, 1H), 0.32 – 0.25 (m, 1H), -0.33 – -0.40 (m, 1H).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta =$ 163.97, 161.39, 157.41, 156.58, 148.72, 135.69, 132.10, 129.85, 127.67, 126.98, 126.22, 125.59, 125.05, 124.62, 123.12, 121.20, 117.98, 117.37, 115.17, 112.68, 106.62, 85.87, 85.65, 85.44, 85.22, 32.30, 18.70, 10.20, 10.08.

5. Endothelial protective Assay of 3x

Protective effects of compound 3x on endothelial cell injury. (A) Chemical structure of compound 3x. (B) Human umbilical endothelial cells (HUVECs) were pretreated with various concentrations (0.25, 0.5 and 1 μM) and time (4, 6, 8 and 12 h), then the cells were exposed to ox-LDL (80 μg/ml) for another 24 h. Cell viability was measured by MTT assay. (C) HUVECs were treated with different concentrations of compound 3x (0.25, 0.5 and 1μM) for 12 h, then cell viability was measured by MTT assay. (D-G) HUVECs were pretreated with compound 3x (0.25 and 0.5 μM) for 6 h, followed by treatment with ox-LDL (80 μg/ml) for another 24 h. (D) After that, HUVECs were stained with Annexin V/PI kit, and the cell apoptosis was detected by a flow cytometry. (E) Representative images of HUVECs stained with Carboxy-H2DCFDA. (F) Bcl-2, Bax, Cleaved-caspase-3 and β-actin were evaluated by western blot analysis. (G) Densitometric analysis was used to quantify the levels of Bcl-2/Bax and Cleaved caspase-3. Values are expressed as the mean ± SD, n = 3. *p < 0.05, **p < 0.01 ox-LDL group vs. control group; *p < 0.05, **p < 0.01 vs. ox-LDL group. STS: sodium tanshinone IIA silate.

a) Ethics statement

This study was administrated according to the Declaration of Helsinki, and the research protocol was permitted by the Ethics Committee of Peking Union Medical College (Beijing, China).

b) Reagents

Ox-LDL (by copper ion-induced LDL oxidation, Malondialdehyde N-40 nmol/ml) was obtained from Union-Bio Technology (Beijing, China). 3-(4, 5-dimethylthiazol-2-yl)-2, 5-diphenyl tetrazolium bromide (MTT) was purchased from Sigma-Aldrich (St. Louis, MO, USA). The VascuLife Basal Medium and growth supplement were obtained from Lifeline Cell Technology (Carlsbad, CA, USA). The ROS fluorometric assay and annexin V/PI assay kits were purchased from BioVision (Milpitas, CA, USA). Antibodies against Bcl-2, Bax, Cleaved-caspase-3 and β-actin were obtained from Santa Cruz Biotechnology (Santa Cruz, CA, USA).
c) Cell culture and treatment

Human umbilical vein endothelial cells (HUVECs) were separated from fresh human umbilical veins and cultured on 1% gelatin-coated plastic dishes as previously described [1]. The neonate cords were donated by the Maternal and Child Care Service Centre in Beijing, China. The study protocol was explained and all participating donors gave written informed consents. Briefly, the VascuLife Basal Medium with growth supplements, streptomycin (100 μg/ml) and penicillin (100 U/ml) were used for the HUVECs culture. Passages 3 to 5 of the HUVECs isolated from different donors were used for the experiments. The cells were incubated in a humidified atmosphere at 37°C containing 5% CO2. Compound 3x was dissolved in DMSO to make a stock solution and diluted to the concentration of working solutions before administration.

d) Measurement of cell viability

Cell viability was measured by MTT assay. Briefly, the cells cultured on 96-well cell culture plates were pretreated with different concentrations and time of compound a followed by treatment with ox-LDL. To measure cell viability, 1 mg/ml MTT assay solution was added, and the plates were incubated for an additional 4 h. The formazan crystals were dissolved in 150 μl of DMSO. Then, the absorbance was measured at 570 nm on a microplate reader (Tecan, Switzerland). The percentage of living cells was calculated by the ratio of optical density compared with that of the normal wells.

e) Flow cytometry detection of apoptosis

After all treatment, the cells were harvested, washed with PBS, and then incubated with 100 μl 1× Annexin V work solution containing for 15 min in the dark at 37 °C. After stained with PI and washed by PBS, the cells were immediately analyzed using a flow cytometer (Becton, Dickinson and Company, CA, USA).

f) Determination of reactive oxygen species (ROS) production

The effects of 3x on intracellular ROS levels were detected using a total ROS detection kit according to the manufacturer's brochure. Briefly, the HUVECs were harvested and washed with PBS. Subsequently, the cells were incubated with 300 μl ROS detection solution (Carboxy-H2DCFDA) and stained at 37 °C for 30 min in the dark. The staining solution was replaced by PBS, and the samples were photographed by a fluorescence microscope.

g) Western blot analysis
Briefly, the cell extracts were lysed in RIPA lysis buffer containing 1% protease inhibitor (Beyotime, Shanghai, China). Protein content was measured with a BCA Protein Assay Kit (Cwbiotech, Beijing, China). 12% sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) was used for protein separation and then transferred onto polyvinylidene difluoride membranes. The membranes were incubated over night with 1:500-diluted primary antibodies at 4 °C, then washed with TBST thrice followed by secondary antibodies at room temperature for 1.5 h. Then, the proteins were developed by an enhanced chemiluminescence detection system. Finally, the blots were scanned, and densitometric analysis was performed using Gel Pro software (Media Cybernetics, Rockville, MD, USA).

h) Statistical analysis
Data are presented as the means ± standard deviation (SD) of three independent experiments. Differences between groups were analyzed by one-way analysis of variance (ANOVA), and the means of two groups were compared by Tukey method using Graphpad 6.0 statistical software. Statistical significance was defined as $p < 0.05$. 
6. Crystallographic data for 3a, 3s, 3y, 4a, 5a

a) X-ray crystallographic data of 3a (CCDC 1909884)

Table 1. Crystal data and structure refinement for 3a.

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<th>Value</th>
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<tbody>
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<td>Identification code</td>
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</tr>
<tr>
<td>Empirical formula</td>
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<tr>
<td>Formula weight</td>
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<td>100(2) K</td>
</tr>
<tr>
<td>Wavelength</td>
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</tr>
<tr>
<td>Crystal system</td>
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</tr>
<tr>
<td>Space group</td>
<td>P2(1)/c</td>
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<td></td>
<td>b = 13.3992(18) Å</td>
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<td></td>
<td>c = 9.5225(13) Å</td>
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<td>Z</td>
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<td>Crystal size</td>
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<td>Reflections collected</td>
<td>11846</td>
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<tr>
<td>Independent reflections</td>
<td>3876 [R(int) = 0.0448]</td>
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<td>Completeness to theta = 27.50°</td>
<td>99.9 %</td>
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<tr>
<td>Absorption correction</td>
<td>Semi-empirical from equivalents</td>
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<tr>
<td>Max. and min. transmission</td>
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<tr>
<td>Refinement method</td>
<td>Full-matrix least-squares on F²</td>
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Data / restraints / parameters 3876 / 0 / 244
Goodness-of-fit on F² 1.039
Final R indices [I>2sigma(I)] R1 = 0.0483, wR2 = 0.1129
R indices (all data) R1 = 0.0635, wR2 = 0.1208
Largest diff. peak and hole 0.373 and -0.247 eÅ⁻³

Note: The crystal is monoclinic, space group P2(1)/c. The asymmetric unit contains one molecule of the compound C₂₄H₁₄Cl₂O₃. Final R values are R1=0.0483 and wR2=0.1129 for 2-theta up to 55°.

b) X-ray crystallographic data of 3s (CCDC 1909885)

Table 2. Crystal data and structure refinement for 3s.

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<td>Empirical formula</td>
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<td>Wavelength</td>
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<td>Crystal system</td>
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<tr>
<td>Space group</td>
<td>P-1</td>
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</table>
| Unit cell dimensions| a = 7.2581(15) Å  
b = 14.444(3) Å  
c = 17.808(4) Å |
| g = 87.362(5)°. |
| Volume              | 1800.2(6) Å³ |
| Z                   | 4 |
| Density (calculated)| 1.547 Mg/m³ |
| Absorption coefficient| 0.386 mm⁻¹ |
| F(000)              | 856 |
| Crystal size        | 0.40 x 0.20 x 0.15 mm³ |
Theta range for data collection 1.18 to 27.50°.

Index ranges -9<=h<=9, -18<=k<=18, -23<=l<=23

Reflections collected 23747

Independent reflections 8254 [R(int) = 0.0340]

Completeness to theta = 27.50° 99.6 %

Absorption correction Semi-empirical from equivalents

Max. and min. transmission 0.7456 and 0.6173

Refinement method Full-matrix least-squares on F²

Data / restraints / parameters 8254 / 0 / 523

Goodness-of-fit on F² 1.107

Final R indices [I>2sigma(I)] R1 = 0.0439, wR2 = 0.1066

R indices (all data) R1 = 0.0511, wR2 = 0.1159

Largest diff. peak and hole 0.523 and -0.298 e.Å⁻³

Note: The crystal is triclinic, space group P-1. The asymmetric unit contains two molecules of the compound C₂₄H₁₂O₃Cl₂. Final R values are R1=0.0439 and wR2=0.1066 for 2-theta up to 55°.

c) X-ray crystallographic data of 3y (CCDC 1909886)

![Image of molecular structure]

Table 3: Crystal data and structure refinement for 3y

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</tr>
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<td>Temperature / K</td>
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<td>Crystal system</td>
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<tr>
<td>Space group</td>
<td>P₂₁/c</td>
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<tr>
<td>a / Å, b / Å, c / Å</td>
<td>13.3669(16), 6.5367(3), 16.8120(14)</td>
</tr>
</tbody>
</table>
α°, β°, γ°  
90.00, 112.656(12), 90.00
Volume / Å³  
1355.6(2)
Z  
4
ρcalc / mg mm⁻³  
1.413
μ / mm⁻¹  
0.095
F(000)  
600
Crystal size / mm³  
0.40 × 0.37 × 0.25
2Θ range for data collection  
6.6 to 52°
Index ranges  
-11 ≤ h ≤ 16, -8 ≤ k ≤ 7, -20 ≤ l ≤ 20
Reflections collected  
5832
Independent reflections  
2657[R(int) = 0.0281 (inf-0.9Å)]
Data/restraints/parameters  
2657/0/200
Goodness-of-fit on F²  
1.035
Final R indexes [I>2σ (I) i.e. Fo>4σ (Fo)]  
R₁ = 0.0467, wR₂ = 0.1033
Final R indexes [all data]  
R₁ = 0.0618, wR₂ = 0.1141
Largest diff. peak/hole / e Å⁻³  
0.258/-0.233
Flack Parameters  
N
Completeness  
0.9964

Note: Single crystals of C₁₉H₁₂O₃  M =288.29, monoclinic,  a = 13.3669(16) Å,  b = 6.5367(3) Å,  c = 16.8120(14) Å,  β = 112.656(12)°,  U = 1355.6(2) Å³,  T = 107.70(10), space group P2₁/c (no. 14),  Z = 4,  µ(Mo Kα) = 0.095, 5832 reflections measured, 2657 unique (Rint = 0.0281) which were used in all calculations. The final wR(F₂) was 0.1141 (all data).

d) X-ray crystallographic data of 4a (CCDC 876846)

Table 4. Crystal data and structure refinement for 4a.

Identification code  
4a
Empirical formula  
C₃₈H₂₄O₃
Formula weight  
528.57
Temperature  
100(2) K
Wavelength  
0.71073 Å
Crystal system: Triclinic  
Space group: P-1  
Unit cell dimensions: 
\[ a = 8.4942(8) \, \text{Å} \quad a = 94.8310(10)°. \]
\[ b = 10.2513(9) \, \text{Å} \quad b = 96.6810(10)°. \]
\[ c = 15.9443(15) \, \text{Å} \quad g = 104.8190(10)°. \]
Volume: \[ 1323.7(2) \, \text{Å}^3 \]
Z: 2  
Density (calculated): 1.326 Mg/m\(^3\)  
Absorption coefficient: 0.083 mm\(^{-1}\)  
F(000): 552  
Crystal size: \[ 0.60 \times 0.54 \times 0.10 \, \text{mm}^3 \]
Theta range for data collection: 1.29 to 27.50°.  
Index ranges: \(-11 \leq h \leq 11, -13 \leq k \leq 13, -20 \leq l \leq 20\)  
Reflections collected: 17382  
Independent reflections: 6076 \([R(int) = 0.0221]\)  
Completeness to theta = 27.50°: 99.9%  
Absorption correction: Semi-empirical from equivalents  
Max. and min. transmission: 0.7457 and 0.6728  
Refinement method: Full-matrix least-squares on F\(^2\)  
Data / restraints / parameters: 6076 / 0 / 370  
Goodness-of-fit on F\(^2\): 1.059  
Final R indices [I>2sigma(I)]: R1 = 0.0433, wR2 = 0.1159  
R indices (all data): R1 = 0.0480, wR2 = 0.1219  
Largest diff. peak and hole: 0.399 and -0.230 e.Å\(^{-3}\)  

Note: The crystal is triclinic, space group P-1. The asymmetric unit contains one molecule of the compound C38H24O3. Final R values are R1=0.0433 and wR2=0.1159 for 2-theta up to 55°.

e) X-ray crystallographic data of 5a (CCDC 1909889)
Table 5: Crystal data and structure refinement for 5a

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identification code</td>
<td>5a</td>
</tr>
<tr>
<td>Empirical formula</td>
<td>C₂₇H₁₇Cl₃F₃NO₆</td>
</tr>
<tr>
<td>Formula weight</td>
<td>614.77</td>
</tr>
<tr>
<td>Temperature / K</td>
<td>110.60(14)</td>
</tr>
<tr>
<td>Crystal system</td>
<td>orthorhombic</td>
</tr>
<tr>
<td>Space group</td>
<td>P2₁2₁2₁ (no. 19)</td>
</tr>
<tr>
<td>a / Å, b / Å, c / Å</td>
<td>6.9362(5), 16.8867(11), 21.0716(11)</td>
</tr>
<tr>
<td>α°, β°, γ°</td>
<td>90.00, 90.00, 90.00</td>
</tr>
<tr>
<td>Volume / Å³</td>
<td>2468.1(3)</td>
</tr>
<tr>
<td>Z</td>
<td>4</td>
</tr>
<tr>
<td>ρcalc / mg mm⁻³</td>
<td>1.654</td>
</tr>
<tr>
<td>μ / mm⁻¹</td>
<td>0.442</td>
</tr>
<tr>
<td>F(000)</td>
<td>1248</td>
</tr>
<tr>
<td>Crystal size / mm³</td>
<td>0.40 × 0.11 × 0.09</td>
</tr>
<tr>
<td>2Θ range for data collection</td>
<td>6.18 to 52°</td>
</tr>
<tr>
<td>Index ranges</td>
<td>-8 ≤ h ≤ 8, -20 ≤ k ≤ 20, -25 ≤ l ≤ 22</td>
</tr>
<tr>
<td>Reflections collected</td>
<td>12224</td>
</tr>
<tr>
<td>Independent reflections</td>
<td>4844[R(int) = 0.0441 (inf-0.9Å)]</td>
</tr>
<tr>
<td>Data/restraints/parameters</td>
<td>4844/0/362</td>
</tr>
<tr>
<td>Goodness-of-fit on F²</td>
<td>1.047</td>
</tr>
<tr>
<td>Final R indexes [I&gt;2σ(I) i.e. F&gt;4σ(Fo)]</td>
<td>R₁ = 0.0518, wR₂ = 0.1180</td>
</tr>
<tr>
<td>Final R indexes [all data]</td>
<td>R₁ = 0.0625, wR₂ = 0.1266</td>
</tr>
<tr>
<td>Largest diff. peak/hole / e Å⁻³</td>
<td>0.385/-0.465</td>
</tr>
<tr>
<td>Flack Parameters</td>
<td>-0.01(8)</td>
</tr>
<tr>
<td>Completeness</td>
<td>0.9966</td>
</tr>
</tbody>
</table>

Single crystals of C₂₇H₁₇Cl₃F₃NO₆, M = 614.77, orthorhombic, a = 6.9362(5) Å, b = 16.8867(11) Å, c = 21.0716(11) Å, U = 2468.1(3) Å³, T = 110.60(14), space group P2₁2₁2₁ (no. 19), Z = 4, μ(Mo Ka) = 0.442,
12224 reflections measured, 4844 unique ($R_{int} = 0.0441$) which were used in all calculations. The final $wR(F^2)$ was 0.1266 (all data).

7. Postulated mechanism
On the basis of the known palladium-catalyzed oxidative annulation reactions, a possible mechanism for this switchable transformation is shown as follows. The formation of angular and linear naphthofuroquinones begins with the palladation of 1a to yield the vinyl-palladium intermediate IIA and IIB. From intermediate IIA the reaction proceeds via an enolate intermediate to form six-membered metallacyclic species III then undergoes cyclization to release the palladium catalyst and furnish the 1,2-naphthofuroquinone 3a. A similar catalytic pathway is postulated for the assembly of 4a via an enol-directed route to form palladacycle IV, which then undergoes carbopalladation of second diphenylacetylene 2a and leads to an intermediate V. A subsequent alkene insertion leads to the palladacycle species VI which regenerates the palladium catalyst through reduction elimination and affords the aim product 4a.
8. Reference


9. NMR Spectrum