Supporting Information

Palladium-catalyzed [6+4] cycloaddition with π-allyl all-carbon 1,6-dipole for the synthesis of ten-membered heterocycles

Jun-Tao Chen,[a,b] Na Lin,[a] Linli Xu,[a] Yi Wang,[b] Xiaoyan Luo,[b] Yang-Zi Liu,*[a] and Wei-Ping Deng*[a,b]

a. Key Laboratory of the Ministry of Education for Advanced Catalysis Materials, Department of Chemistry, Zhejiang Normal University, 688 Yingbin Road, Jinhua, 321004, P. R. China.

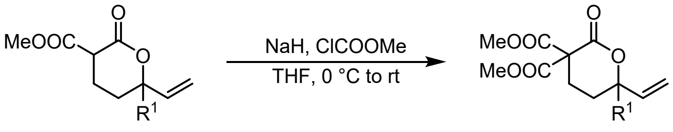
b. Shanghai Frontiers Science Center of Optogenetic Techniques for Cell Metabolism, School of Pharmacy, East China University of Science and Technology, Shanghai 200237, P. R. China

Contents

1. General information

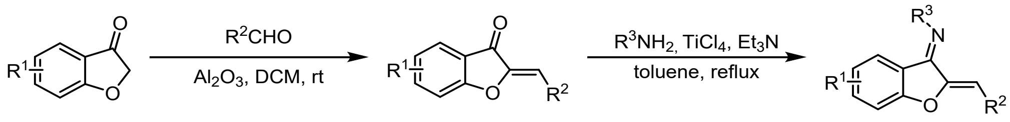
^{1}H NMR spectra were recorded on a Bruker DPX 400 MHz or 600 MHz spectrometer in $CDCl_3$. Chemical shifts were reported in ppm with the internal TMS signal at 0.0 ppm as a standard. The spectra are interpreted as: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, dd = doublet of doublets, td = triplet of doublets, dt = doublet of triplets, ddd = doublet of doublet of doublets, ddt = doublet of doublet of triplets, dtd = doublet of triplet of doublets, brs = broad signals, coupling constant (s) *J* are reported in Hz and relative integrations are reported. ^{13}C NMR spectra were recorded on a Bruker DPX 400 MHz or 600 MHz spectrometer in $CDCl_3$. Chemical shifts were reported in ppm with the internal chloroform signal at 77.16 ppm as a standard. ^{19}F NMR (377 MHz) spectra were recorded on a Bruker DPX 400 MHz or 600 MHz spectrometer in $CDCl_3$ and referenced relative to $CFCl_3$. Melting points were obtained in open capillary tubes using SGW X-4 micro melting point apparatus which were uncorrected. High-resolution mass spectra (HRMS) were recorded on a Waters GCT Premier mass spectrometer using EI-TOF (electron ionization-time of flight) or on a JEOC AccuTOF LC-plus 4G mass spectrometer using ESI (electrospray ionization). Anhydrous CH_2Cl_2 was distilled from calcium hydride. Anhydrous toluene was distilled from sodium/benzophenone. Other anhydrous solvents (<30 ppm water, Karl-Fischer titration) were purchased from Energy or J&K and stored over molecular sieves under an argon atmosphere. $Pd_2(dba)_3$, $Pd_2(dba)_3 \cdot CHCl_3$ and $Pd(PPh_3)_4$ were purchased from Laajoo.

2. Preparation of all-carbon 1,6-dipole precursor 1



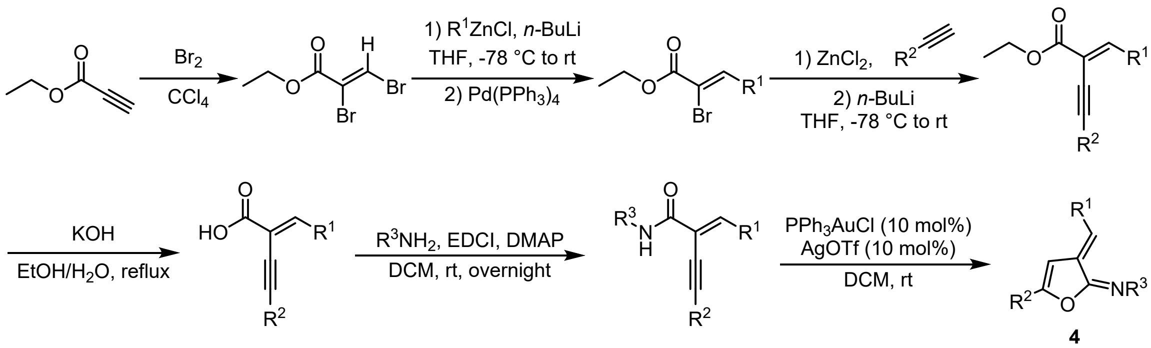
Under nitrogen atmosphere, to a solution of **S1** (1.0 equiv.) in anhydrous tetrahydrofuran (2.0 mL/mmol) was added NaH (3.0 equiv.) at 0 ºC.[1] Then ClCOOMe (3.0 equiv.) was added dropwise via syringe at the same temperature. After the starting material was completely consumed (detected by TLC), the reaction mixture was quenched with saturated aqueous NH_4Cl. Then, the mixture was extracted with ethyl acetate, washed with brine and dried over Na_2SO_4. After evaporation, the mixture was purified by column chromatography (petroleum ether/ ethyl acetate = 6:1) to give the corresponding cycloadducts **1**.

3. Preparation of benzofuran-derived azadienes 2



Substrates 2 were synthesized according to the literature procedure.[2] Spectral data of compounds were in accordance with those reported in the literature.

4. Preparation of furan-derived azadienes 4



Substrates **4** was synthesized according to the literature procedure.[3] Spectral data of compound was in accordance with that reported in the literature.

References

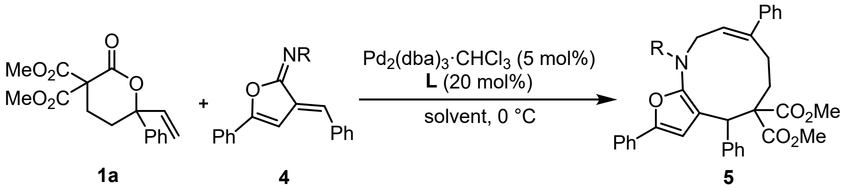
[1] K. Li; S. Yang; B. Zheng; W. Wang; Y Wu; J. Li and H. Guo, A new type of δ-vinylvalerolactone for palladium-catalyzed cycloaddition: synthesis of nine-membered heterocycles, *Chem. Commun.*, 2022, **58**, 6646–6649.

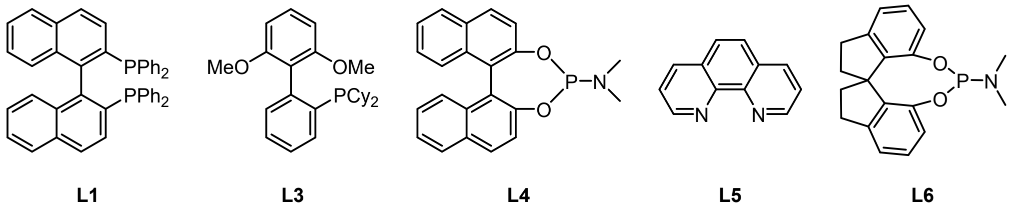
[2] H. Ni; X. Tang; W. Zheng; W. Yao; N. Ullah; Y. Lu, Enantioselective phosphine-catalyzed formal [4+4] annulation of *α,β*-unsaturated imines and allene ketones: construction of eight-membered rings, *Angew. Chem. Int. Ed.* 2017, **56**, 14222–14226.

[3] W.-L. Yang, J.-H. Shen, Z.-H. Zhao, Z. Wang and W.-P. Deng, Stereoselective synthesis of functionalized azepines *via* gold and palladium relay catalysis, *Org. Chem. Front.* 2022, **9**, 4685–4691.

5. Optimization of reaction conditions

Table S1. Optimization of the reaction conditions for Pd-catalyzed [6+4] cycloaddition of all-carbon 1,6-dipole precursor **1a** and furan-derived azadiene **4**

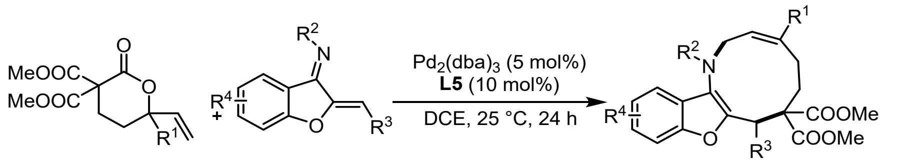




Entry	R	[Pd]	Ligand	Solvent	Yield[b]/%
1	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L1**	DCM	32
2	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L3**[c]	DCM	25
3	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L4**[c]	DCM	12
4	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L5**	DCM	20
5	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L6**	DCM	45
6	Ts	$Pd_2(dba)_3$	**L6**	DCM	42
7	Ts	$Pd(PPh_3)_4$[d]	**L6**	DCM	40
8	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L6**	THF	57
9	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L6**	toluene	65
10	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L6**	$PhCF_3$	58
11	Ts	$Pd_2(dba)_3{\cdot}CHCl_3$	**L6**	*o*-xylene	49
12[e]	Ts	**$Pd_2(dba)_3{\cdot}CHCl_3$**	**L6**	toluene	**75**
13[e]	Ms	$Pd_2(dba)_3{\cdot}CHCl_3$	**L6**	toluene	40

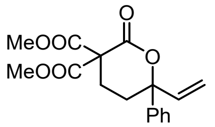
[a] Reaction conditions: **1a** (0.15 mmol), **4a** (0.10 mmol), $Pd_2(dba)_3{\cdot}CHCl_3$ (5 mol%) and ligand (20 mol%) in 1.0 mL of solvent under a N_2 atmosphere at 25 °C for 24 h. [b] Yield of **5a** was determined by ^{1}H-NMR spectroscopic analysis of the crude product with 1,3,5-trimethoxybenzene as an internal standard. [c] 20 mol%. [d] 10 mol% [e] at 0 °C

6. General procedure for Pd-catalyzed [6+4] cycloaddition

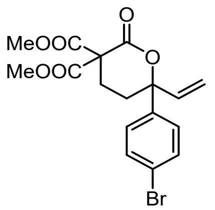


1 2 3

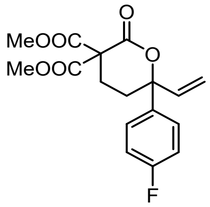
General procedure A: An oven-dried Schlenk tube was added $Pd_2(dba)_3$ (0.005 mmol, 4.6 mg, 5 mol%), **L5** (0.01 mmol, 1.8 mg, 10 mol%) followed by the addition of anhydrous DCE (1 mL) under N_2. The reaction mixture was allowed to stir for 30 mins at 25 °C, and all-carbon 1,6-dipole precursor **1** (0.15 mmol) and benzofuran-derived azadienes **2** (0.1 mmol) were then added. After 24 h, the mixture was concentrated and purified by column chromatography (petroleum ether/ ethyl acetate = 4:1) to give the corresponding cycloadducts **3**.



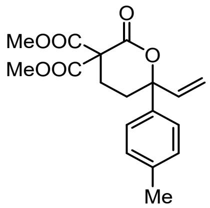
1a was obtained as white solid; m.p. = 75.4 – 79.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.42 – 7.28 (m, 5H), 6.05 (dd, *J* = 17.2, 10.8 Hz, 1H), 5.38 (d, *J* = 17.2 Hz, 1H), 5.31 (d, *J* = 10.8 Hz, 1H), 3.86 (s, 3H), 3.79 (s, 3H), 2.67 – 2.56 (m, 1H), 2.50 – 2.41 (m, 1H), 2.31 – 2.14 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 167.3, 167.2, 164.5, 141.8, 140.0, 128.8(2C), 128.1, 125.1(2C), 115.9, 88.6, 62.7, 53.9, 53.8, 30.7, 25.7; **HRMS** (ESI-TOF, m/z): calcd for $C_{17}H_{18}O_6Na$ $[M+Na]^+$: 341.0996, found: 341.0998.



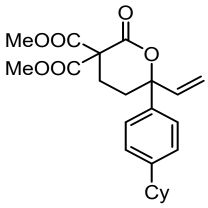
1b was obtained as light yellow oil; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.57 – 7.43 (m, 2H), 7.36 – 7.17 (m, 2H), 6.01 (dd, *J* = 17.2, 10.8 Hz, 1H), 5.38 (d, *J* = 17.1 Hz, 1H), 5.33 (d, *J* = 10.8 Hz, 1H), 3.86 (s, 3H), 3.80 (s, 3H), 2.68 – 2.56 (m, 1H), 2.52 – 2.39 (m, 1H), 2.29 – 2.09 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 167.0(6), 167.0(5), 164.2, 141.0, 139.5, 131.9(2C), 126.9(2C), 122.3, 116.4, 88.1, 62.6, 53.9(2C), 30.5, 25.6; **HRMS** (ESI-TOF, m/z): calcd for $C_{17}H_{17}O_6{}^{79}BrNa$ $[M+Na]^+$: 419.0101, found: 419.0103; $C_{17}H_{17}O_6{}^{81}BrNa$ $[M+Na]^+$: 421.0081 found: 421.0086.



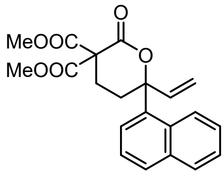
1c was obtained as light yellow oil; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.45 – 7.33 (m, 2H), 7.11 – 6.98 (m, 2H), 6.03 (dd, *J* = 17.2, 10.8 Hz, 1H), 5.38 (d, *J* = 17.1 Hz, 1H), 5.33 (d, *J* = 10.9 Hz, 1H), 3.85 (s, 3H), 3.80 (s, 3H), 2.68 – 2.57 (m, 1H), 2.51 – 2.40 (m, 1H), 2.31 – 2.11 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 167.0(3), 167.0(2), 164.2, 162.3 (d, $J_{C–F}$ = 247.4 Hz), 139.7, 137.6 (d, $J_{C–F}$ = 3.3 Hz), 127.0 (d, $J_{C–F}$ = 8.2 Hz) (2C), 116.0, 115.5 (d, $J_{C–F}$ = 21.6 Hz) (2C), 88.1, 62.6, 53.7(2C), 30.5, 25.6; **^{19}F NMR** (377 MHz, $CDCl_3$) δ -114.2.(s, 1F); **HRMS** (ESI-TOF, m/z): calcd for $C_{17}H_{17}O_6FNa$ $[M+Na]^+$: 359.0902, found: 359.0903.



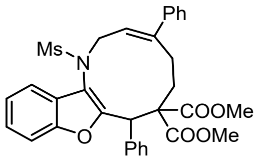
1d was obtained as light yellow oil; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.30 – 7.23 (m, 2H), 7.26 – 7.14 (m, 2H), 6.03 (dd, *J* = 17.2, 10.8 Hz, 1H), 5.36 (d, *J* = 17.1 Hz, 1H), 5.29 (d, *J* = 10.8 Hz, 1H), 3.85 (s, 3H), 3.79 (s, 3H), 2.66 – 2.54 (m, 1H), 2.52 – 2.38 (m, 1H), 2.34 (s, 3H), 2.28 – 2.13 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 167.3, 167.2, 164.5, 140.2, 138.9, 137.9, 129.4(2C), 125.1(2C), 115.7, 88.7, 62.7, 53.9, 53.8, 30.6, 25.8, 21.1; **HRMS** (ESI-TOF, m/z): calcd for $C_{18}H_{20}O_6Na$ $[M+Na]^+$: 355.1153, found: 355.1144.



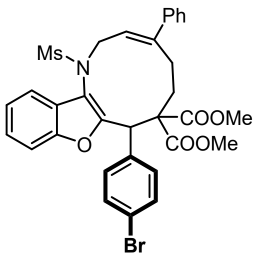
1e was obtained as light yellow oil; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.25 (m, 2H), 7.23 – 7.17 (m, 2H), 6.03 (dd, *J* = 17.2, 10.8 Hz, 1H), 5.37 (d, *J* = 17.1 Hz, 1H), 5.29 (d, *J* = 10.9 Hz, 1H), 3.85 (s, 3H), 3.79 (s, 3H), 2.66 – 2.56 (m, 1H), 2.56 – 2.41 (m, 2H), 2.25 – 2.17 (m, 2H), 1.89 – 1.80 (m, 4H), 1.78 – 1.71 (m, 1H), 1.46 – 1.22 (m, 5H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 167.4, 167.2, 164.5, 148.1, 140.2, 139.1, 127.2(2C), 125.1(2C), 115.6, 88.7, 62.7, 53.8(4), 53.8(2), 44.2, 34.4(2C), 30.6, 26.9(2C), 26.2, 25.8; **HRMS** (ESI-TOF, m/z): calcd for $C_{23}H_{28}O_6Na$ $[M+Na]^+$: 423.1779, found: 423.1778.



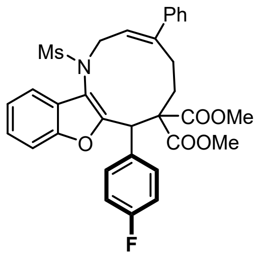
1f was obtained as light yellow oil; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.89 – 7.81 (m, 4H), 7.53 – 7.48 (m, 2H), 7.47 – 7.43 (m, 1H), 6.13 (dd, *J* = 17.2, 10.8 Hz, 1H), 5.44 (d, *J* = 17.2 Hz, 1H), 5.35 (d, *J* = 10.8 Hz, 1H), 3.88 (s, 3H), 3.76 (s, 3H), 2.70 – 2.61 (m, 1H), 2.53 – 2.44 (m, 1H), 2.35 – 2.30 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 167.3, 167.2, 164.5, 140.0, 139.0, 133.1, 132.9, 128.7, 128.5, 127.7, 126.7, 126.7, 124.2, 123.1, 116.2, 88.8, 62.8, 53.9(4), 53.8(8), 30.6, 25.8; **HRMS** (ESI-TOF, m/z): calcd for $C_{21}H_{20}O_6Na$ $[M+Na]^+$: 391.1153, found: 391.1154.



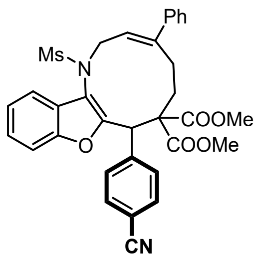
3aa was obtained as white solid; m.p. = 188.4 – 192.1 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.74 – 7.67 (m, 2H), 7.59 – 7.46 (m, 2H), 7.39 – 7.31 (m, 2H), 7.30 – 7.24 (m, 2H), 7.23 – 7.18 (m, 1H), 7.15 – 7.05 (m, 3H), 6.64 – 6.54 (m, 2H), 5.64 (s, 1H), 5.54 – 5.46 (m, 1H), 4.78 – 4.68 (m, 1H), 4.63 – 4.54 (m, 1H), 3.77 (s, 3H), 3.42 (s, 3H), 2.84 – 2.75 (m, 4H), 2.43 – 2.31 (m, 1H), 2.27 – 2.14 (m, 1H), 1.15 – 1.05 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$)δ 171.1, 170.2, 155.7, 153.6, 149.0, 140.4, 136.4, 130.7(2C), 128.4(2C), 127.9(2C), 127.8, 127.6, 126.7, 126.4(2C), 125.1, 123.9, 119.2, 117.9, 117.7, 112.4, 63.1, 53.0, 52.1, 46.6, 43.4, 37.9, 33.0, 22.3; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{31}NO_7SNa$ $[M+Na]^+$: 596.1714, found: 596.1717.



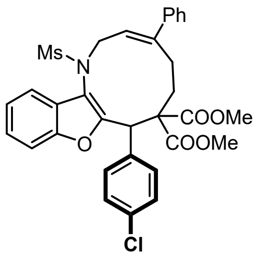
3ab was obtained as white solid; m.p. = 186.6 – 189.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.66 – 7.58 (m, 2H), 7.57 – 7.46 (m, 2H), 7.43 – 7.38 (m, 2H), 7.37 – 7.33 (m, 2H), 7.15 – 7.05 (m, 3H), 6.65 – 6.58 (m, 2H), 5.65 (s, 1H), 5.53 – 5.45 (m, 1H), 4.82 – 4.73 (m, 1H), 4.56 – 4.47 (m, 1H), 3.77 (s, 3H), 3.46 (s, 3H), 2.85 – 2.76 (m, 4H), 2.43 – 2.30 (m, 1H), 2.25 – 2.12 (m, 1H), 1.08 – 0.98 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.9, 170.1, 155.5, 153.6, 148.9, 140.3, 135.4, 132.6(2C), 131.0(2C), 128.4(2C), 127.9, 126.3(2C), 126.1, 125.2, 124.0, 121.9, 118.9, 118.0, 117.4, 112.6, 62.8, 53.1, 52.2, 46.8, 42.8, 37.6, 33.1, 22.5; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}NO_7SBr^{79}Na$ $[M+Na]^+$: 674.0819, found: 674.0816; $C_{32}H_{30}NO_7SBr^{81}Na$ $[M+Na]^+$: 676.0799, found: 676.0793.



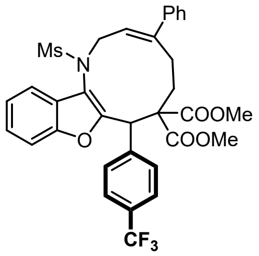
3ac was obtained as white solid; m.p. = 189.6 – 193.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.76 – 7.66 (m, 2H), 7.56 – 7.47 (m, 2H), 7.40 – 7.31 (m, 2H), 7.16 – 7.05 (m, 3H), 7.02 – 6.91 (m, 2H), 6.65 – 6.58 (m, 2H), 5.67 (s, 1H), 5.54 – 5.46 (m, 1H), 4.81 – 4.72 (m, 1H), 4.58 – 4.49 (m, 1H), 3.77 (s, 3H), 3.45 (s, 3H), 2.87 – 2.73 (m, 4H), 2.43 – 2.30 (m, 1H), 2.25 – 2.12 (m, 1H), 1.10 – 1.00 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 170.2, 162.2 (d, $J_{C–F}$ = 247.2 Hz), 155.8, 153.6, 149.0, 140.4, 132.6 (d, $J_{C–F}$ = 8.1 Hz) (2C), 132.1 (d, $J_{C–F}$ = 3.4 Hz), 128.5(2C), 127.9, 126.4(2C), 126.3, 125.2, 124.0, 119.0, 117.9, 117.5, 114.8 (d, $J_{C–F}$ = 21.1 Hz) (2C), 112.6, 63.0, 53.1, 52.2, 46.8, 42.6, 37.7, 33.1, 22.5; **^{19}F NMR** (377 MHz, $CDCl_3$) δ -115.0. (s, 1F); **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}FNO_7SNa$ $[M+Na]^+$: 614.1620, found: 614.1622.



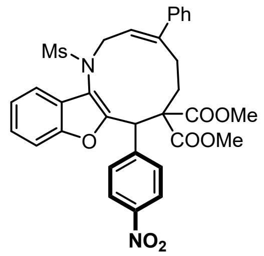
3ad was obtained as white solid; m.p. = 189.7 – 192.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.92 – 7.86 (m, 2H), 7.60 – 7.56 (m, 2H), 7.56 – 7.52 (m, 1H), 7.50 – 7.47 (m, 1H), 7.40 – 7.36 (m, 2H), 7.16 – 7.07 (m, 3H), 6.66 – 6.59 (m, 2H), 5.77 (s, 1H), 5.53 – 5.45 (m, 1H), 4.86 – 4.77 (m, 1H), 4.53 – 4.43 (m, 1H), 3.78 (s, 3H), 3.44 (s, 3H), 2.85 (s, 4H), 2.45 – 2.32 (m, 1H), 2.25 – 2.12 (m, 1H), 1.06 – 0.96 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.7, 169.9, 155.1, 153.6, 148.8, 141.9, 140.2, 131.9(2C), 131.5(2C), 128.5(2C), 127.9, 126.3(2C), 125.7, 125.4, 124.2, 119.0, 118.6, 118.4, 117.2, 112.8, 111.3, 62.8, 53.2, 52.2, 46.9, 43.2, 37.3, 33.2, 22.6; **HRMS** (ESI-TOF, m/z): calcd for $C_{33}H_{30}N_2O_7SNa$ $[M+Na]^+$: 621.1666, found: 621.1662.



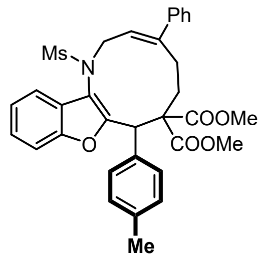
3ae was obtained as white solid; m.p. = 188.4 – 189.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.72 – 7.64 (m, 2H), 7.56 – 7.46 (m, 2H), 7.41 – 7.32 (m, 2H), 7.29 – 7.21 (m, 2H), 7.18 – 7.05 (m, 3H), 6.65 – 6.58 (m, 2H), 5.66 (s, 1H), 5.53 – 5.45 (m, 1H), 4.82 – 4.73 (m, 1H), 4.57 – 4.48 (m, 1H), 3.77 (s, 3H), 3.46 (s, 3H), 2.86 – 2.76 (m, 4H), 2.43 – 2.30 (m, 1H), 2.25 – 2.12 (m, 1H), 1.09 – 0.99 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 170.2, 155.6, 153.6, 148.9, 140.4, 134.9, 133.6, 132.3(2C), 128.5(2C), 128.1(2C), 127.9, 126.4(2C), 126.2, 125.2, 124.1, 118.9, 118.0, 117.4, 112.6, 62.9, 53.1, 52.2, 46.8, 42.7, 37.6, 33.2, 22.5; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Cl^{35}NO_7SNa$ $[M+Na]^+$: 630.1324, found: 630.1354; $C_{32}H_{30}Cl^{37}NO_7SNa$ $[M+Na]^+$: 632.1294, found: 632.1320.



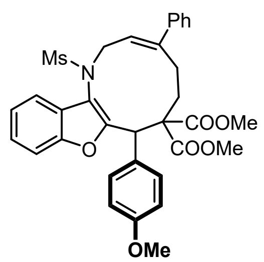
3af was obtained as white solid; m.p. = 187.5 – 190.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.92 – 7.85 (m, 2H), 7.58 – 7.45 (m, 4H), 7.42 – 7.31 (m, 2H), 7.19 – 7.05 (m, 3H), 6.67 – 6.59 (m, 2H), 5.77 (s, 1H), 5.54 – 5.46 (m, 1H), 4.85 – 4.76 (m, 1H), 4.56 – 4.46 (m, 1H), 3.78 (s, 3H), 3.43 (s, 3H), 2.88 – 2.80 (m, 4H), 2.45 – 2.32 (m, 1H), 2.26 – 2.13 (m, 1H), 1.10 – 0.99 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.8, 170.0, 155.4, 153.7, 148.9, 140.4, 140.3, 131.4(2C), 129.6 (q, $J_{C–F}$ = 32.4 Hz), 128.5(2C), 127.9, 126.3(2C), 125.9, 125.3, 124.7 (q, $J_{C–F}$ = 3.8 Hz) (2C), 124.3 (q, $J_{C–F}$ = 272.0 Hz), 124.1, 118.8, 118.3, 117.3, 112.7, 62.9, 53.1, 52.2, 46.9, 43.1, 37.5, 33.2, 22.6; **^{19}F NMR** (377 MHz, $CDCl_3$) δ -62.6. (s, 3F); **HRMS** (ESI-TOF, m/z): calcd for $C_{33}H_{30}F_3NO_7SNa$ $[M+Na]^+$: 664.1588, found: 664.1583.



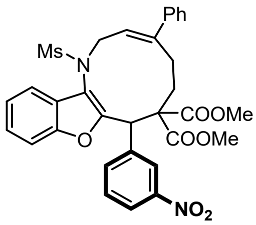
3ag was obtained as white solid; m.p. = 187.6 – 189.4 ℃; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.18 – 8.11 (m, 2H), 7.99 – 7.92 (m, 2H), 7.59 – 7.52 (m, 1H), 7.50 – 7.46 (m, 1H), 7.44 – 7.33 (m, 2H), 7.20 – 7.06 (m, 3H), 6.67 – 6.60 (m, 2H), 5.83 (s, 1H), 5.54 – 5.46 (m, 1H), 4.89 – 4.79 (m, 1H), 4.53 – 4.43 (m, 1H), 3.78 (s, 3H), 3.46 (s, 3H), 2.89 – 2.81 (m, 4H), 2.46 – 2.33 (m, 1H), 2.26 – 2.13 (m, 1H), 1.07 – 0.97 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.7, 169.9, 155.0, 153.7, 148.9, 147.2, 143.9, 140.3, 132.1(2C), 128.5(2C), 128.0, 126.3(2C), 125.6, 125.5, 124.3, 122.9(2C), 118.6, 118.5, 117.2, 112.8, 62.8, 53.2, 52.3, 47.0, 43.1, 37.3, 33.2, 22.7; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}N_2O_9SNa$ $[M+Na]^+$: 641.1565, found: 641.1557.



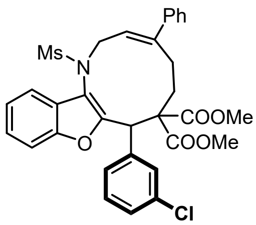
3ah was obtained as white solid; m.p. = 192.5 – 194.6 ℃; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.61 – 7.51 (m, 3H), 7.53 – 7.45 (m, 1H), 7.41 – 7.28 (m, 2H), 7.18 – 7.03 (m, 5H), 6.65 – 6.57 (m, 2H), 5.59 (s, 1H), 5.54 – 5.46 (m, 1H), 4.78 – 4.68 (m, 1H), 4.63 – 4.53 (m, 1H), 3.77 (s, 3H), 3.46 (s, 3H), 2.82 – 2.70 (m, 4H), 2.45 – 2.30 (m, 1H), 2.29 – 2.16 (m, 4H), 1.14 – 1.03 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.2, 170.3, 155.9, 153.6, 149.0, 140.4, 137.2, 133.2, 130.6(2C), 128.7(2C), 128.4(2C), 127.8, 126.7, 126.4(2C), 125.0, 123.9, 119.2, 117.7(0), 117.6(6), 112.4, 63.1, 53.0, 52.1, 46.6, 43.1, 37.9, 33.1, 22.4, 21.2; **HRMS** (ESI-TOF, m/z): calcd for $C_{33}H_{33}NO_7SNa$ $[M+Na]^+$: 610.1870, found: 610.1871.



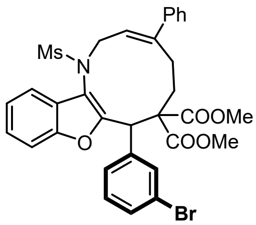
3ai was obtained as white solid; m.p. = 188.9 – 192.9 ℃; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.66 – 7.58 (m, 2H), 7.58 – 7.45 (m, 2H), 7.38 – 7.28 (m, 2H), 7.16 – 7.03 (m, 3H), 6.85 – 6.77 (m, 2H), 6.64 – 6.57 (m, 2H), 5.60 (s, 1H), 5.54 – 5.46 (m, 1H), 4.78 – 4.69 (m, 1H), 4.62 – 4.52 (m, 1H), 3.77 (s, 3H), 3.76 (s, 3H), 3.47 (s, 3H), 2.80 (s, 4H), 2.43 – 2.30 (m, 1H), 2.26 – 2.13 (m, 1H), 1.12 – 1.03 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.2, 170.3, 158.9, 156.0, 153.6, 149.0, 140.4, 131.9(2C), 128.4(2C), 128.3, 127.9, 126.7, 126.4(2C), 125.0, 123.9, 119.2, 117.6, 117.5, 113.3(2C), 112.4, 63.1, 55.2, 53.0, 52.2, 46.6, 42.7, 37.9, 33.1, 22.4; **HRMS** (ESI-TOF, m/z): calcd for $C_{33}H_{33}NO_8SNa$ $[M+Na]^+$: 626.1820, found: 626.1821.



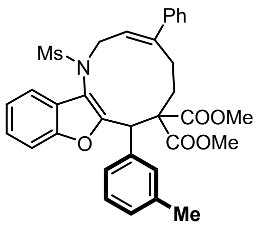
3aj was obtained as white solid; m.p. = 185.9–189.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.66 – 8.60 (m, 1H), 8.16 – 8.06 (m, 2H), 7.62 – 7.55 (m, 1H), 7.54 – 7.43 (m, 2H), 7.43 – 7.32 (m, 2H), 7.20 – 7.07 (m, 3H), 6.71 – 6.64 (m, 2H), 5.83 (s, 1H), 5.54 – 5.46 (m, 1H), 4.90 – 4.81 (m, 1H), 4.54 – 4.45 (m, 1H), 3.78 (s, 3H), 3.52 (s, 3H), 2.94 – 2.83 (m, 4H), 2.46 – 2.33 (m, 1H), 2.28 – 2.15 (m, 1H), 1.10 – 0.99 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.7, 169.9, 155.0, 153.7, 148.6, 147.8, 140.4, 138.3, 138.2, 128.6, 128.5(2C), 127.9, 126.3(2C), 125.7, 125.5, 125.5, 124.2, 122.6, 118.6, 118.4, 117.3, 113.0, 62.8, 53.2, 52.4, 47.1, 42.9, 37.3, 33.3, 22.7; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}N_2O_9SNa$ $[M+Na]^+$: 641.1565, found: 641.1559.



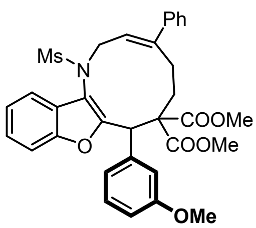
3ak was obtained as white solid; m.p. = 188.4 – 191.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.76 – 7.71 (m, 1H), 7.67 – 7.60 (m, 1H), 7.59 – 7.47 (m, 2H), 7.40 – 7.31 (m, 2H), 7.25 – 7.18 (m, 2H), 7.16 – 7.05 (m, 3H), 6.64 – 6.58 (m, 2H), 5.65 (s, 1H), 5.53 – 5.45 (m, 1H), 4.81 – 4.72 (m, 1H), 4.59 – 4.49 (m, 1H), 3.78 (s, 3H), 3.47 (s, 3H), 2.85 – 2.75 (m, 4H), 2.43 – 2.30 (m, 1H), 2.25 – 2.12 (m, 1H), 1.09 – 0.99 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.8, 170.1, 155.3, 153.7, 148.9, 140.3, 138.3, 133.5, 130.6, 129.5, 129.1, 128.4(2C), 127.9, 127.8, 126.4(2C), 126.2, 125.2, 124.1, 118.9, 118.1, 117.5, 112.7, 62.9, 53.1, 52.2, 46.8, 43.0, 37.6, 33.1, 22.4; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Cl^{35}NO_7SNa$ $[M+Na]^+$: 630.1324, found: 630.1320; calcd for $C_{32}H_{30}Cl^{37}NO_7SNa$ $[M+Na]^+$: 632.1294, found: 632.1305.



3al was obtained as white solid; m.p. = 198.4 – 199.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.90 – 7.85 (m, 1H), 7.71 – 7.65 (m, 1H), 7.59 – 7.47 (m, 2H), 7.41 – 7.31 (m, 3H), 7.21 – 7.05 (m, 4H), 6.65 – 6.58 (m, 2H), 5.63 (s, 1H), 5.53 – 5.45 (m, 1H), 4.82 – 4.72 (m, 1H), 4.59 – 4.49 (m, 1H), 3.78 (s, 3H), 3.49 (s, 3H), 2.87 – 2.74 (m, 4H), 2.43 – 2.30 (m, 1H), 2.25 – 2.12 (m, 1H), 1.08 – 0.98 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.9, 170.1, 155.3, 153.7, 148.9, 140.4, 138.6, 133.5, 130.7, 130.1, 129.4, 128.5(2C), 127.9, 126.4(2C), 126.2, 125.3, 124.1, 121.7, 118.9, 118.1, 117.5, 112.7, 63.0, 53.1, 52.2, 46.8, 43.0, 37.7, 33.1, 22.5; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Br^{79}NO_7SNa$ $[M+Na]^+$: 674.0819, found: 674.0811; calcd for $C_{32}H_{30}Br^{81}NO_7SNa$ $[M+Na]^+$: 676.0799, found: 676.0793.

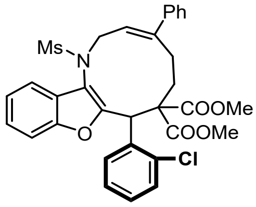


3am was obtained as white solid; m.p. = 184.8 – 186.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.60 – 7.53 (m, 1H), 7.53 – 7.46 (m, 3H), 7.37 – 7.30 (m, 2H), 7.18 – 7.03 (m, 5H), 6.63 – 6.56 (m, 2H), 5.57 (s, 1H), 5.54 – 5.46 (m, 1H), 4.76 – 4.67 (m, 1H), 4.65 – 4.56 (m, 1H), 3.77 (s, 3H), 3.44 (s, 3H), 2.80 – 2.72 (m, 4H), 2.44 – 2.28 (m, 4H), 2.26 – 2.14 (m, 1H), 1.15 – 1.05 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.1, 170.2, 155.7, 153.7, 149.0, 140.4, 137.4, 136.2, 131.3, 128.4(2C), 128.4, 127.8(2C), 127.8, 126.9, 126.4(2C), 125.1, 123.9, 119.3, 117.8(5), 117.7(9), 112.4, 63.1, 53.0, 52.0, 46.6, 43.4, 38.0, 33.0, 22.3, 21.8; **HRMS** (ESI-TOF, m/z): calcd for $C_{33}H_{33}NO_7SNa$ $[M+Na]^+$: 610.1870, found: 610.1865.

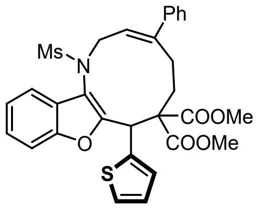


3an was obtained as white solid; m.p. = 189.9 – 195.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.59 – 7.53 (m, 1H), 7.52 – 7.46 (m, 1H), 7.38 – 7.26 (m, 4H), 7.21 – 7.04 (m, 4H), 6.79 – 6.72 (m, 1H), 6.61 – 6.55 (m, 2H), 5.61 (s, 1H), 5.54 – 5.46 (m, 1H), 4.76 – 4.67 (m, 1H), 4.64 – 4.54 (m, 1H), 3.78 (d, J = 2.2 Hz, 6H), 3.44 (s, 3H), 2.85 – 2.72 (m, 4H), 2.42 – 2.30 (m, 1H), 2.26

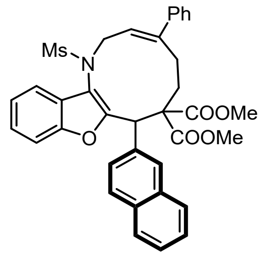
– 2.13 (m, 1H), 1.19 – 1.04 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.1, 170.1, 159.1, 155.5, 153.6, 149.0, 140.4, 137.8, 128.8, 128.4(2C), 127.9, 126.8, 126.4(2C), 125.1, 123.9, 123.0, 119.3, 118.0, 117.7, 116.8, 112.8, 112.4, 63.1, 55.3, 53.0, 52.1, 46.6, 43.3, 38.0, 33.0, 22.3; **HRMS** (ESI-TOF, m/z): calcd for $C_{33}H_{33}NO_8SNa$ $[M+Na]^+$: 626.1820, found: 626.1821.



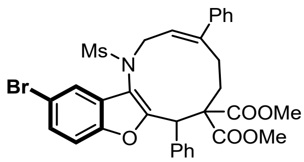
3ao was obtained as white solid; m.p. = 178.4 – 180.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.99 – 7.88 (m, 1H), 7.67 – 7.56 (m, 1H), 7.47 – 7.41 (m, 1H), 7.41 – 7.30 (m, 3H), 7.25 – 7.05 (m, 5H), 6.70 – 6.63 (m, 2H), 5.97 (s, 1H), 5.61 – 5.53 (m, 1H), 4.81 – 4.71 (m, 1H), 4.69 – 4.59 (m, 1H), 3.70 (s, 3H), 3.63 (s, 3H), 3.01 – 2.91 (m, 1H), 2.78 (s, 3H), 2.76 – 2.63 (m, 1H), 2.50 – 2.37 (m, 1H), 1.05 – 0.95 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.2, 169.9, 153.7, 153.5, 149.6, 140.5, 135.2, 134.2, 133.5, 129.6, 129.0, 128.4(2C), 127.9, 127.1, 126.5(2C), 126.2, 125.3, 123.9, 120.1, 118.5, 118.1, 112.1, 62.4, 53.1, 52.4, 46.3, 39.6, 38.1, 33.3, 23.3; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Cl^{35}NO_7SNa$ $[M+Na]^+$: 630.1324, found: 630.1327; calcd for $C_{32}H_{30}Cl^{37}NO_7SNa$ $[M+Na]^+$: 632.1294, found: 632.1308.



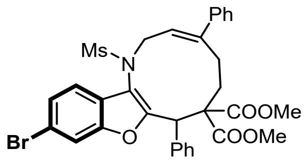
3ap was obtained as white solid; m.p. = 187.4 – 189.8 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.64 – 7.54 (m, 1H), 7.55 – 7.45 (m, 1H), 7.42 – 7.30 (m, 2H), 7.24 – 7.19 (m, 1H), 7.21 – 7.15 (m, 1H), 7.17 – 7.04 (m, 3H), 6.93 – 6.84 (m, 1H), 6.67 – 6.59 (m, 2H), 5.91 (s, 1H), 5.56 – 5.48 (m, 1H), 4.73 – 4.55 (m, 2H), 3.84 (s, 3H), 3.47 (s, 3H), 2.80 (s, 3H), 2.78 – 2.71 (m, 1H), 2.44 – 2.31 (m, 1H), 2.29 – 2.16 (m, 1H), 1.14 – 1.04 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.2, 169.7, 154.3, 153.6, 148.9, 140.3, 138.2, 128.5(2C), 128.4, 127.9, 126.8, 126.3(8)(2C), 126.3(5), 125.7, 125.3, 124.1, 119.5, 117.8, 117.7, 112.3, 63.6, 53.2, 52.5, 46.5, 39.1, 37.7, 32.7, 22.2; **HRMS** (ESI-TOF, m/z): calcd for $C_{30}H_{29}NO_7S_2Na$ $[M+Na]^+$: 602.1278, found: 602.1276.



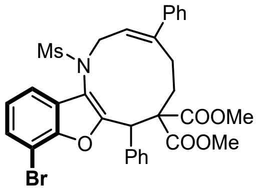
3aq was obtained as white solid; m.p. = 188.4 – 189.9 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.20 – 8.16 (m, 1H), 7.87 – 7.80 (m, 2H), 7.79 – 7.71 (m, 2H), 7.60 – 7.51 (m, 2H), 7.46 – 7.39 (m, 2H), 7.39 – 7.33 (m, 2H), 7.19 – 7.05 (m, 3H), 6.66 – 6.59 (m, 2H), 5.82 (s, 1H), 5.56 – 5.48 (m, 1H), 4.83 – 4.73 (m, 1H), 4.65 – 4.55 (m, 1H), 3.76 (s, 3H), 3.35 (s, 3H), 2.92 – 2.79 (m, 1H), 2.75 (s, 3H), 2.47 – 2.34 (m, 1H), 2.30 – 2.17 (m, 1H), 1.19 – 1.09 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.1, 170.3, 155.7, 153.7, 149.0, 140.4, 133.9, 133.2, 132.7, 130.0, 128.7, 128.5(2C), 128.4, 127.9, 127.6, 127.2, 126.7, 126.4(2C), 126.1, 126.0, 125.1, 124.0, 119.2, 118.0, 117.7, 112.5, 63.1, 53.1, 52.2, 46.7, 43.5, 37.9, 33.1, 22.4; **HRMS** (ESI-TOF, m/z): calcd for $C_{36}H_{33}NO_7SNa$ $[M+Na]^+$: 646.1870, found: 646.1870.



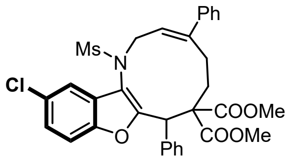
3ar was obtained as white solid; m.p. = 189.8 – 193.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.72 – 7.68 (m, 1H), 7.68 – 7.62 (m, 2H), 7.48 – 7.42 (m, 1H), 7.40 – 7.35 (m, 1H), 7.30 – 7.21 (m, 3H), 7.18 – 7.10 (m, 3H), 6.70 – 6.65 (m, 2H), 5.60 (s, 1H), 5.57 – 5.52 (m, 1H), 4.76 – 4.66 (m, 1H), 4.63 – 4.54 (m, 1H), 3.77 (s, 3H), 3.42 (s, 3H), 2.82 – 2.73 (m, 4H), 2.44 – 2.32 (m, 1H), 2.31 – 2.18 (m, 1H), 1.15 – 1.05 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 170.1, 156.9, 152.4, 149.3, 140.1, 136.1, 130.6(2C), 129.0, 128.6(2C), 128.2, 128.1(3C), 127.8, 126.4(2C), 122.0, 117.5(0), 117.4(9), 117.1, 113.9, 63.1, 53.1, 52.2, 46.5, 43.5, 38.2, 33.1, 22.2; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Br^{79}NO_7SNa$ $[M+Na]^+$: 674.0819, found: 674.0814; calcd for $C_{32}H_{30}Br^{81}NO_7SNa$ $[M+Na]^+$: 676.0799, found: 676.0809.



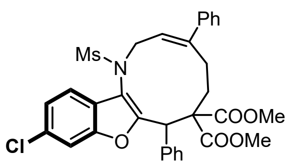
3as was obtained as white solid; m.p. = 188.6–190.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.73 – 7.68 (m, 1H), 7.68 – 7.61 (m, 2H), 7.52 – 7.42 (m, 2H), 7.31 – 7.09 (m, 6H), 6.69 – 6.63 (m, 2H), 5.58 (s, 1H), 5.55 – 5.47 (m, 1H), 4.75 – 4.65 (m, 1H), 4.65 – 4.55 (m, 1H), 3.77 (s, 3H), 3.43 (s, 3H), 2.81 – 2.71 (m, 4H), 2.44 – 2.32 (m, 1H), 2.31 – 2.18 (m, 1H), 1.15 – 1.05 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0(1), 169.9(7), 156.0, 153.8, 149.2, 140.1, 136.1, 130.5(2C), 128.6(2C), 128.1(3C), 127.8, 127.4, 126.4(2C), 126.1, 120.5, 118.5, 118.0, 117.5, 115.8, 63.1, 53.1, 52.2, 46.5, 43.5, 38.1, 33.1, 22.2; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Br^{79}NO_7SNa$ $[M+Na]^+$: 674.0819, found: 674.0816; calcd for $C_{32}H_{30}Br^{81}NO_7SNa$ $[M+Na]^+$: 676.0799, found: 676.0798.



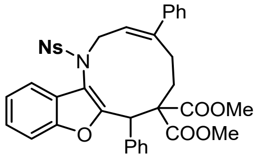
3at was obtained as white solid; m.p. = 192.4–195.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.72 – 7.65 (m, 2H), 7.56 – 7.47 (m, 2H), 7.33 – 7.08 (m, 7H), 6.75 – 6.67 (m, 2H), 5.60 (s, 1H), 5.57 – 5.48 (m, 1H), 4.79 – 4.69 (m, 1H), 4.67 – 4.58 (m, 1H), 3.77 (s, 3H), 3.59 (s, 3H), 2.91 – 2.81 (m, 1H), 2.74 – 2.70 (m, 3H), 2.45 – 2.23 (m, 2H), 1.14 – 1.04 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 169.7, 156.1, 150.7, 149.1, 140.3, 135.9, 130.8(2C), 128.6(2C), 128.4, 128.2, 128.1(2C), 128.1, 127.8, 126.4(2C), 125.2, 118.8, 118.5, 117.7, 105.1, 63.3, 53.1, 52.4, 46.6, 43.8, 37.9, 33.1, 22.3; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Br^{79}NO_7SNa$ $[M+Na]^+$: 674.0819, found: 674.0819; $C_{32}H_{30}Br^{81}NO_7SNa$ $[M+Na]^+$: 676.0799, found: 676.0802.



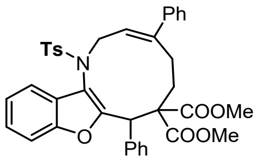
3au was obtained as white solid; m.p. = 194.4–198.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.69 – 7.63 (m, 2H), 7.56 – 7.51 (m, 1H), 7.46 – 7.35 (m, 1H), 7.34 – 7.08 (m, 7H), 6.71 – 6.64 (m, 2H), 5.60 (s, 1H), 5.57 – 5.51 (m, 1H), 4.76 – 4.66 (m, 1H), 4.63 – 4.53 (m, 1H), 3.77 (s, 3H), 3.42 (s, 3H), 2.83 – 2.74 (m, 4H), 2.45 – 2.32 (m, 1H), 2.30 – 2.18 (m, 1H), 1.15 – 1.04 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 170.1, 157.1, 152.0, 149.3, 140.1, 136.1, 130.6(2C), 129.7, 128.6(2C), 128.3, 128.1(3C), 127.8, 126.4(2C), 125.5, 118.9, 117.6, 117.5, 113.5, 63.1, 53.1, 52.2, 46.5, 43.5, 38.1, 33.1, 22.2; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Cl^{35}NO_7SNa$ $[M+Na]^+$: 630.1324, found: 630.1323; calcd for $C_{32}H_{30}Cl^{37}NO_7SNa$ $[M+Na]^+$: 632.1294, found: 632.1328.



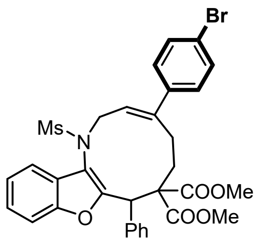
3av was obtained as white solid; m.p. = 185.4–189.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.68 – 7.62 (m, 2H), 7.57 – 7.46 (m, 2H), 7.37 – 7.32 (m, 1H), 7.30 – 7.08 (m, 6H), 6.70 – 6.63 (m, 2H), 5.58 (s, 1H), 5.55 – 5.48 (m, 1H), 4.75 – 4.65 (m, 1H), 4.65 – 4.55 (m, 1H), 3.77 (s, 3H), 3.43 (s, 3H), 2.81 – 2.73 (m, 4H), 2.45 – 2.32 (m, 1H), 2.31 – 2.18 (m, 1H), 1.15 – 1.05 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 170.0, 156.1, 153.6, 149.2, 140.1, 136.1, 131.1, 130.5(2C), 128.5(2C), 128.1(3C), 127.8, 126.3(2C), 125.7, 124.7, 120.1, 118.0, 117.5, 112.9, 63.1, 53.1, 52.2, 46.5, 43.5, 38.1, 33.0, 22.1; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Cl^{35}NO_7SNa$ $[M+Na]^+$: 630.1324, found: 630.1326; $C_{32}H_{30}Cl^{37}NO_7SNa$ $[M+Na]^+$: 632.1294, found: 632.1307.



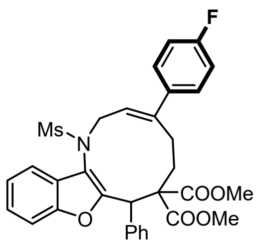
3aw was obtained as white solid; m.p. = 200.4–202.6 °C;**^{1}H NMR** (400 MHz, $CDCl_3$) 8.09 – 7.94 (m, 2H), 7.75 – 7.67 (m, 2H), 7.49 – 7.46 (m, 1H), 7.44 – 7.40 (m, 2H), 7.34 – 7.29 (m, 1H), 7.20 – 7.03 (m, 8H), 6.58 – 6.51 (m, 2H), 5.51 – 5.38 (m, 1H), 5.34 (s, 1H), 4.78 – 4.68 (m, 1H), 4.68 – 4.58 (m, 1H), 3.75 (s, 3H), 3.33 (s, 3H), 2.76 – 2.66 (m, 1H), 2.37 – 2.27 (m, 1H), 2.21 – 2.11 (m, 1H), 1.03 – 0.94 (m, 1H); **^{13}C NMR** (151 MHz, $CDCl_3$) δ 171.1, 169.9, 155.5, 153.5, 150.2, 149.5, 143.8, 140.1, 136.8, 130.0(2C), 128.8(2C), 128.5(2C), 128.0, 127.8(2C), 127.5, 126.6, 126.4(2C), 125.2, 124.2(2C), 123.8, 119.4, 117.5, 117.1, 112.3, 63.3, 53.1, 52.1, 46.9, 43.1, 32.9, 22.1; **HRMS** (ESI-TOF, m/z): calcd for $C_{37}H_{32}N_2O_9SNa$ $[M+Na]^+$: 703.1721, found: 703.1719.



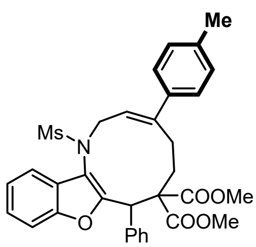
3ax was obtained as white solid; m.p. = 188.4–189.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.72 – 7.66 (m, 2H), 7.50 – 7.41 (m, 3H), 7.32 – 7.17 (m, 4H), 7.15 – 6.99 (m, 6H), 6.67 – 6.57 (m, 3H), 5.68 (s, 1H), 5.42 – 5.35 (m, 1H), 4.81 – 4.72 (m, 1H), 4.39 – 4.29 (m, 1H), 3.76 (s, 3H), 3.40 (s, 3H), 2.94 – 2.84 (m, 1H), 2.37 – 2.27 (m, 4H), 2.22 – 2.09 (m, 1H), 1.07 – 0.97 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.1, 170.5, 156.1, 153.4, 148.3, 143.9, 140.6, 136.6, 134.9, 130.9(2C), 129.7(2C), 128.4(2C), 128.1(2C), 127.7(3C), 127.2, 126.3(2C), 126.0, 124.5, 123.1, 119.2, 118.4, 117.8, 112.2, 63.1, 52.9, 52.0, 46.9, 43.3, 33.5, 22.7, 21.7; **HRMS** (ESI-TOF, m/z): calcd for $C_{38}H_{35}NO_7SNa$ $[M+Na]^+$: 672.2027, found: 672.2025.



3ba was obtained as white solid; m.p. = 189.8–192.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.72 – 7.66 (m, 2H), 7.58 – 7.47 (m, 2H), 7.37 – 7.31 (m, 2H), 7.30 – 7.25 (m, 2H), 7.24 – 7.19 (m, 3H), 6.47 – 6.39 (m, 2H), 5.62 (s, 1H), 5.53 – 5.45 (m, 1H), 4.76 – 4.66 (m, 1H), 4.63 – 4.53 (m, 1H), 3.77 (s, 3H), 3.43 (s, 3H), 2.78 (s, 4H), 2.37 – 2.25 (m, 1H), 2.24 – 2.11 (m, 1H), 1.10 – 1.01 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 170.1, 155.7, 153.6, 148.0, 139.3, 136.3, 131.6(2C), 130.7(2C), 128.1(2C), 128.0(2C), 127.6, 126.7, 125.2, 124.0, 121.9, 119.2, 118.3, 117.8, 112.5, 63.0, 53.1, 52.2, 46.5, 43.3, 38.0, 32.9, 22.2; ; **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}Br^{79}NO_7SNa$ $[M+Na]^+$: 674.0819, found: 674.0822; $C_{32}H_{30}Br^{81}NO_7SNa$ $[M+Na]^+$: 676.0799, found: 676.0803.

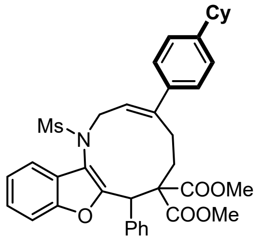


3ca was obtained as white solid; m.p. = 187.5–189.8 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.74 – 7.67 (m, 2H), 7.59 – 7.46 (m, 2H), 7.37 – 7.14 (m, 5H), 6.80 – 6.71 (m, 2H), 6.58 – 6.49 (m, 2H), 5.64 (s, 1H), 5.49 – 5.41 (m, 1H), 4.76 – 4.66 (m, 1H), 4.62 – 4.52 (m, 1H), 3.76 (s, 3H), 3.42 (s, 3H), 2.85 – 2.74 (m, 4H), 2.38 – 2.26 (m, 1H), 2.25 – 2.12 (m, 1H), 1.12 – 1.02 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.0, 170.1, 162.4 (d, J_{C-F} = 247.1 Hz), 155.7, 153.5, 147.9, 136.4 (d, J_{C-F} = 3.2 Hz) (2C), 136.3, 130.6(2C), 128.0 (d, J_{C-F} = 8.0 Hz) (2C), 127.9(2C), 127.5, 126.6, 125.0, 123.9, 119.1, 117.8, 117.7, 115.2 (d, J_{C-F} = 21.4 Hz), 112.3, 63.0, 53.0, 52.0, 46.4, 43.3, 37.8, 32.9, 22.3; **^{19}F NMR** (377 MHz, $CDCl_3$) δ -114.4. (s, 1F); **HRMS** (ESI-TOF, m/z): calcd for $C_{32}H_{30}FNO_7SNa$ $[M+Na]^+$: 614.1620, found: 614.1618.

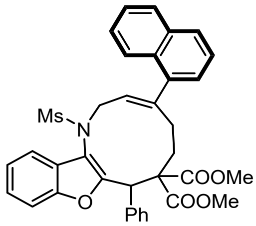


3da was obtained as white solid; m.p. = 185.4 – 189.3 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.73 – 7.66 (m, 2H), 7.58 – 7.53 (m, 1H), 7.51 – 7.41 (m, 1H), 7.37 – 7.16 (m, 5H), 6.92 – 6.85 (m, 2H), 6.53 – 6.46 (m, 2H), 5.63 (s, 1H), 5.52 – 5.44 (m, 1H), 4.76 – 4.66 (m, 1H), 4.62 – 4.53

(m, 1H), 3.77 (s, 3H), 3.42 (s, 3H), 2.82 – 2.71 (m, 4H), 2.42 – 2.29 (m, 1H), 2.27 – 2.12 (m, 4H), 1.14 – 1.04 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.1, 170.2, 155.6, 153.6, 148.9, 137.7, 137.4, 136.5, 130.7(2C), 129.1(2C), 127.9(2C), 127.6, 126.8, 126.3(2C), 125.0, 123.9, 119.3, 117.9, 116.9, 112.3, 63.2, 53.0, 52.1, 46.6, 43.4, 37.9, 33.0, 22.2, 21.1; **HRMS** (ESI-TOF, m/z): calcd for $C_{33}H_{33}NO_7SNa$ $[M+Na]^+$: 610.1870, found: 610.1856.



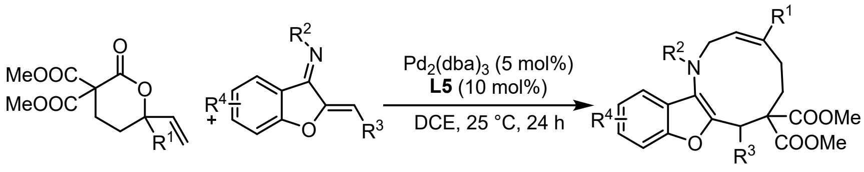
3ea was obtained as white solid; m.p. = 187.3–189.9 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.74 – 7.67 (m, 2H), 7.56 – 7.52 (m, 1H), 7.52 – 7.47 (m, 1H), 7.37 – 7.31 (m, 2H), 7.30 – 7.23 (m, 2H), 7.22 – 7.18 (m, 1H), 6.95 – 6.88 (m, 2H), 6.57 – 6.50 (m, 2H), 5.63 (s, 1H), 5.52 – 5.44 (m, 1H), 4.77 – 4.67 (m, 1H), 4.62 – 4.53 (m, 1H), 3.77 (s, 3H), 3.42 (s, 3H), 2.84 – 2.69 (m, 4H), 2.42 – 2.29 (m, 2H), 2.29 – 2.16 (m, 1H), 1.87 – 1.72 (m, 4H), 1.42 – 1.23 (m, 6H), 1.15 – 1.04 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.1, 170.3, 155.6, 153.6, 148.9, 147.8, 137.8, 136.5, 130.7(2C), 127.9(2C), 127.6, 126.9(2C), 126.8, 126.2(2C), 125.0, 123.9, 119.3, 117.9, 116.9, 112.4, 63.1, 53.0, 52.1, 46.6, 44.2, 43.4, 37.9, 34.5, 34.3, 33.1, 26.9(2C), 26.2, 22.2; **HRMS** (ESI-TOF, m/z): calcd for $C_{38}H_{41}NO_7SNa$ $[M+Na]^+$: 678.2496, found: 678.2496.



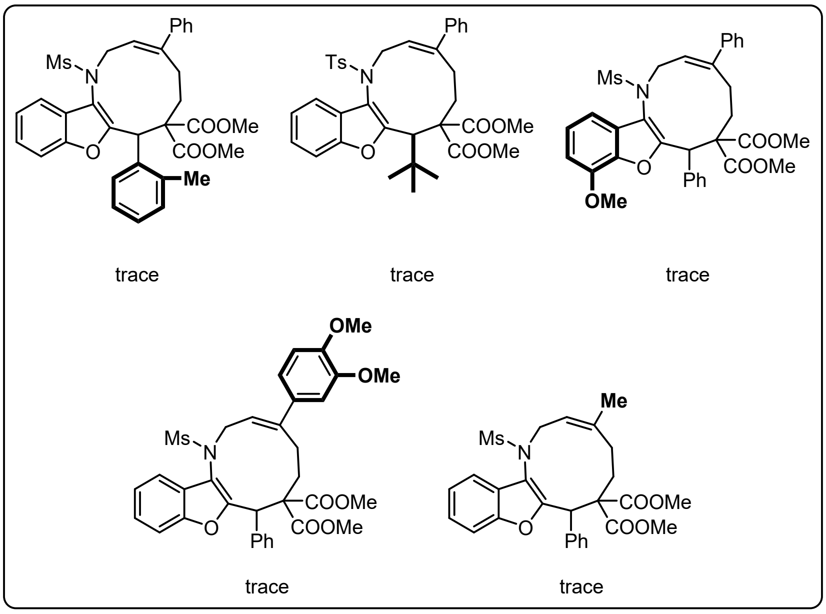
3fa was obtained as white solid; m.p. = 189.4–192.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.73 – 7.62 (m, 4H), 7.60 – 7.54 (m, 1H), 7.53 – 7.48 (m, 1H), 7.47 – 7.36 (m, 5H), 7.30 – 7.25 (m, 2H), 7.25 – 7.16 (m, 1H), 6.89 – 6.82 (m, 1H), 6.71 – 6.68 (m, 1H), 5.67 – 5.58 (m, 2H), 4.80 – 4.69 (m, 1H), 4.68 – 4.60 (m, 1H), 3.79 (s, 3H), 3.40 (s, 3H), 2.86 – 2.76 (m, 4H), 2.56 – 2.43 (m, 1H), 2.28 – 2.15 (m, 1H), 1.20 – 1.10 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.2, 170.1, 155.8, 153.8, 149.3, 137.9, 136.5, 133.3, 132.9, 130.6(2C), 128.2, 128.0(2C), 128.0, 127.6, 127.5, 127.2, 126.3, 126.2, 126.0, 125.2, 124.3, 124.0, 119.5, 118.4, 118.0, 112.5, 63.3, 53.1, 52.1, 46.5, 43.4, 38.2, 32.8, 22.3; **HRMS** (ESI-TOF, m/z): calcd for $C_{36}H_{33}NO_7SNa$ $[M+Na]^+$: 646.1870, found: 646.1869.

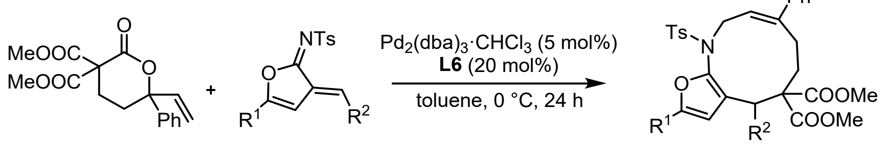
Faild examples:

All the reaction were carried out following the general procedure **A** to further test the substrate scope of [6+4] annulation reaction protocol.



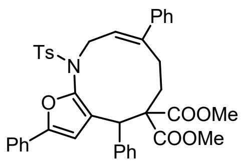
1 **2** **3**



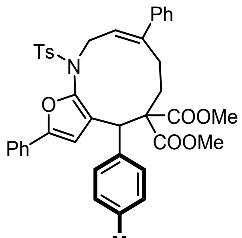


1a **4** **5**

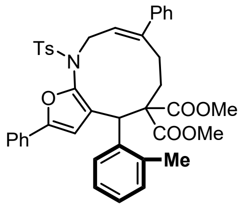
General procedure B: An oven-dried Schlenk tube was added $Pd_2(dba)_3{\cdot}CHCl_3$ (0.005 mmol, 5.1 mg, 5 mol%), **L6** (0.01 mmol, 6.5 mg, 20 mol%) followed by the addition of anhydrous toluene (1 mL) under N_2. The reaction mixture was allowed to stir for 30 mins at 25 ℃, and all-carbon 1,6-dipole precursor **1a** (0.15 mmol) and furan-derived azadienes **4** (0.1 mmol) were then added. After 24 h, the mixture was concentrated and purified by column chromatography (petroleum ether/ ethyl acetate = 4:1) to give the corresponding cycloadducts **5**.



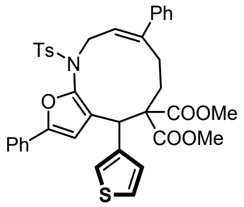
5aa was obtained as white solid; m.p. = 167.4–169.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.66 – 7.61 (m, 2H), 7.57 – 7.52 (m, 2H), 7.50 – 7.45 (m, 2H), 7.37 – 7.32 (m, 2H), 7.29 – 7.16 (m, 6H), 7.15 – 7.08 (m, 3H), 7.04 – 6.97 (m, 2H), 6.97 – 6.93 (m, 1H), 5.55 – 5.47 (m, 1H), 5.21 (s, 1H), 4.65 – 4.56 (m, 1H), 4.15 – 4.04 (m, 1H), 3.72 (s, 3H), 3.42 (s, 3H), 2.78 – 2.68 (m, 1H), 2.46 – 2.32 (m, 4H), 2.22 – 2.12 (m, 1H), 1.68 – 1.61 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.8, 171.6, 151.2, 149.3, 144.1, 141.4, 140.7, 139.3, 135.2, 130.4, 130.2(2C), 129.6(2C), 128.7(2C), 128.4(2C), 128.3(2C), 127.9, 127.8, 127.8(2C), 126.9, 126.6(2C), 124.8, 124.0(2C), 117.5, 107.8, 62.2, 52.7, 52.1, 47.0, 42.8, 34.5, 22.7, 21.7; **HRMS** (ESI-TOF, m/z): calcd for $C_{40}H_{37}NO_7SNa$ $[M+Na]^+$: 698.2183, found: 698.2181.



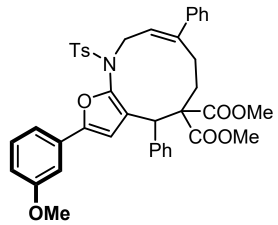
5ab was obtained as light yellow oil; **^{1}H NMR** (600 MHz, $CDCl_3$) δ 7.67 – 7.62 (m, 2H), 7.49 – 7.41 (m, 4H), 7.37 – 7.31 (m, 2H), 7.30 – 7.21 (m, 3H), 7.18 – 7.05 (m, 5H), 7.04 – 6.99 (m, 2H), 6.94 (s, 1H), 5.52 – 5.47 (m, 1H), 5.18 (s, 1H), 4.64 – 4.57 (m, 1H), 4.09 – 4.02 (m, 1H), 3.73 (s, 3H), 3.46 (s, 3H), 2.78 – 2.71 (m, 1H), 2.46-2.34 (m, 4H), 2.28 (s, 3H), 2.22 – 2.14 (m, 1H), 1.63 – 1.56 (m, 1H); **^{13}C NMR** (151 MHz, $CDCl_3$) δ 172.0, 171.6, 151.1, 149.3, 144.1, 141.3, 140.8, 136.3, 136.2, 135.2, 130.4, 130.1(2C), 129.6(2C), 128.7(2C), 128.5(2C), 128.4(3)(2C), 128.3(8)(2C), 127.8(2), 127.7(8), 126.6(2C), 125.1, 124.0(2C), 117.5, 107.8, 62.1, 52.7, 52.1, 47.0, 42.5, 34.5, 22.7, 21.7, 21.2; **HRMS** (ESI-TOF, m/z): calcd for $C_{41}H_{39}NO_7SNa$ $[M+Na]^+$: 712.2340, found: 712.2338.



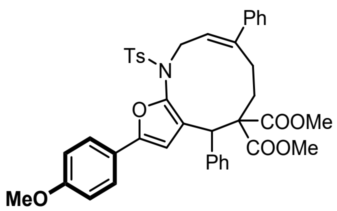
5ac was obtained as light yellow oil; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.84 – 7.77 (m, 2H), 7.49 – 7.41 (m, 3H), 7.36 – 7.30 (m, 4H), 7.26 – 7.23 (m, 1H), 7.21 – 7.18 (m, 1H), 7.16 – 7.07 (m, 5H), 7.06 – 7.03 (m, 2H), 6.99 (s, 1H), 5.57 – 5.48 (m, 1H), 5.42 (s, 1H), 4.62 – 4.52 (m, 1H), 4.05 – 3.96 (m, 1H), 3.62 (s, 3H), 3.60 (s, 3H), 2.82 (s, 3H), 2.76 – 2.65 (m, 1H), 2.52 – 2.41 (m, 4H), 2.34 – 2.21 (m, 1H), 1.83 – 1.74 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 172.3, 171.6, 150.7, 149.7, 144.2, 141.4, 140.6, 138.6, 137.6, 135.4, 131.4, 130.4, 129.6(2C), 129.0, 128.8(2C), 128.7(2C), 128.5(2C), 127.9, 127.8, 126.9, 126.5(2C), 125.7, 124.9, 123.9(2C), 117.9, 108.3, 62.1, 52.5, 52.2, 47.6, 38.6, 35.1, 23.4, 21.8, 20.6; **HRMS** (ESI-TOF, m/z): calcd for $C_{41}H_{39}NO_7SNa$ $[M+Na]^+$: 712.2340, found: 712.2338.



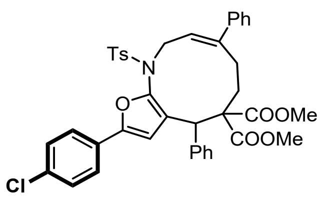
5ad was obtained as light yellow oil; **^{1}H NMR** (600 MHz, $CDCl_3$) δ 7.65 – 7.61 (m, 2H), 7.52 – 7.47 (m, 2H), 7.39 – 7.33 (m, 2H), 7.32 – 7.26 (m, 1H), 7.24 – 7.20 (m, 2H), 7.19 – 7.07 (m, 5H), 7.04 – 6.99 (m, 2H), 6.94 (s, 1H), 6.91 – 6.87 (m, 1H), 5.56 – 5.51 (m, 1H), 5.47 (s, 1H), 4.59 – 4.51 (m, 1H), 4.21 – 4.14 (m, 1H), 3.80 (s, 3H), 3.45 (s, 3H), 2.71 – 2.64 (m, 1H), 2.46 – 2.34 (m, 4H), 2.22 – 2.14 (m, 1H), 1.56 – 1.46 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 171.3(2C), 151.3, 149.1, 145.3, 144.2, 141.9, 140.7, 140.6, 135.1, 130.3, 129.7(2C), 128.7(2C), 128.5(2C), 128.2(2C), 128.0, 127.8(2C), 126.6(2C), 126.1, 124.5, 124.1(2C), 117.6, 107.8, 63.0, 52.9, 52.5, 51.8, 47.0, 34.2, 33.2, 21.8; **HRMS** (ESI-TOF, m/z): calcd for $C_{38}H_{35}NO_7S_2Na$ $[M+Na]^+$: 704.1748, found: 704.1747.



5ae was obtained as light yellow oil; **¹H NMR** (400 MHz, $CDCl_3$) δ 7.68 – 7.61 (m, 2H), 7.50 – 7.43 (m, 2H), 7.42 – 7.32 (m, 2H), 7.30 – 7.27 (m, 1H), 7.25 – 7.21 (m, 2H), 7.18 – 7.09 (m, 6H), 7.04 – 6.97 (m, 2H), 6.93 (s, 1H), 6.78 – 6.64 (m, 1H), 5.55 – 5.47 (m, 1H), 5.18 (s, 1H), 4.64 – 4.55 (m, 1H), 4.15 – 4.04 (m, 1H), 3.81 (s, 3H), 3.73 (s, 3H), 3.46 (s, 3H), 2.77 – 2.67 (m, 1H), 2.44 – 2.32 (m, 4H), 2.23 – 2.15 (m, 1H), 1.67 – 1.62 (m, 1H); **¹³C NMR** (101 MHz, $CDCl_3$) δ 171.8, 171.6, 159.0, 151.1, 149.3, 144.1, 141.4, 140.8(5), 140.7(6), 135.2, 130.4, 129.6(2C), 128.7(2C), 128.5, 128.4(2C), 128.3(2C), 127.9, 127.8, 126.6(2C), 124.8, 124.0(2C), 122.3, 117.6, 116.5, 112.3, 107.9, 62.1, 55.3, 52.7, 52.1, 47.1, 42.8, 34.6, 22.7, 21.7; **HRMS** (ESI-TOF, m/z): calcd for $C_{41}H_{39}NO_8SNa$ $[M+Na]^+$: 728.2289, found: 728.2287.



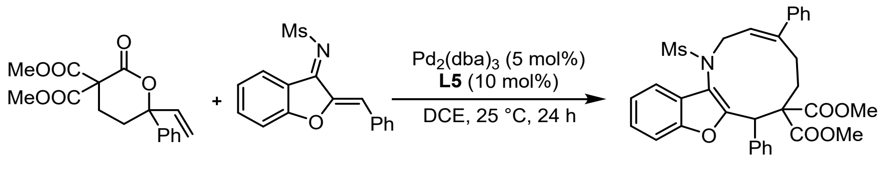
5af was obtained as light yellow oil; **¹H NMR** (400 MHz, $CDCl_3$) δ 7.67 – 7.60 (m, 2H), 7.57 – 7.46 (m, 2H), 7.45 – 7.33 (m, 2H), 7.29 – 7.08 (m, 8H), 7.04 – 6.98 (m, 2H), 6.92 – 6.84 (m, 2H), 6.81 (s, 1H), 5.55 – 5.47 (m, 1H), 5.19 (s, 1H), 4.64 – 4.54 (m, 1H), 4.13 – 4.04 (m, 1H), 3.84 (s, 3H), 3.72 (s, 3H), 3.41 (s, 3H), 2.77 – 2.67 (m, 1H), 2.46 – 2.31 (m, 4H), 2.23 – 2.10 (m, 1H), 1.68 – 1.60 (m, 1H); **¹³C NMR** (101 MHz, $CDCl_3$) δ 171.8, 171.6, 159.5, 151.3, 149.4, 144.0, 140.8(1), 140.7(5), 139.4, 135.3, 130.2(2C), 129.6(2C), 128.4(2C), 128.3(2C), 127.8, 127.7(2C), 126.9, 126.6(2C), 125.5(2C), 124.7, 123.5, 117.6, 114.1(2C), 106.3, 62.2, 55.5, 52.7, 52.0, 47.0, 42.8, 34.5, 22.7, 21.7; **HRMS** (ESI-TOF, m/z): calcd for $C_{41}H_{39}NO_8SNa$ $[M+Na]^+$: 728.2289, found: 728.2287.



5ag was obtained as light yellow oil; **¹H NMR** (400 MHz, $CDCl_3$) δ 7.66 – 7.60 (m, 2H), 7.55 – 7.49 (m, 2H), 7.44 – 7.38 (m, 2H), 7.35 – 7.30 (m, 2H), 7.29 – 7.26 (m, 1H), 7.25 – 7.09 (m, 7H), 7.03 – 6.97 (m, 2H), 6.95 (s, 1H), 5.56 – 5.48 (m, 1H), 5.19 (s, 1H), 4.64 – 4.54 (m, 1H), 4.15 – 4.04 (m, 1H), 3.72 (s, 3H), 3.42 (s, 3H), 2.75 – 2.61 (m, 1H), 2.48 – 2.33 (m, 4H), 2.24

– 2.12 (m, 1H), 1.65 – 1.58 (m, 1H); **^{13}C NMR** (151 MHz, $CDCl_3$) δ 171.9, 171.5, 150.1, 149.4, 144.2, 141.7, 140.6, 139.1, 135.2, 133.6, 130.1(2C), 129.7(2C), 129.0(2C), 128.8, 128.5(2C), 128.3(2C), 127.9, 127.8(2C), 127.0, 126.5(2C), 125.2(2C), 125.0, 117.5, 108.3, 62.1, 52.8, 52.1, 47.0, 34.5, 29.8, 22.6, 21.8; **HRMS** (ESI-TOF, m/z): calcd for $C_{40}H_{36}Cl^{35}NO_7SNa$ $[M+Na]^+$: 732.1794, found: 732.1795; calcd for $C_{40}H_{36}Cl^{37}NO_7SNa$ $[M+Na]^+$: 734.1764, found: 734.1777.

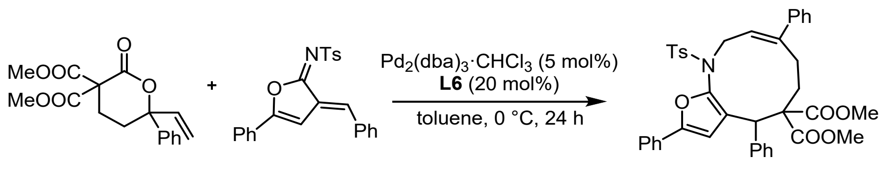
7. Scale-up experiment



1a **2a** **3aa**

60% yield

Under a nitrogen atmosphere, $Pd_2(dba)_3$ (0.1 mmol, 91.5 mg, 5 mol%), **L5** (0.2 mmol, 36.0 mg, 10 mol%) were added sequentially into a flame-dried Schlenk flask equipped with a magnetic stir bar. The flask was evacuated and back-filled with nitrogen for three times. Then the anhydrous DCE (20.0 mL) was added via syringe sequentially and the resulting mixture stirred at 25 °C for 30 mins. Then, all-carbon 1,6-dipole precursor **1a** (3.0 mmol, 954.3 mg) and benzofuran-derived azadienes **2a** (2.0 mmol, 598.1 mg) were added. After 24 h, the mixture was concentrated and purified by column chromatography (petroleum ether/dichloromethane = 4:1) to give the corresponding cycloadduct **3aa** in 60% yield (689.0 mg).

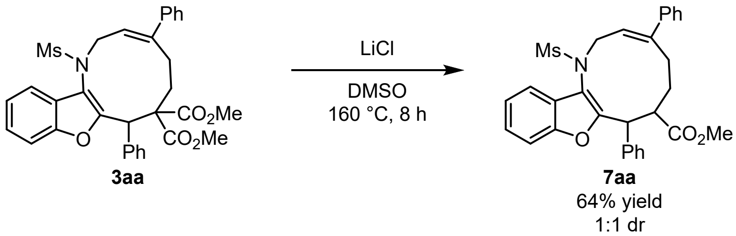


1a **4a** **5aa**

51% yield

Under a nitrogen atmosphere, $Pd_2(dba)_3 \cdot CHCl_3$ (0.1 mmol, 102.3 mg, 5 mol%), **L6** (0.4 mmol, 130.1 mg, 20 mol%) were added sequentially into a flame-dried Schlenk flask equipped with a magnetic stir bar. The flask was evacuated and back-filled with nitrogen for three times. Then the anhydrous toluene (20.0 mL) was added via syringe sequentially and the resulting mixture stirred at 25 °C for 30 mins. Then, all-carbon 1,6-dipole precursor **1a** (3.0 mmol, 954.3 mg) and furan-derived azadienes **4a** (2.0 mmol, 802.2 mg) were added. After 24 h, the mixture was concentrated and purified by column chromatography (petroleum ether/dichloromethane = 4:1) to give the corresponding cycloadduct **5aa** in 51% yield (685.0 mg).

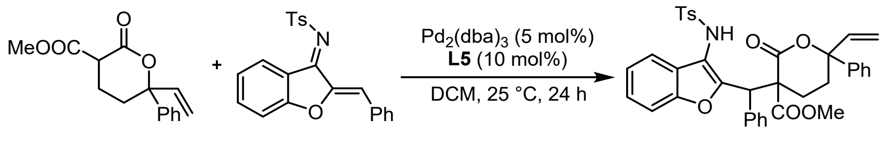
8. Synthetic transformation



3aa (57.3 mg, 0.1 mmol) and LiCl (16.8 mg, 0.4 mmol) in 2 mL DMSO was stirred for 8 h at 160℃. After 8 h, the reaction mixture was then cooled to room temperature. The reaction mixture was quenched with H_2O, and extracted with 3 × 5.0 mL EtOAc. The combined organic layers were washed with saturated aqueous NH_4Cl, brine, dried over anhydrous Na_2SO_4, and concentrated under reduced pressure. The residue was purified by flash chromatography on petroleum ether/ ethyl acetate = 4:1) to give the product **7aa**.

7aa (as a mixture of diastereomers, 1:1 dr)was obtained as light yellow solid; m.p. = 188.4–191.6 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.65 – 7.57 (m, 3H), 7.55 – 7.49 (m, 2H), 7.44 – 7.40 (m, 3H), 7.36 – 7.28 (m, 8H), 7.25 – 7.18 (m, 5H), 7.15 – 7.01 (m, 5H), 6.66 – 6.60 (m, 2H), 5.85 – 5.77 (m, 1H), 5.54 – 5.46 (m, 1H), 5.27 – 5.22 (m, 1H), 5.03 – 4.92 (m, 1H), 4.87 – 4.62 (m, 3H), 4.49 – 4.39 (m, 1H), 3.56 (s, 3H), 3.50 – 3.44 (m, 4H), 3.44 – 3.32 (m, 1H), 3.14 – 2.96 (m, 1H), 2.91 (s, 3H), 2.86 (s, 3H), 2.75 – 2.59 (m, 1H), 2.45 – 2.33 (m, 1H), 2.07 – 1.88 (m, 2H), 1.45 – 1.37 (m, 1H), 0.92 – 0.72 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 173.9, 173.6, 156.2, 155.5, 153.8, 153.8, 150.1, 147.9, 141.3, 141.0, 138.2, 138.1, 129.3(2C), 129.1(2C), 128.7(2C), 128.5(5)(2C), 128.5(2)(2C), 128.4(2C), 127.8(2), 127.7(8), 127.7(7), 127.6, 127.3, 126.6(2C), 126.5(2C), 125.8, 124.9, 124.9, 123.9, 123.8, 120.6, 119.6, 119.1, 118.6, 117.7, 117.2, 112.6, 111.8, 52.0, 51.7, 50.4, 48.4, 48.2, 46.6, 42.9, 42.1, 38.3, 38.1, 28.9, 28.2, 26.1, 21.8.; **HRMS** (ESI-TOF, m/z): calcd for $C_{30}H_{29}NO_5SNa$ $[M+Na]^+$: 538.1659, found: 538.1637.

9. Control experiment



6a **2x** **8ax** 65% yield 1.7:1:1.7:1.2 dr

An oven-dried Schlenk tube was added $Pd_2(dba)_3$ (0.005 mmol, 4.6 mg, 5 mol%), **L5** (0.01 mmol, 1.8 mg, 10 mol%) followed by the addition of anhydrous DCE (1 mL) under N_2. The reaction mixture was allowed to stir for 30 mins at 25 °C, and 1,6-dipole precursor **6a** (0.15 mmol) and benzofuran-derived azadienes **2x** (0.1 mmol) were then added. After 24 h, the mixture was concentrated and purified by column chromatography (petroleum ether/ ethyl acetate = 4:1) to give the corresponding cycloadducts **8ax.**

8ax (as a mixture of diastereomers, 1.7:1:1.7:1.2 dr)was obtained as light yellow solid; m.p. = 200.6–202.7 °C; **^{1}H NMR** (600 MHz, $CDCl_3$) δ 7.83 – 7.76 (m, 1H), 7.50 – 7.45 (m, 2H), 7.37 – 7.32 (m, 2H), 7.27 – 7.12 (m, 9H), 7.11 – 7.07 (m, 2H), 6.98 – 6.90 (m, 3H), 5.56 (dd, *J* = 17.1, 10.9 Hz, 1H), 4.73 (s, 1H), 4.36 (d, *J* = 17.1 Hz, 1H), 4.29 (d, *J* = 10.9 Hz, 1H), 3.50 (s, 3H), 2.74 – 2.66 (m, 1H), 2.43 – 2.37 (m, 1H), 2.24 (s, 3H), 2.20 – 2.11 (m, 2H); **^{13}C NMR** (151 MHz, $CDCl_3$) δ 169.5, 167.7, 153.8, 148.9, 143.5, 142.0, 140.0, 136.5, 133.9, 129.9(2C), 129.7(2C), 128.6(2C), 128.1(5), 128.0(8)(2C), 127.9, 127.4(2C), 125.7, 125.2, 124.9(2C), 123.6, 121.8, 116.9, 115.0, 111.1, 87.8, 59.5, 53.4, 47.1, 31.0, 22.2, 21.7.; **HRMS** (ESI-TOF, m/z): calcd for $C_{37}H_{33}NO_7SNa$ $[M+Na]^+$: 658.1870, found: 658.1874.

10. Crystallographic data for compound 3aa and 8ax

The corresponding compound **3aa** and **8ax** (10.0 mg) were dissolved in 1.0 mL DCM. The solution was filtered by millipore filter and transferred to a vial. Then, drops of hexane were added subsequently. A single crystal was obtained by natural volatilization at room temperature. The data set was collected by a Bruker APEX-II CCD at 293(2) K equipped with micro-focus Cu radiation source (Kα = 1.54178 Å). Applied with faceindexed numerical absorption correction, the structure solution was solved and refinement was processed by SHELXTL program package.

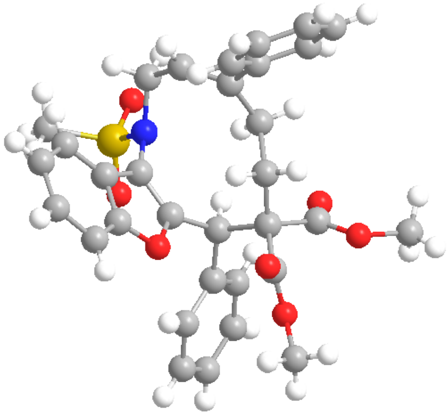


Figure S1 The X-ray crystal structure of **3aa** with thermal ellipsoids at the 30% probability level (CCDC: 2297302).

Identification code	data_2023091201_0m	
Empirical formula	C32 H31 N O7 S	
Formula weight	573.64	
Temperature	273.15	
Wavelength	0.71073 Å	
Crystal system	monoclinic	
Space group	P 1 21/c 1	
Unit cell dimensions	a = 10.9167(7) Å	α = 90°
	b = 15.9481(8) Å	β = 103.422(2)°
	c = 17.0402(10) Å	γ = 90°
Volume	2885.7(3) $Å^3$	
Z	4	
Density (calculated)	1.320 Mg/m^3	
Absorption coefficient	0.162 mm^{-1}	
F(000)	1208	
Crystal size	0.220×0.190×0.160 mm^3	
Theta range for data collection	2.304 to 27.491°	
Index ranges	-14<=h<=14, -20<=k<=20, -22<=l<=22	
Reflections collected	27088	
Independent reflections	4155 [R(int) = 0.0546]	
Completeness to theta = 27.491°	99.7 %	
Absorption correction	multi-scan	

Max. and min. transmission	0.9085
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	6599 / 0 / 373
Goodness-of-fit on F^2	1.038
Final R indices [I>2sigma(I)]	R1 = 0.0546, wR2 = 0.1105
R indices (all data)	R1 = 0.1024, wR2 = 0.1341
Largest diff. peak and hole	0.186 and -0.360 e.Å^{-3}

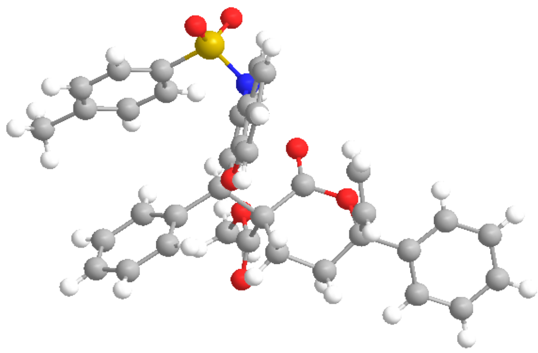


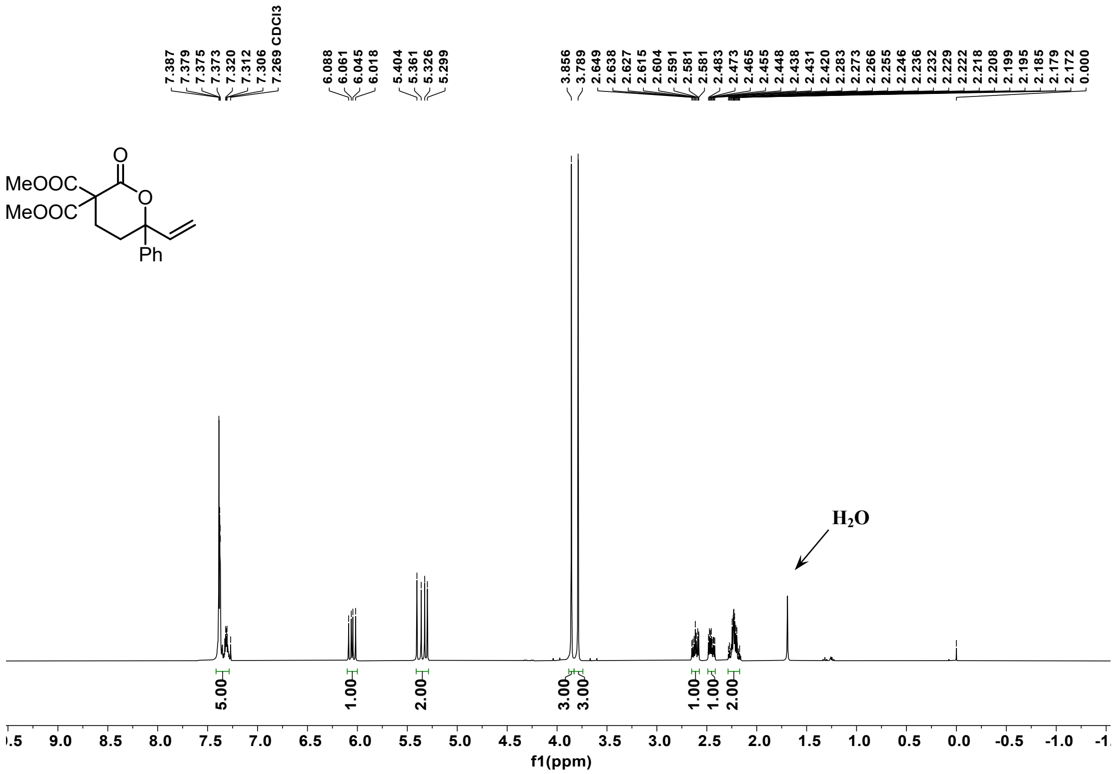
Figure S2 The X-ray crystal structure of **8ax** with thermal ellipsoids at the 30% probability level (CCDC: 2297449).

Identification code	2022092101_0ma	
Empirical formula	C37 H33 N O7 S	
Formula weight	635.70	
Temperature	298.00	
Wavelength	0.71073 Å	
Crystal system	orthorhombic	
Space group	P n a 21	
Unit cell dimensions	a = 19.7154(12) Å	α = 90°
	b = 9.3448(7) Å	β = 90°
	c = 17.9767(10) Å	γ = 90°
Volume	3312.0(4) Å^3	
Z	4	
Density (calculated)	1.275 Mg/m^3	
Absorption coefficient	0.148 mm^{-1}	
F(000)	1336	
Crystal size	0.33 × 0.2 × 0.15 mm^3	
Theta range for data collection	2.266 to 25.392°	
Index ranges	-23<=h<=23, -11<=k<=11, -20<=l<=21	
Reflections collected	21371	
Independent reflections	4227 [R(int) = 0.0770]	
Completeness to theta = 25.392°	99.5 %	
Absorption correction	multi-scan	
Max. and min. transmission	0.8662	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	5910 / 1 / 430	
Goodness-of-fit on F^2	1.084	

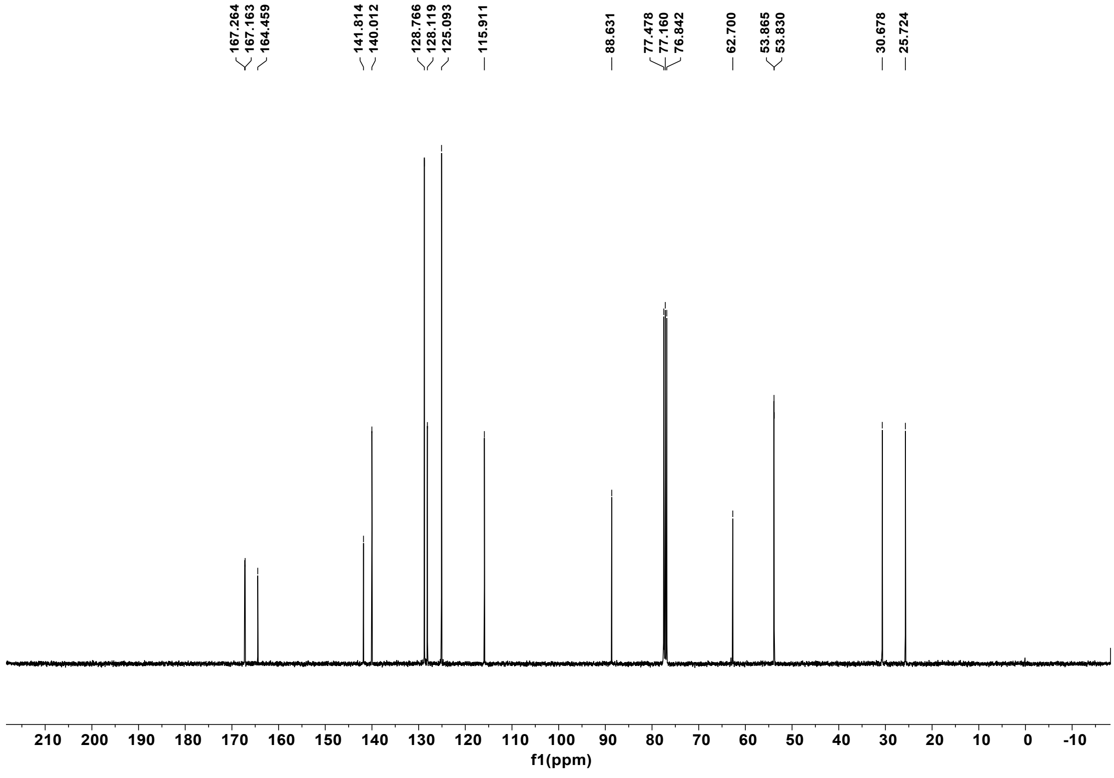
Final R indices [I>2sigma(I)]	R1 = 0.0477, wR2 = 0.1090
R indices (all data)	R1 = 0.0748, wR2 = 0.1353
Extinction coefficient	0.0110(11)
Largest diff. peak and hole	0.181 and -0.178 e.Å^{-3}

11. ^{1}H NMR, ^{19}F NMR and ^{13}C NMR spectra

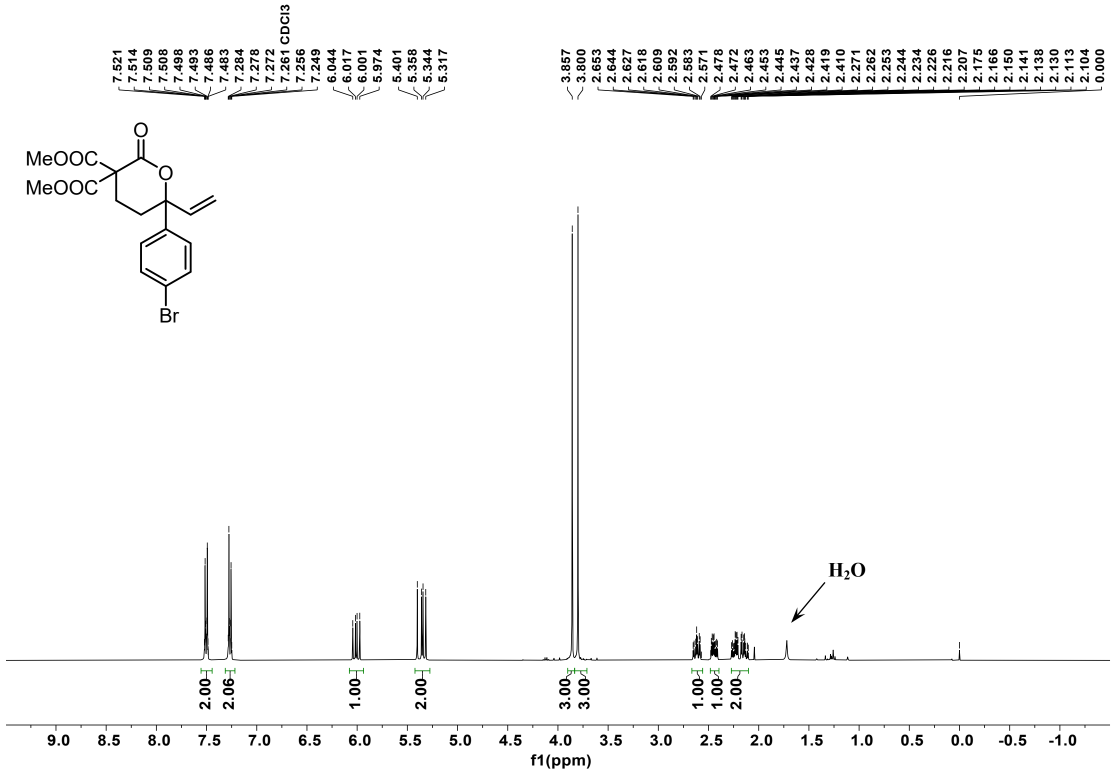
^{1}H NMR of **1a** in $CDCl_3$ (400 MHz)



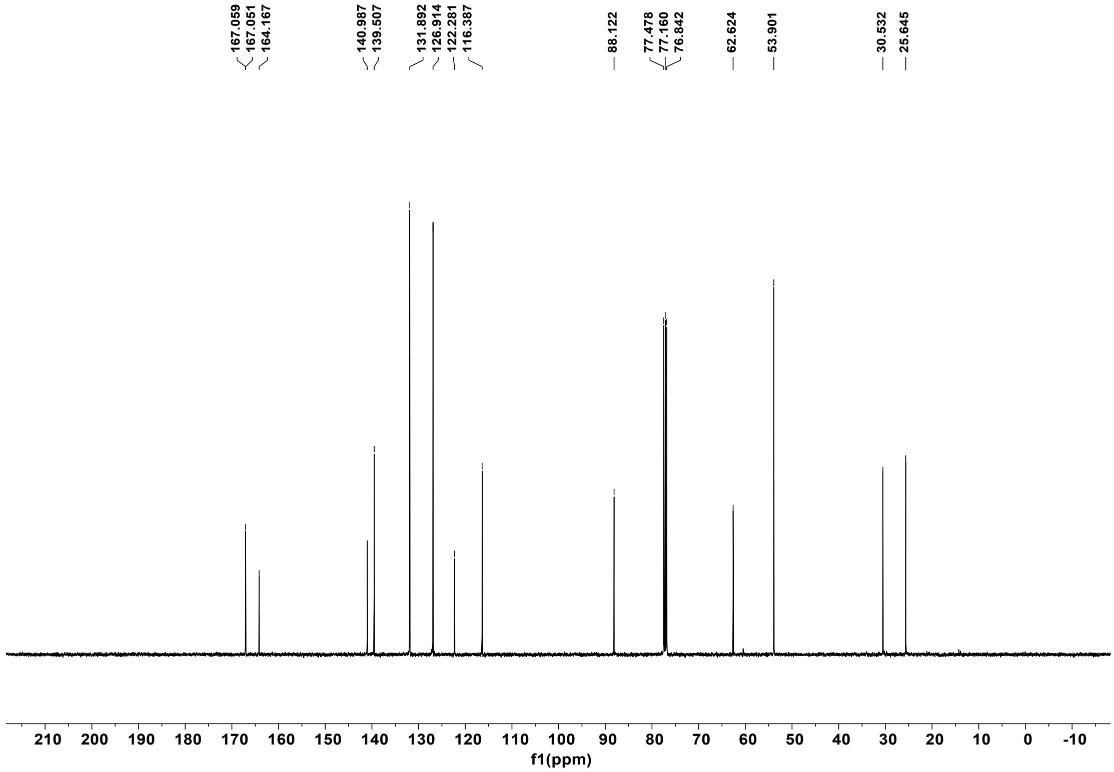
^{13}C NMR of **1a** in $CDCl_3$ (101 MHz)



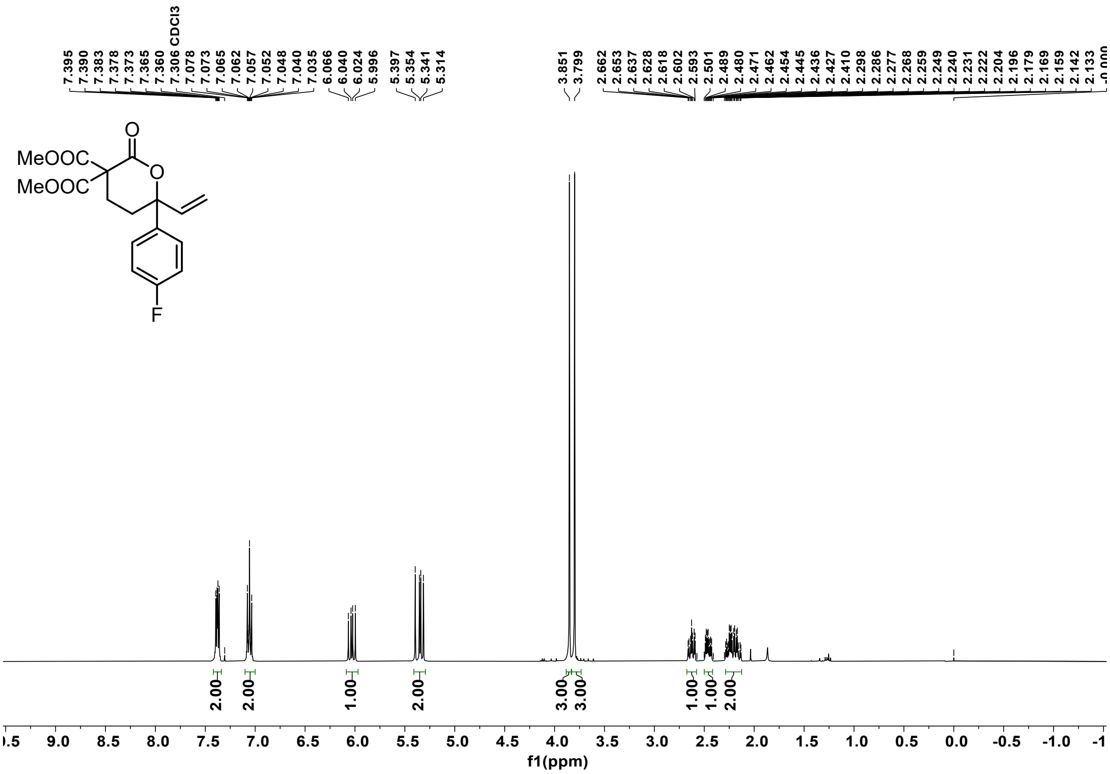
[1]H NMR of **1b** in $CDCl_3$ (400 MHz)



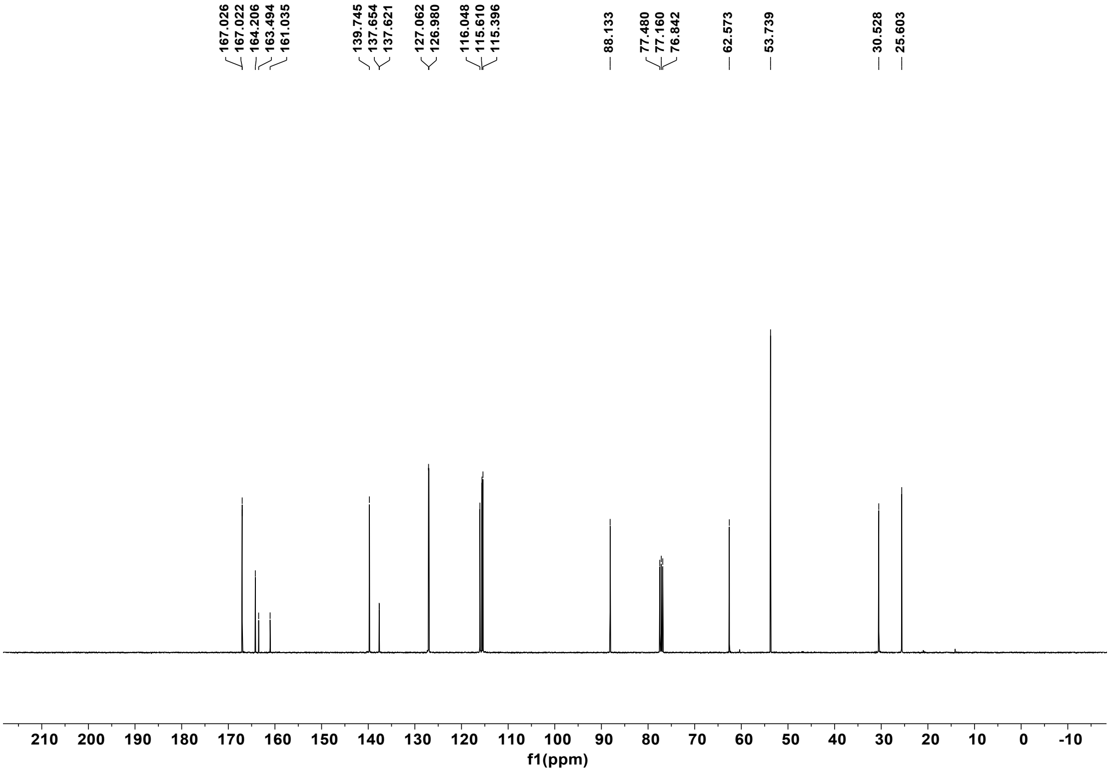
[13]C NMR of **1b** in $CDCl_3$ (101 MHz)



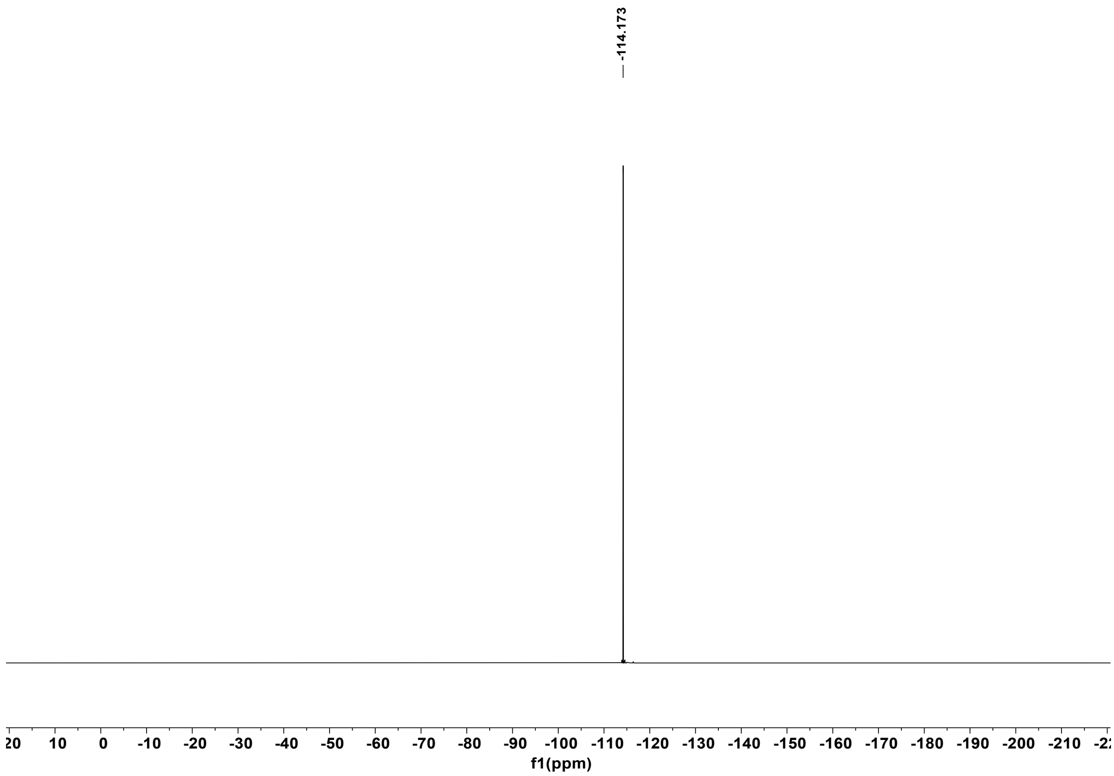
^{1}H NMR of **1c** in $CDCl_3$ (400 MHz)



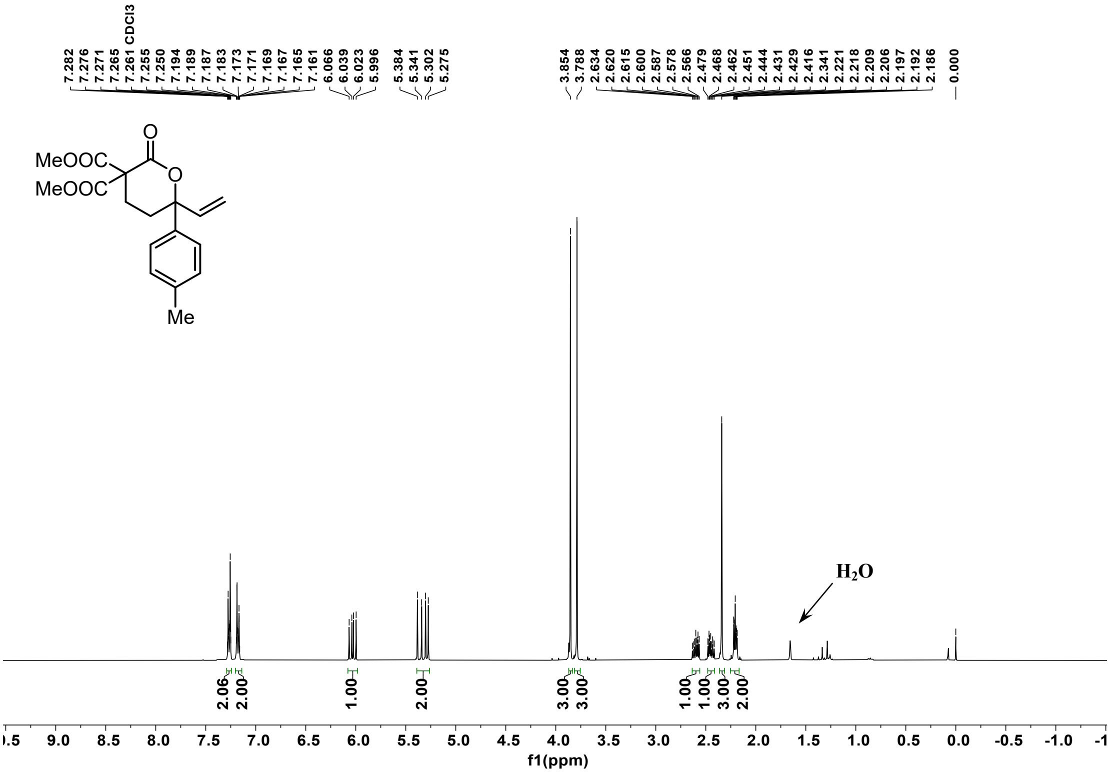
^{13}C NMR of **1c** in $CDCl_3$ (101 MHz)



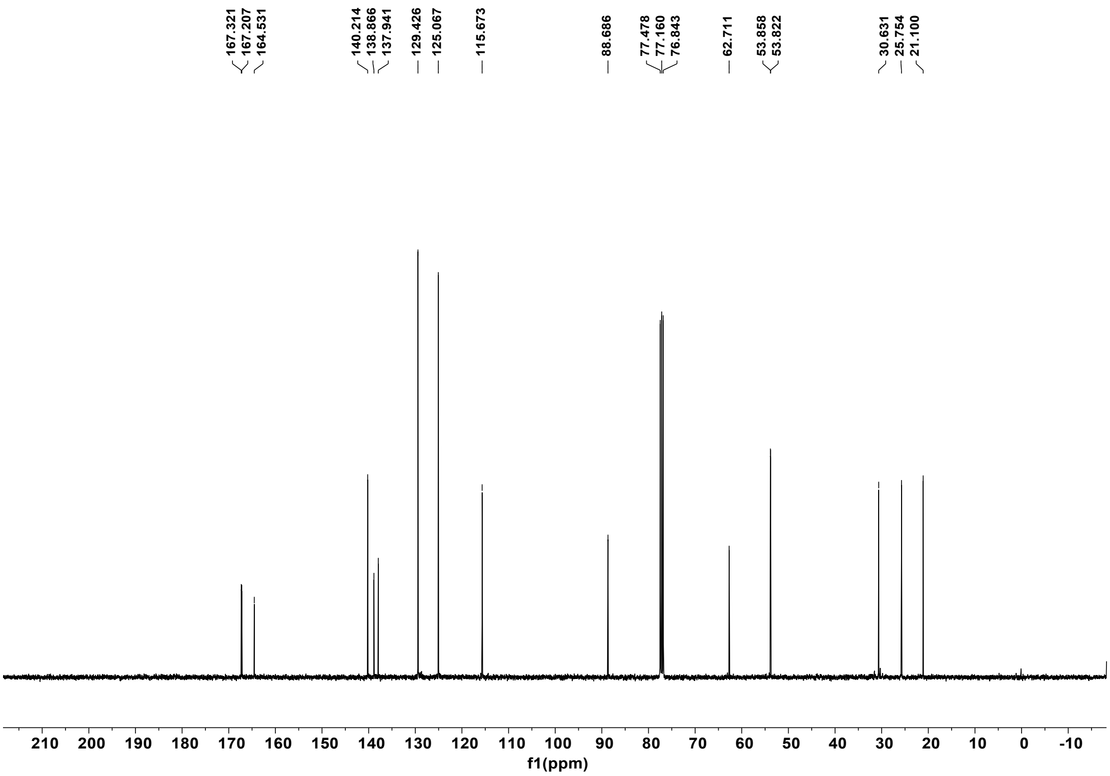
^{19}F NMR of **1c** in $CDCl_3$ (377 MHz)



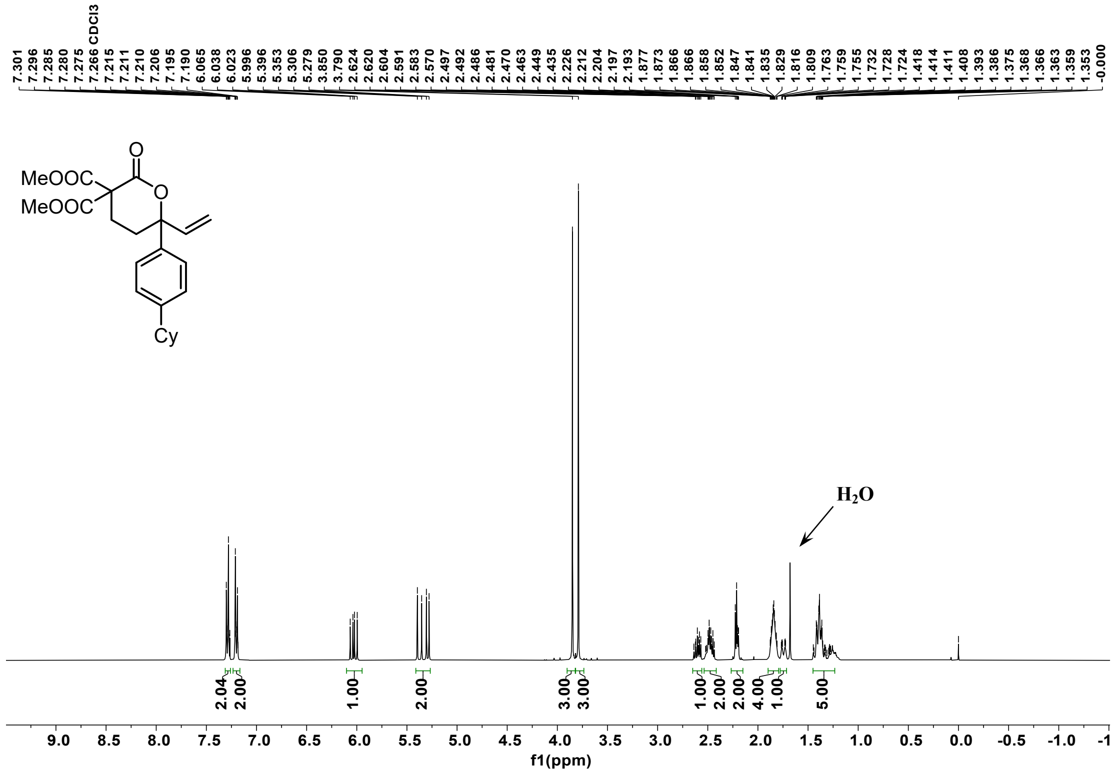
^{1}H NMR of **1d** in $CDCl_3$ (400 MHz)



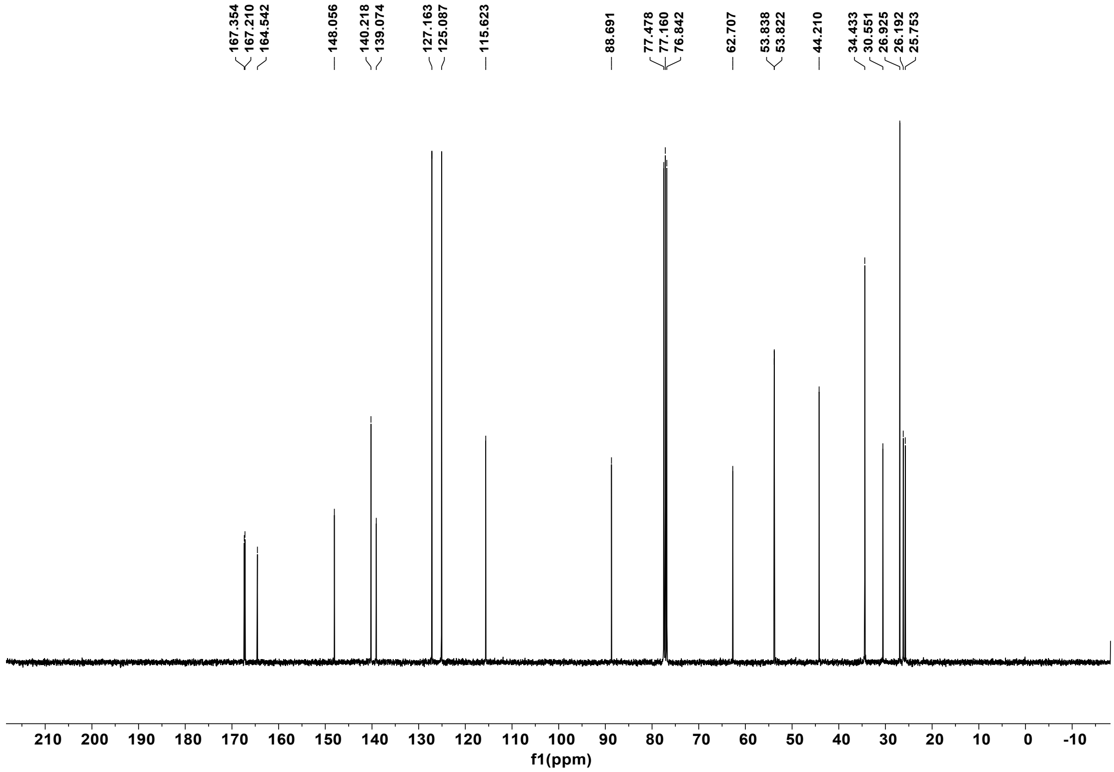
^{13}C NMR of **1d** in $CDCl_3$ (101 MHz)



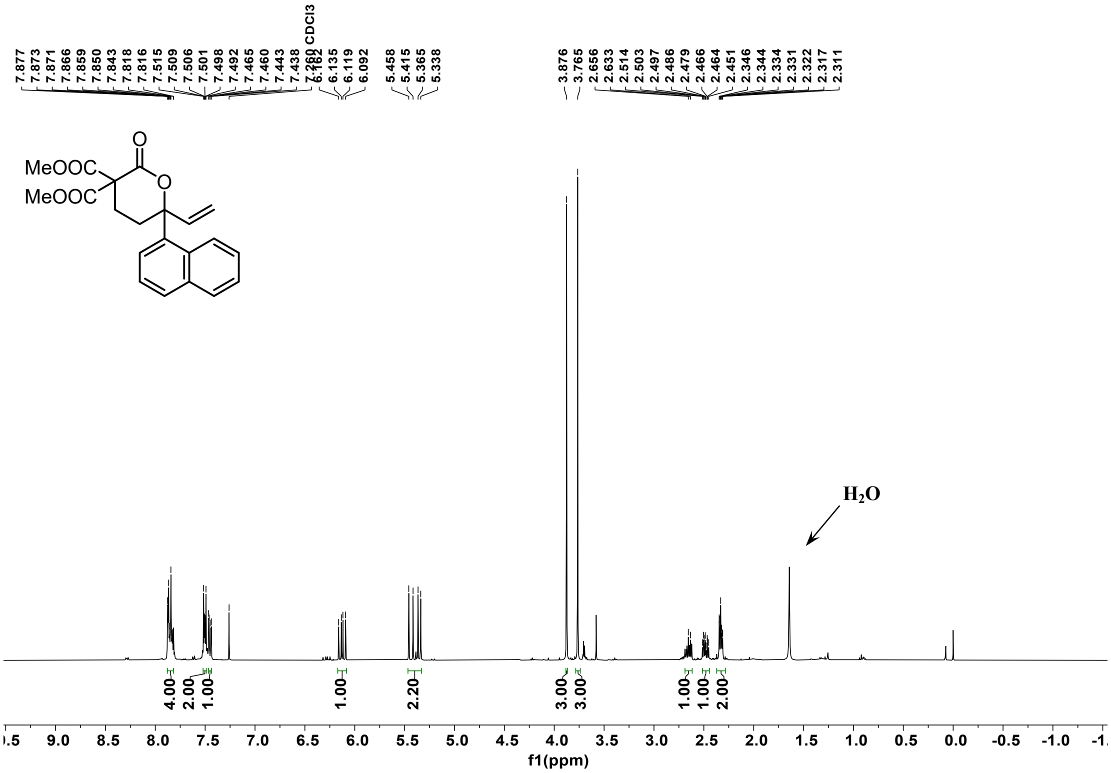
^{1}H NMR of **1e** in $CDCl_3$ (400 MHz)



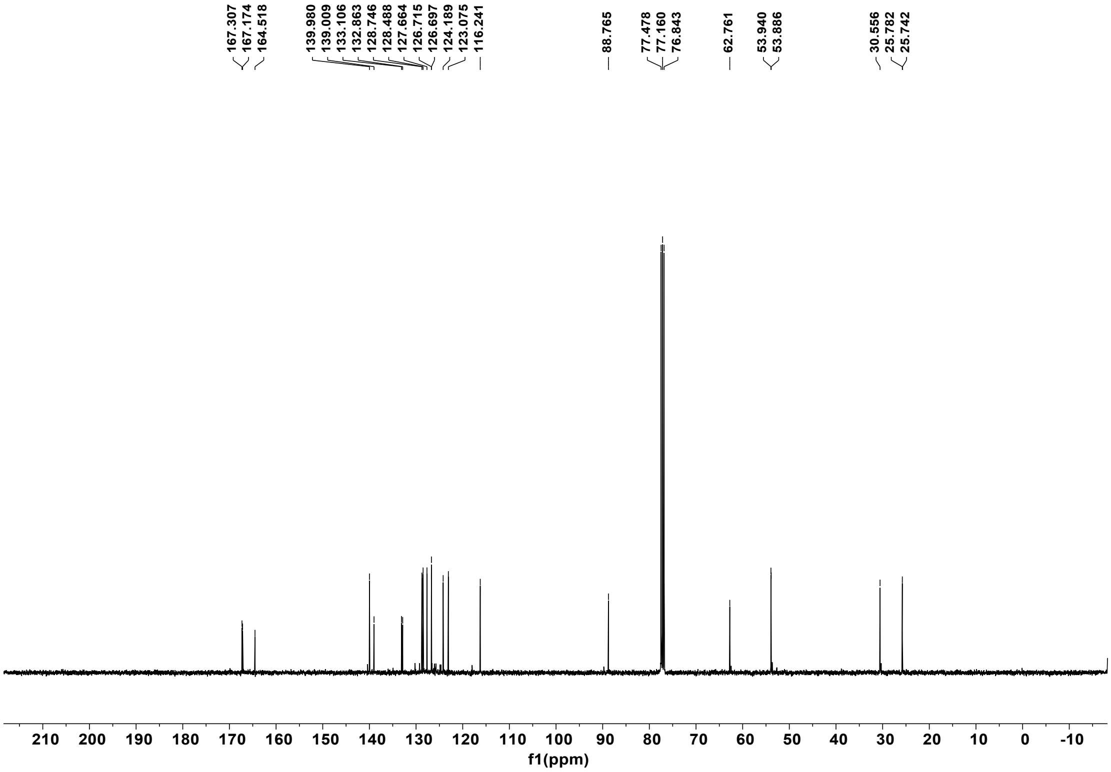
^{13}C NMR of **1e** in $CDCl_3$ (101 MHz)



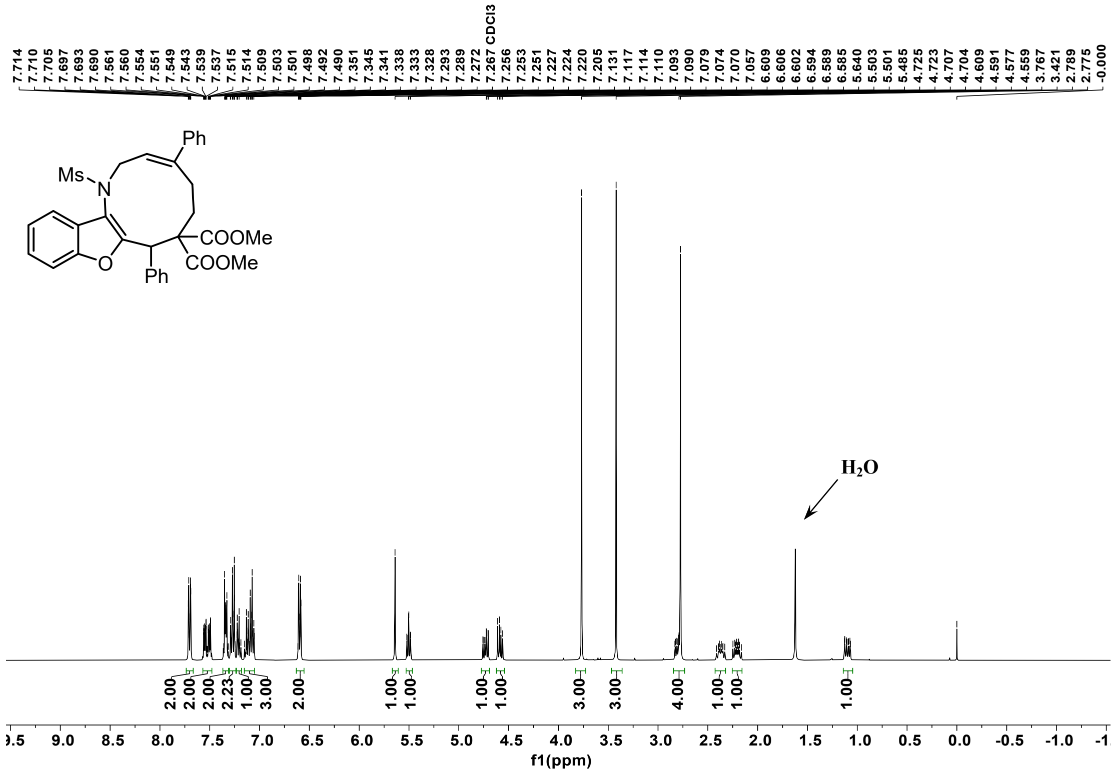
^{1}H NMR of **1f** in $CDCl_3$ (400 MHz)



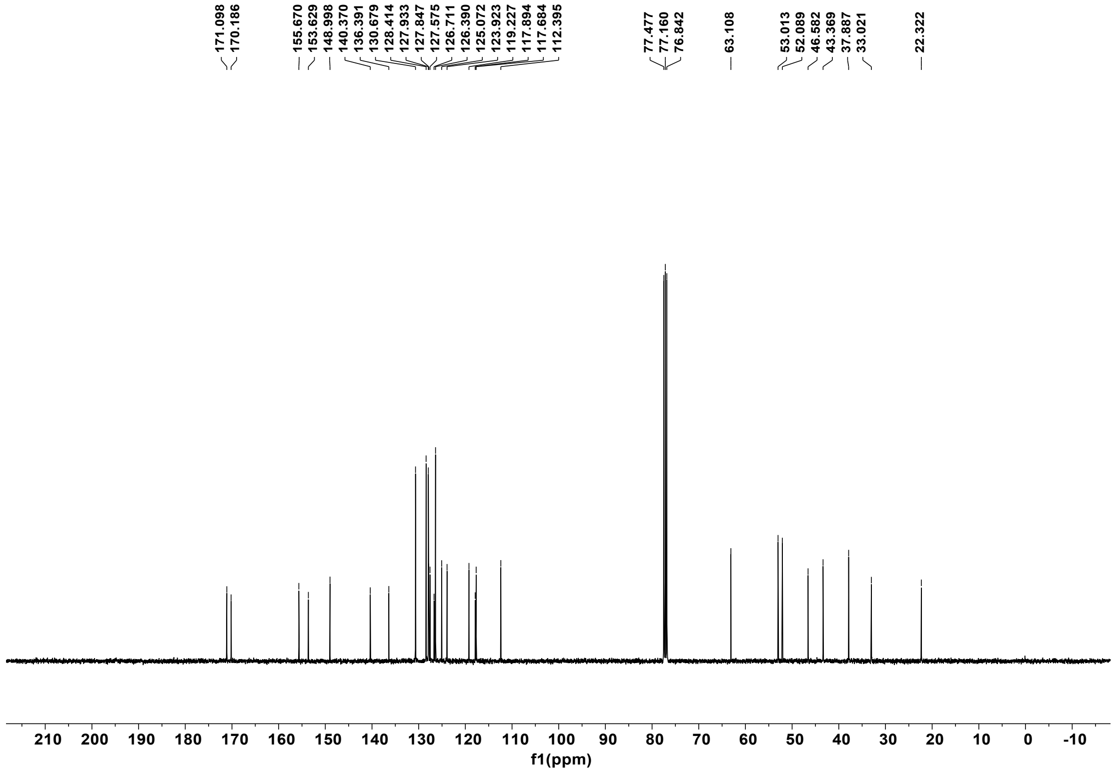
^{13}C NMR of **1f** in $CDCl_3$ (101 MHz)



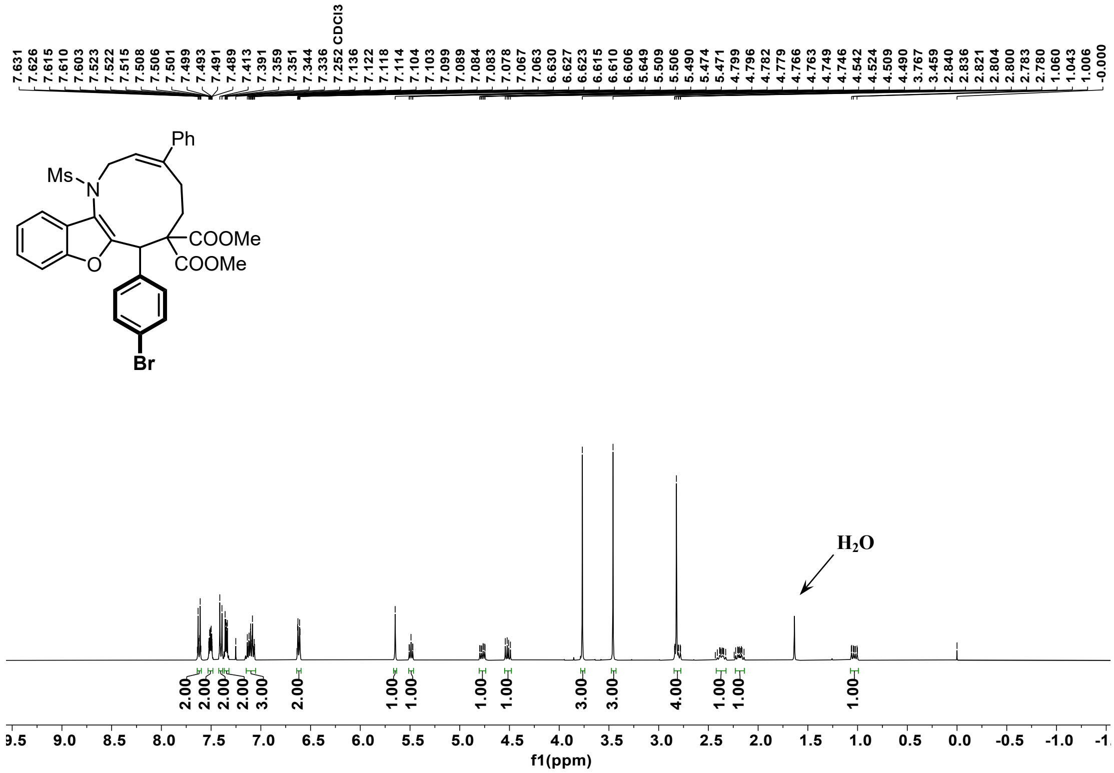
^{1}H NMR of **3aa** in $CDCl_3$ (400 MHz)



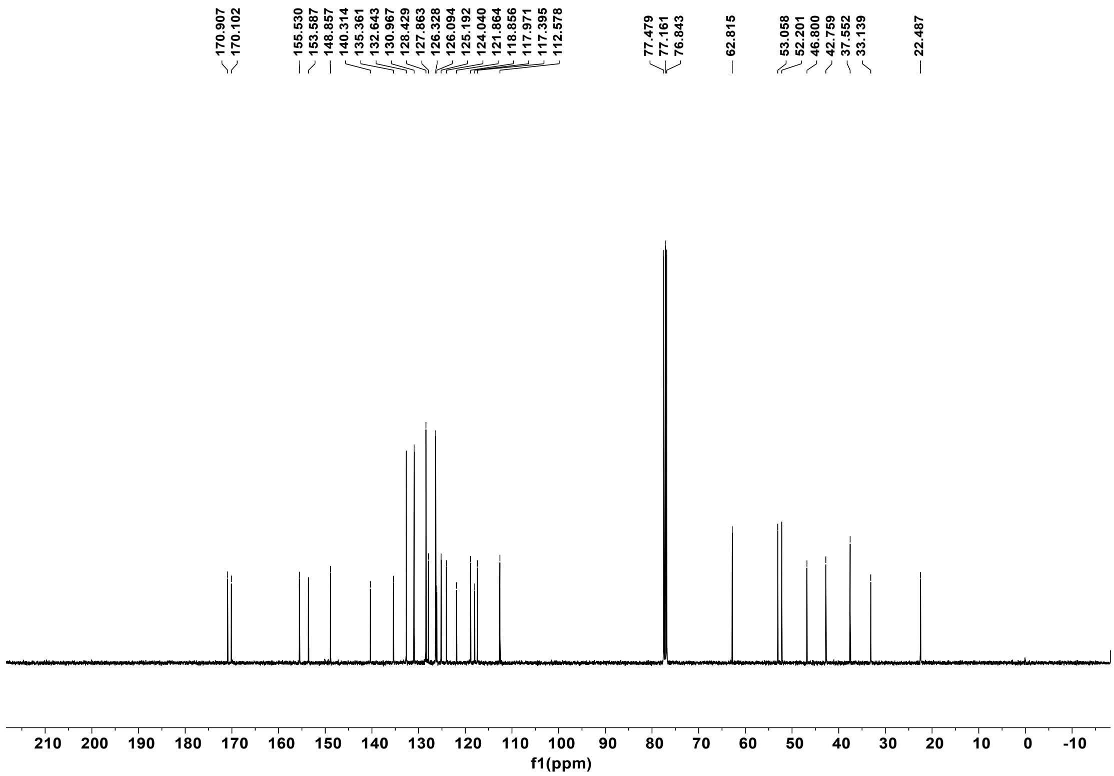
^{13}C NMR of **3aa** in $CDCl_3$ (101 MHz)



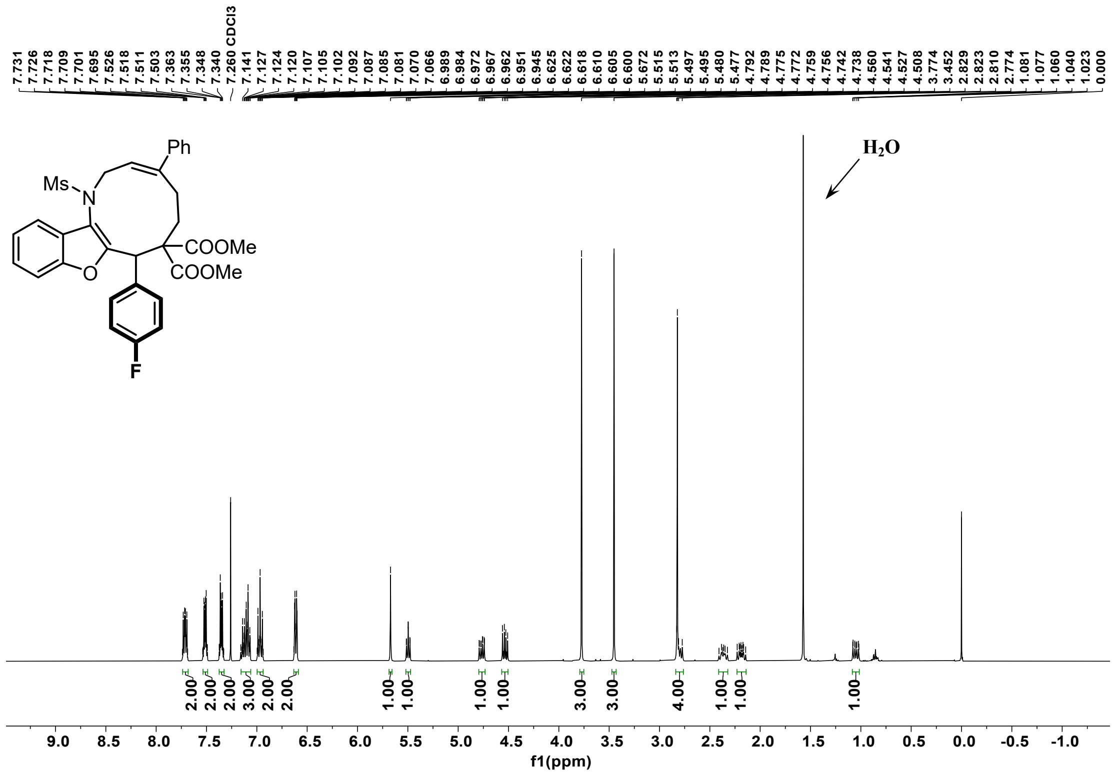
^{1}H NMR of **3ab** in $CDCl_3$ (400 MHz)



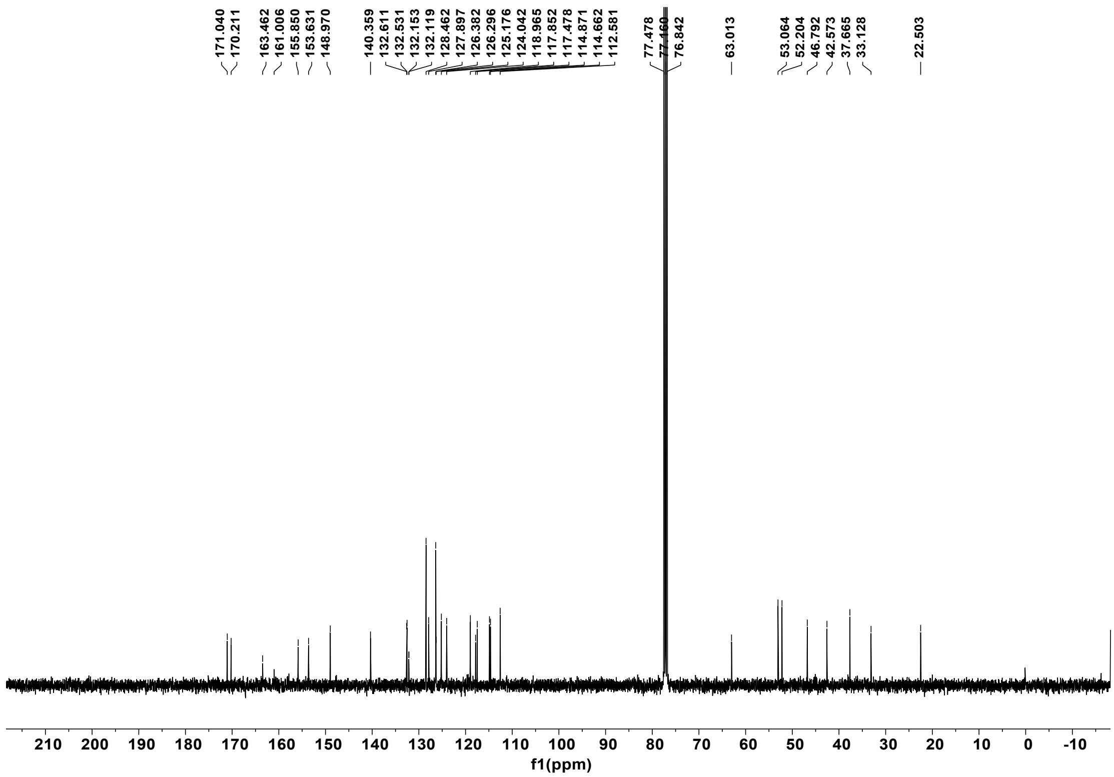
^{13}C NMR of **3ab** in $CDCl_3$ (101 MHz)



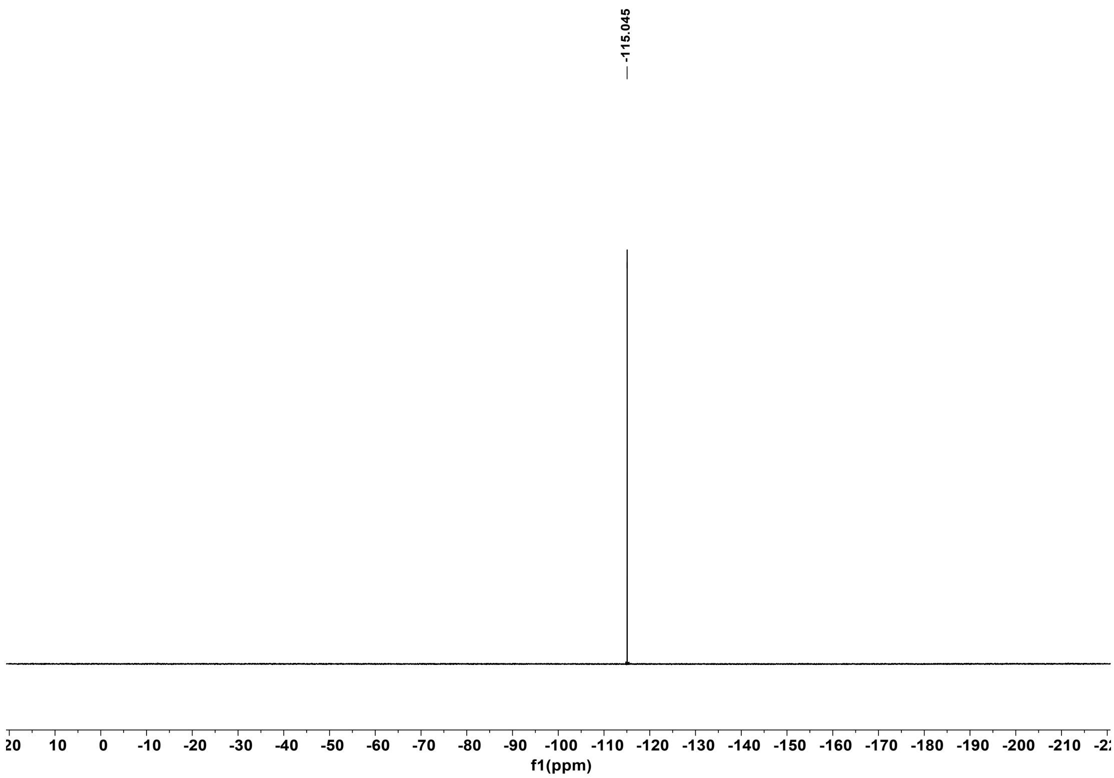
^{1}H NMR of **3ac** in $CDCl_3$ (400 MHz)



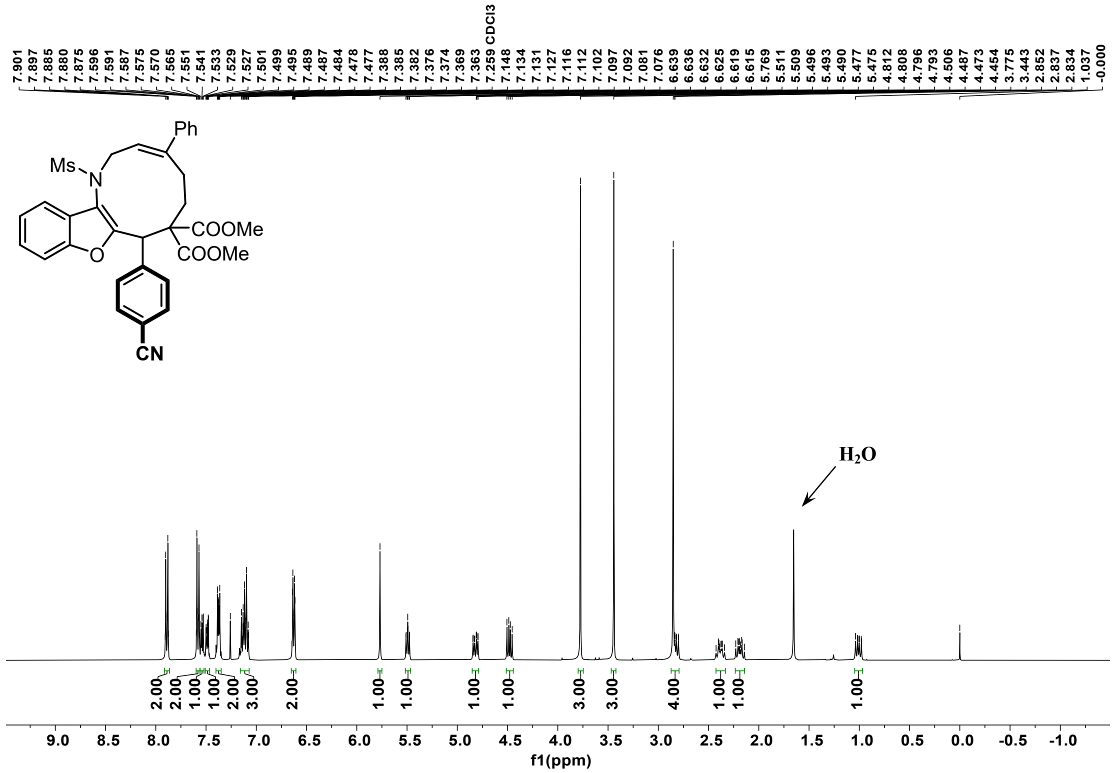
^{13}C NMR of **3ac** in $CDCl_3$ (101 MHz)



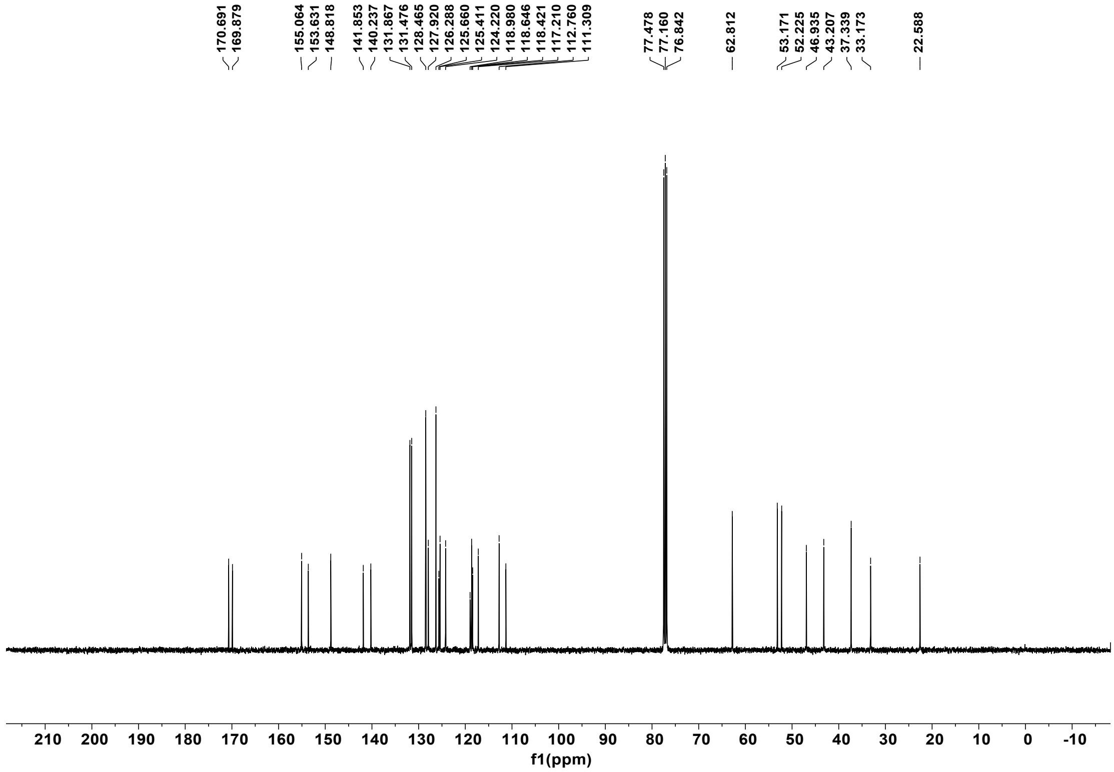
^{19}F NMR of **3ac** in $CDCl_3$ (377 MHz)



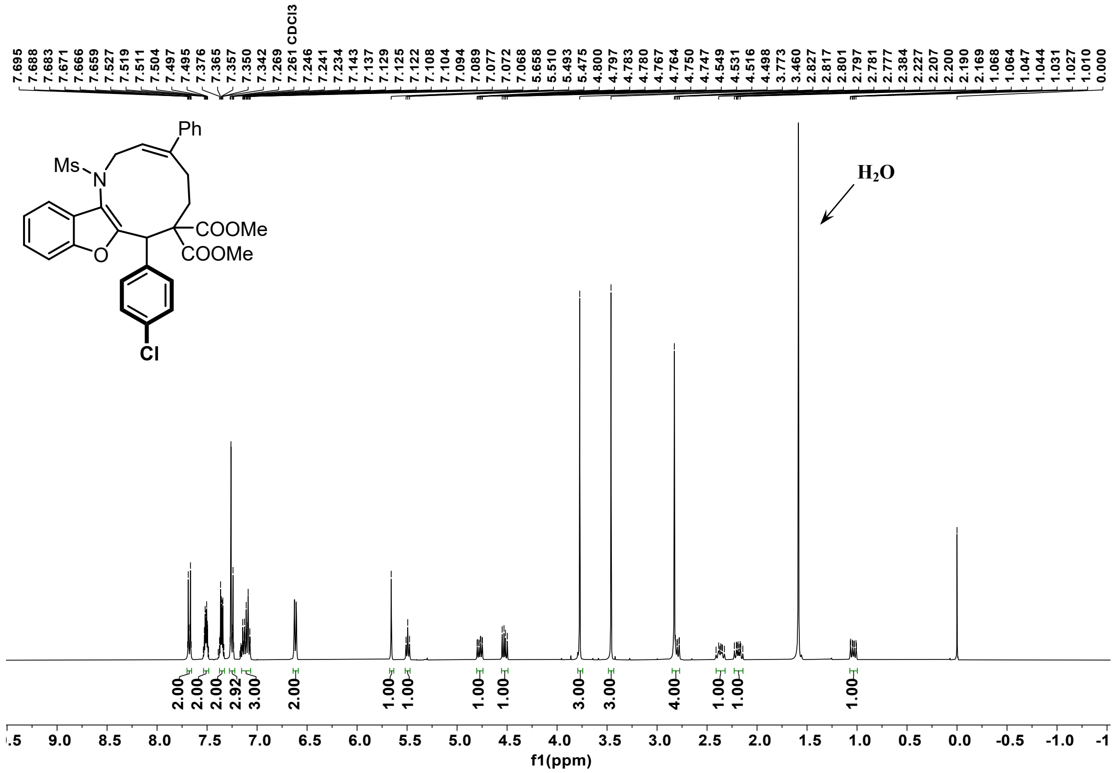
[1]H NMR of **3ad** in $CDCl_3$ (400 MHz)



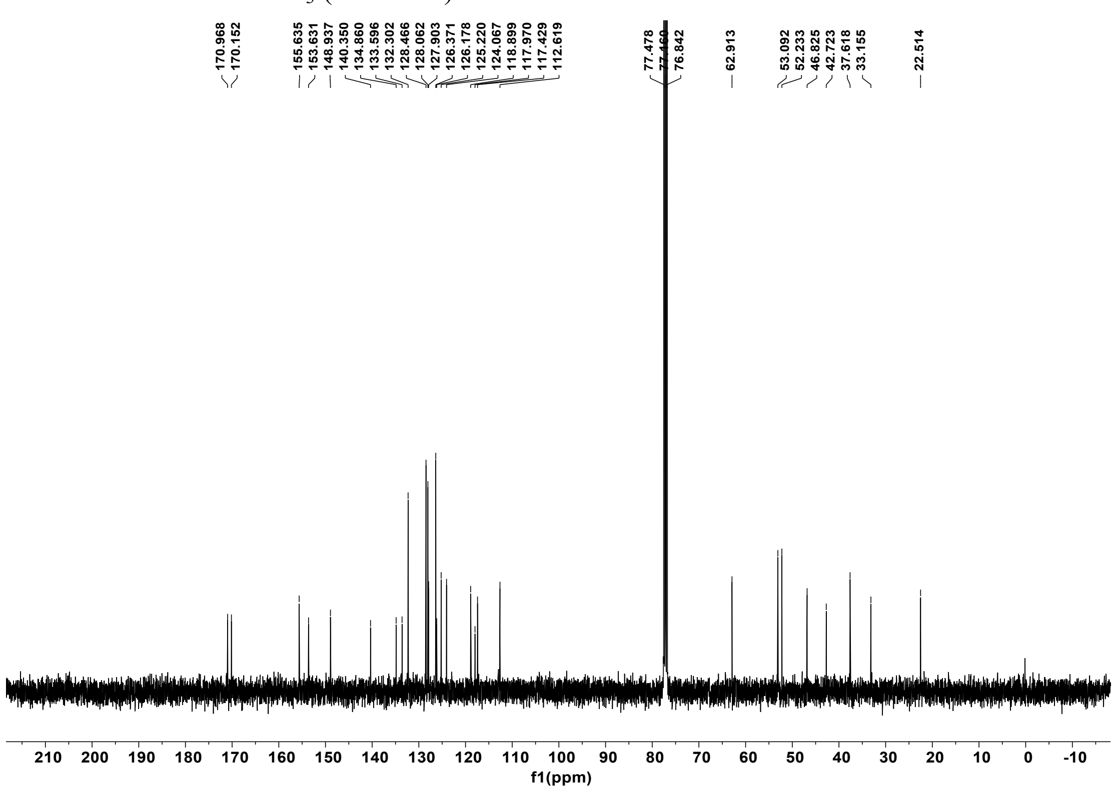
[13]C NMR of **3ad** in $CDCl_3$ (101 MHz)



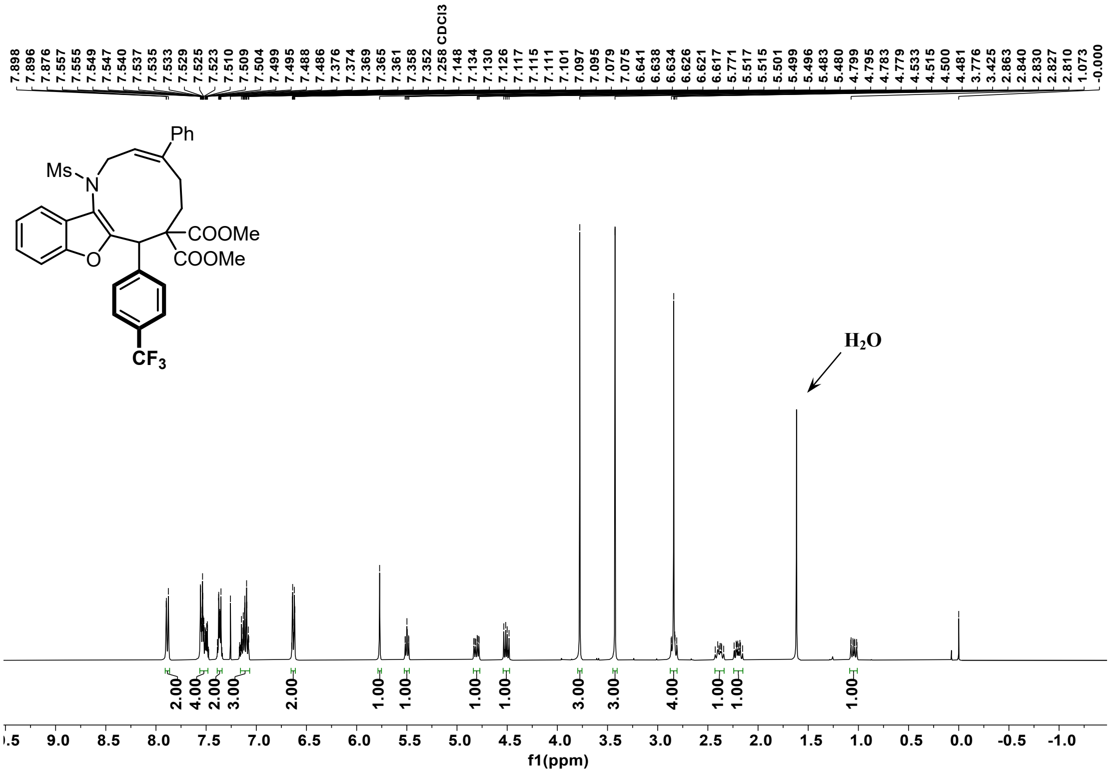
^{1}H NMR of **3ae** in $CDCl_3$ (400 MHz)



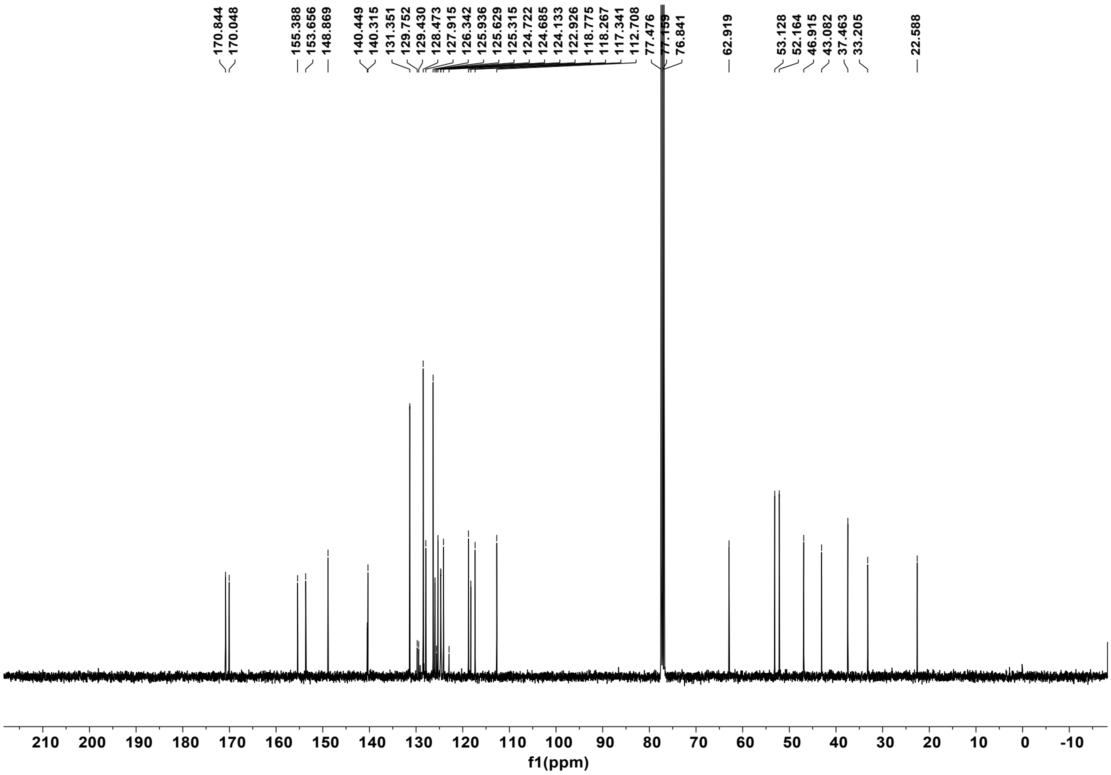
^{13}C NMR of **3ae** in $CDCl_3$ (101 MHz)



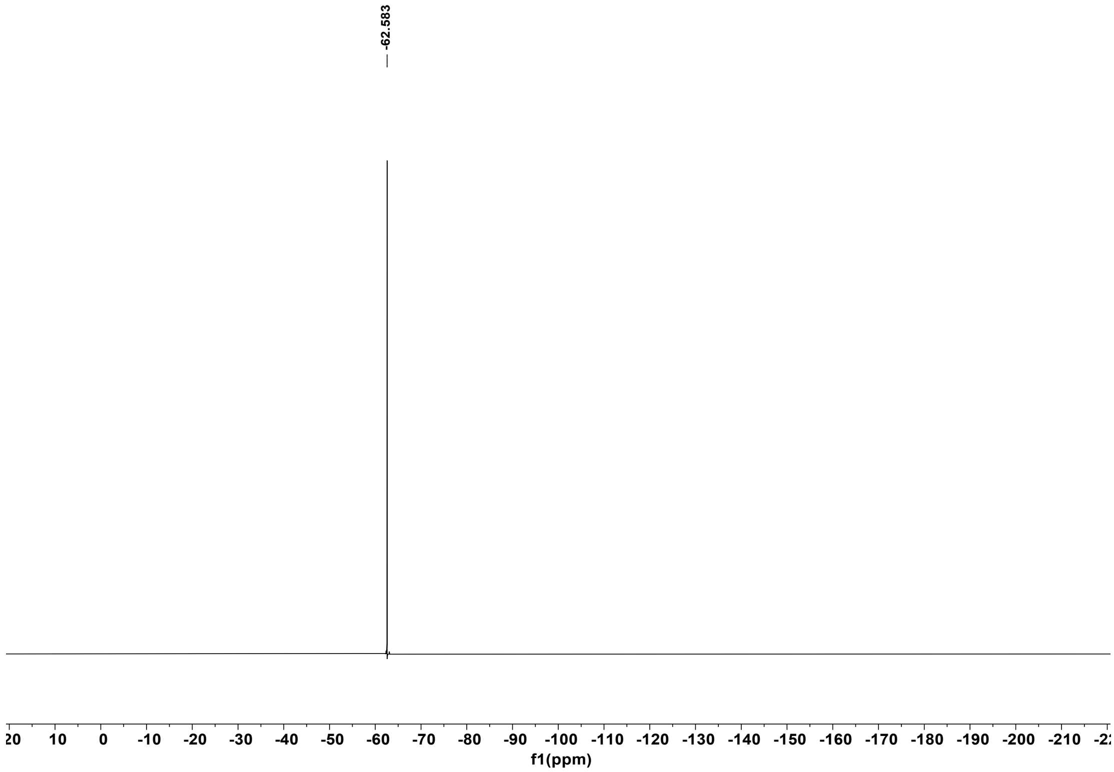
[1]H NMR of **3af** in $CDCl_3$ (400 MHz)



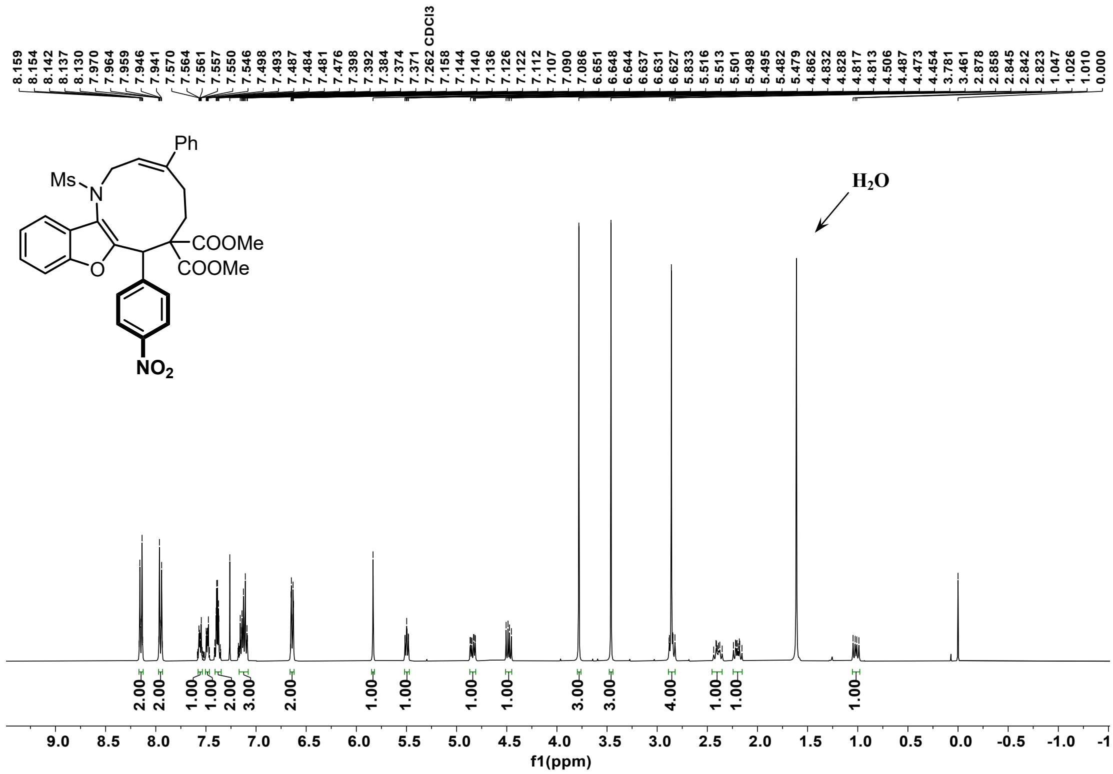
[13]C NMR of **3af** in $CDCl_3$ (101 MHz)



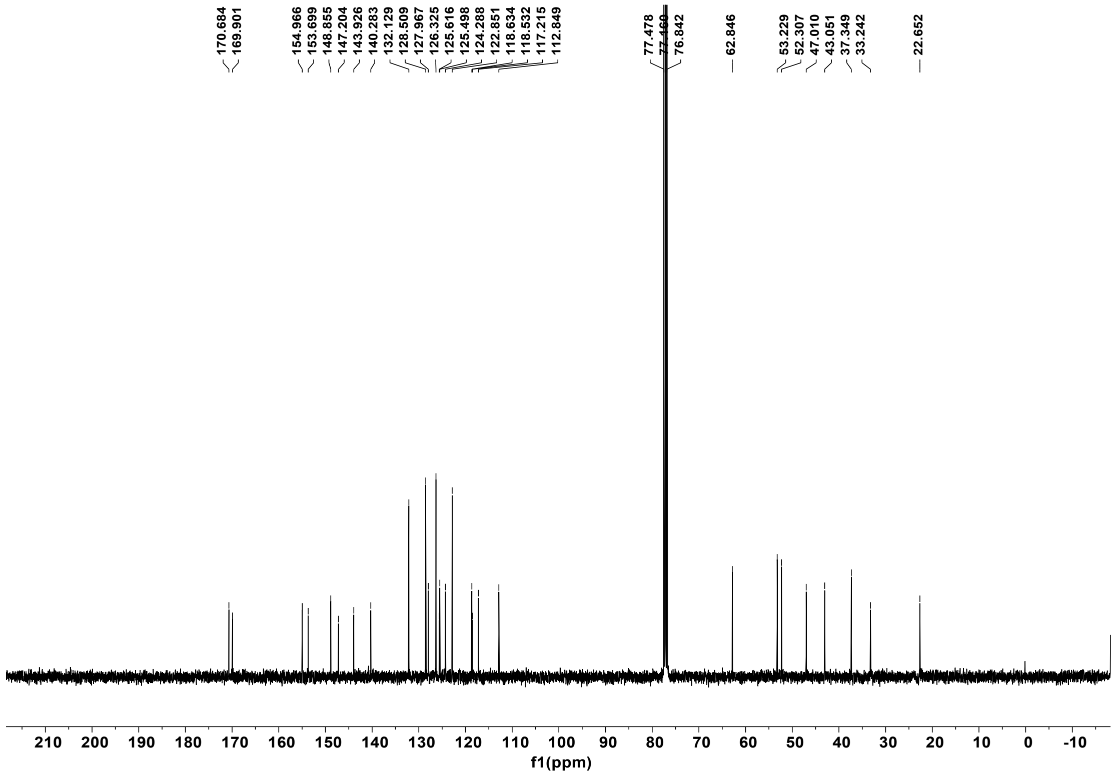
^{19}F NMR of **3af** in $CDCl_3$ (377 MHz)



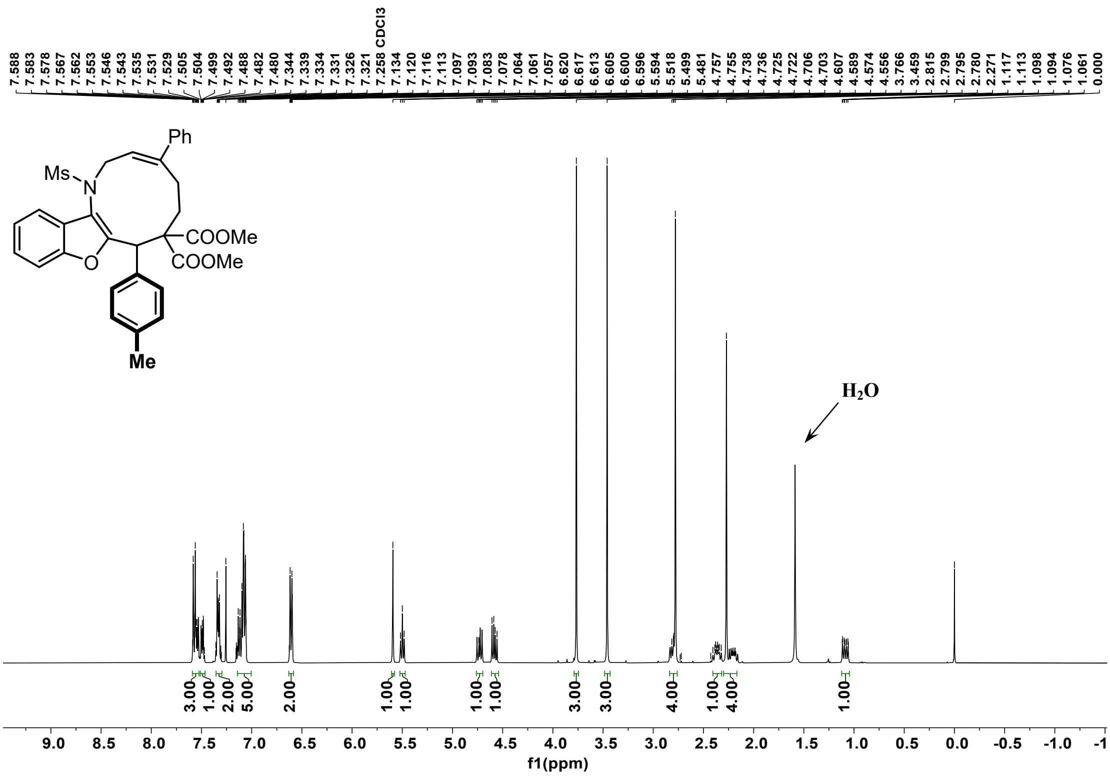
^{1}H NMR of **3ag** in $CDCl_3$ (400 MHz)



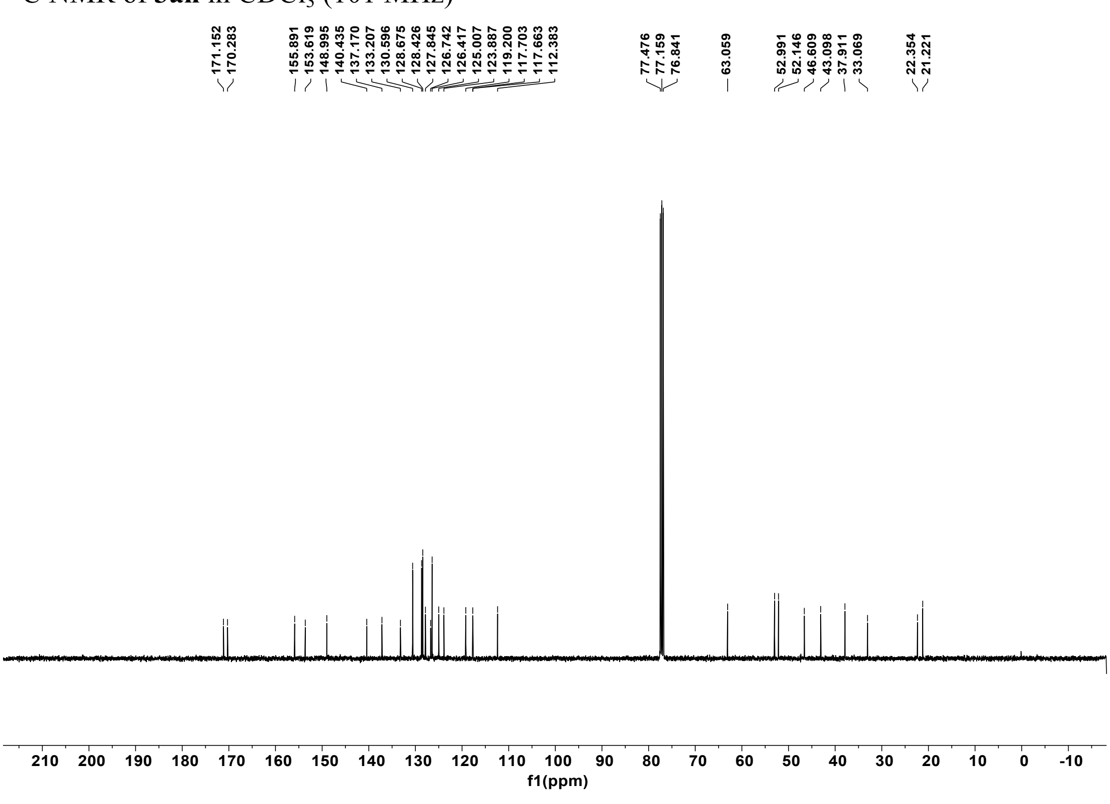
^{13}C NMR of **3ag** in $CDCl_3$ (101 MHz)



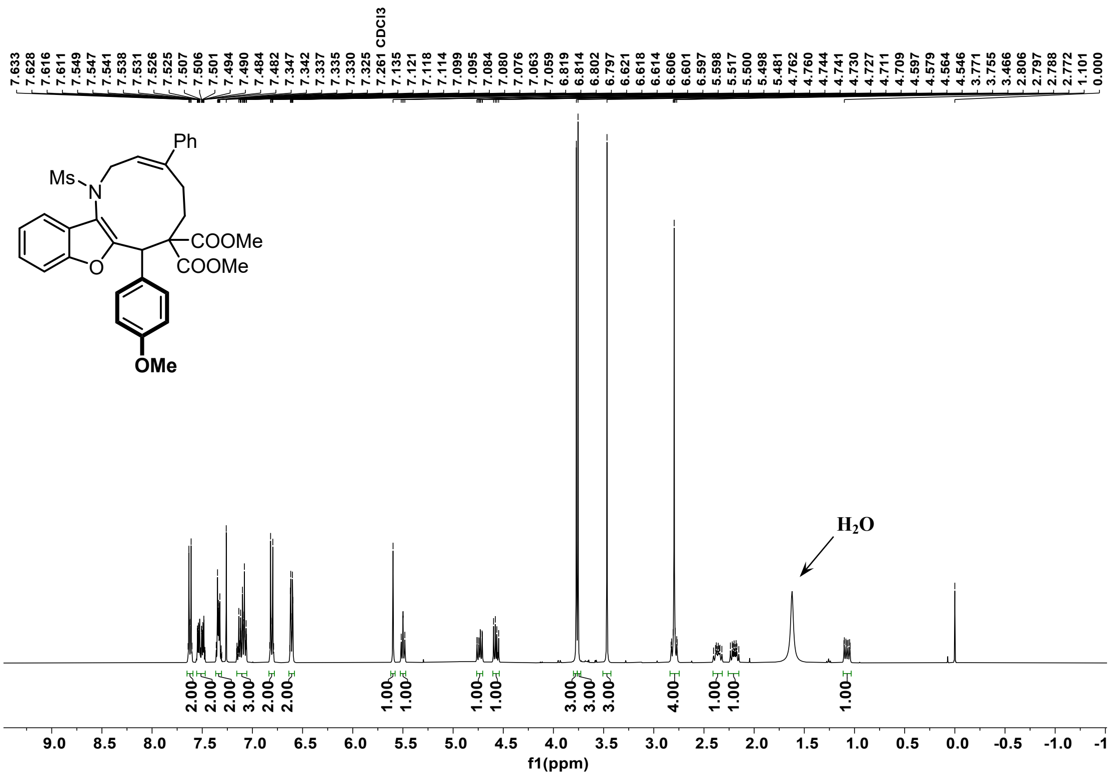
[1]H NMR of **3ah** in $CDCl_3$ (400 MHz)



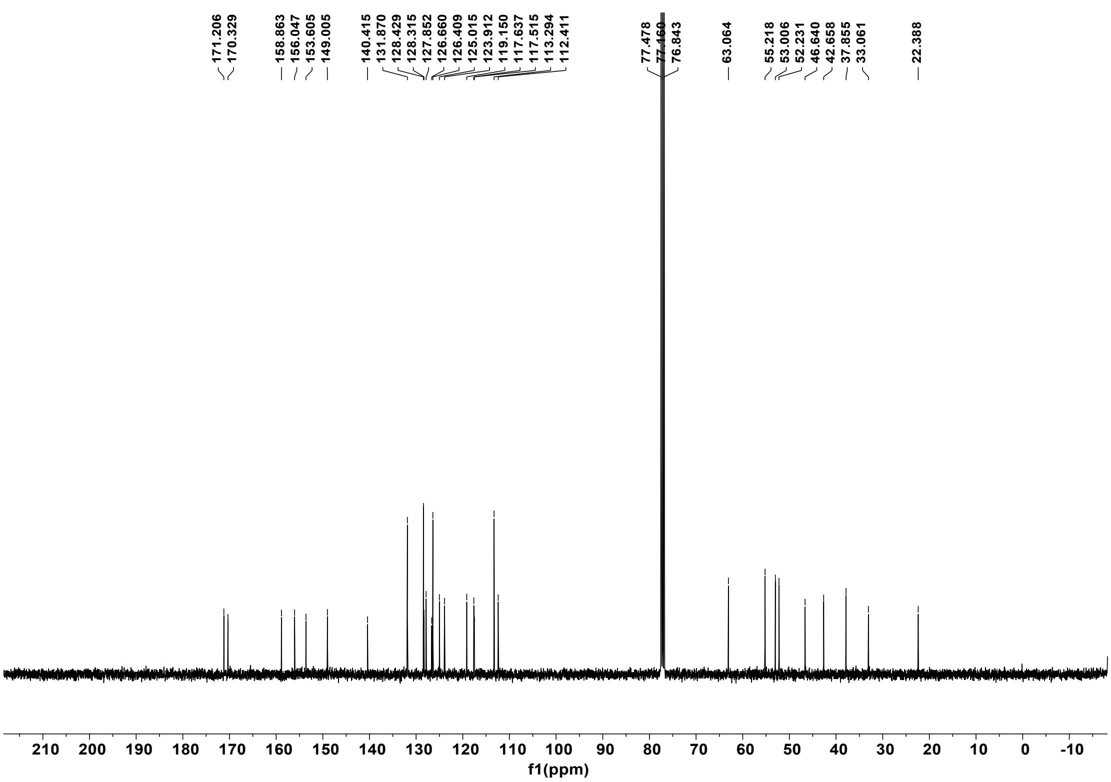
[13]C NMR of **3ah** in $CDCl_3$ (101 MHz)



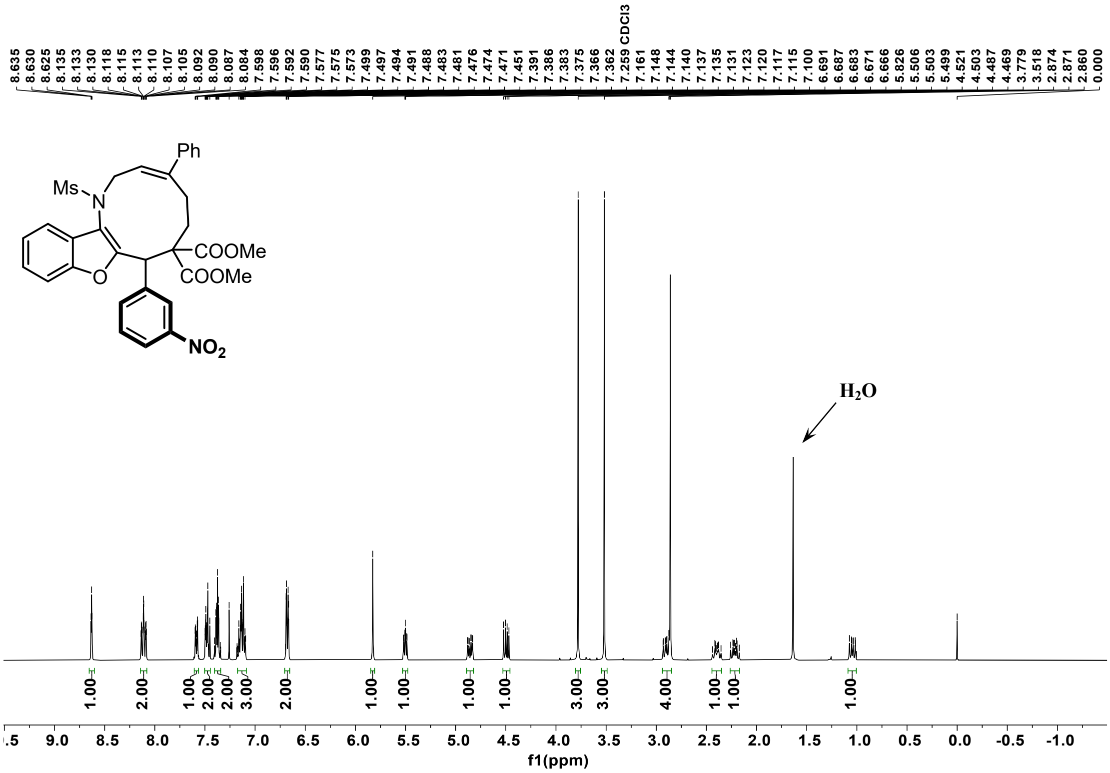
[1]H NMR of **3ai** in $CDCl_3$ (400 MHz)



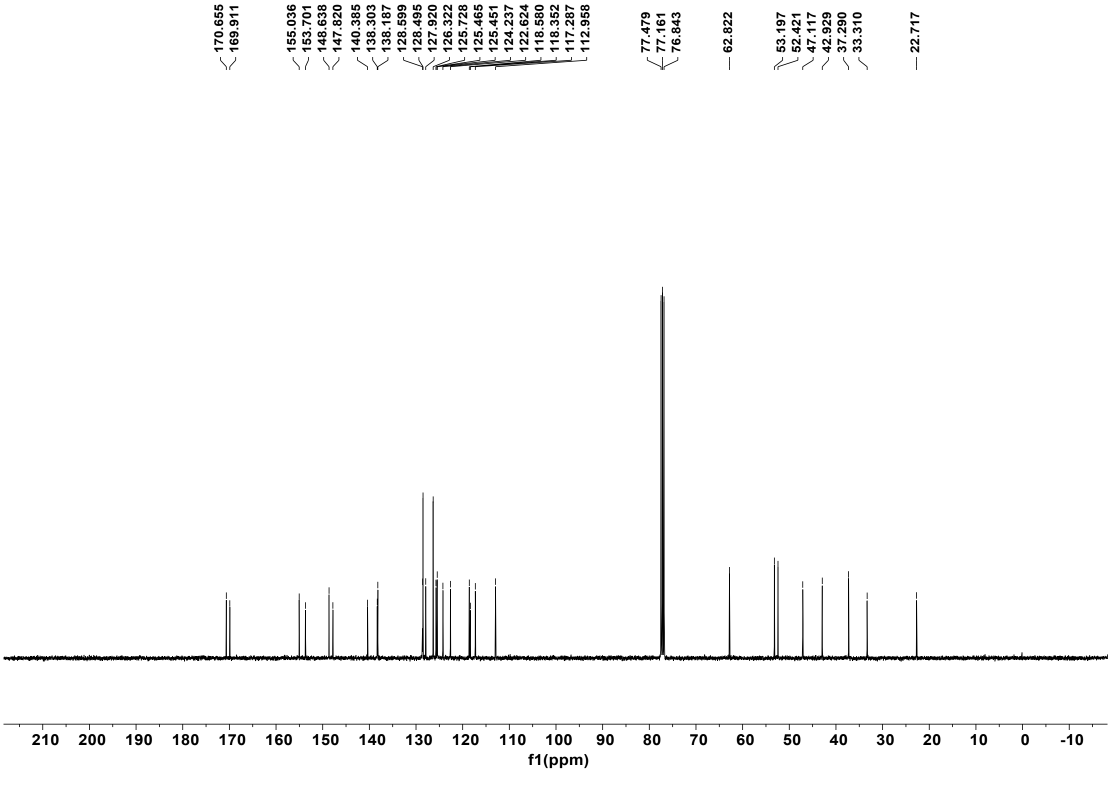
[13]C NMR of **3ai** in $CDCl_3$ (101 MHz)



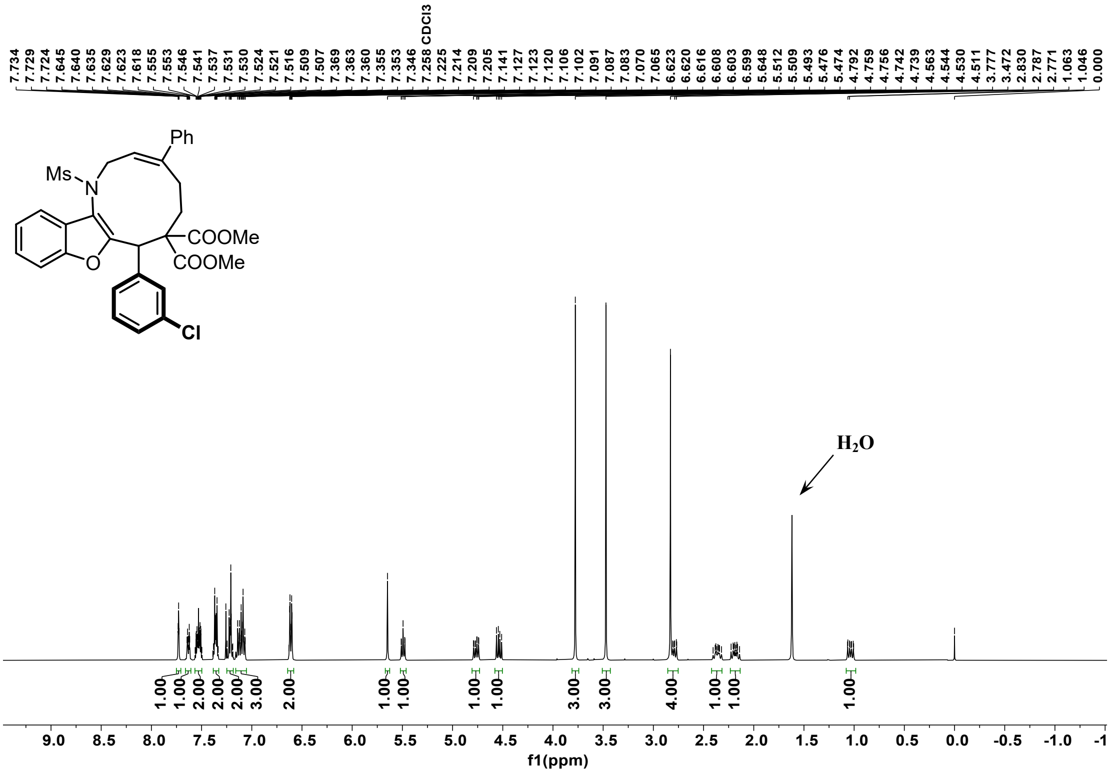
^{1}H NMR of **3aj** in $CDCl_3$ (400 MHz)



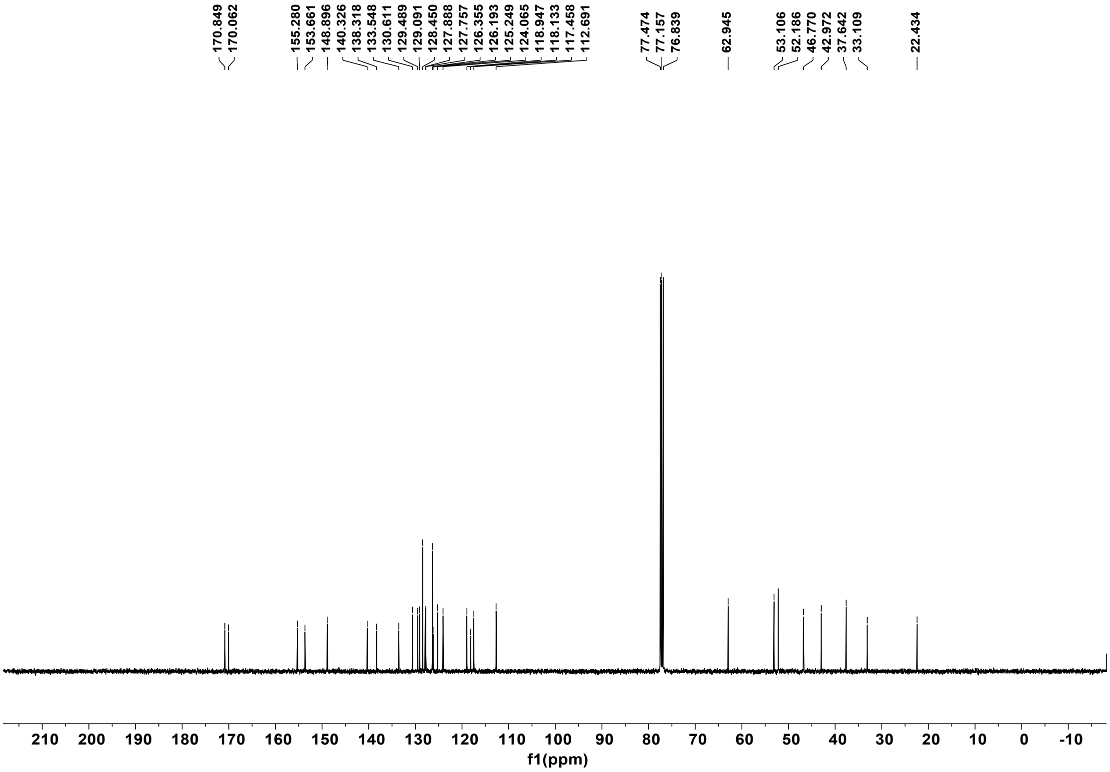
^{13}C NMR of **3aj** in $CDCl_3$ (101 MHz)



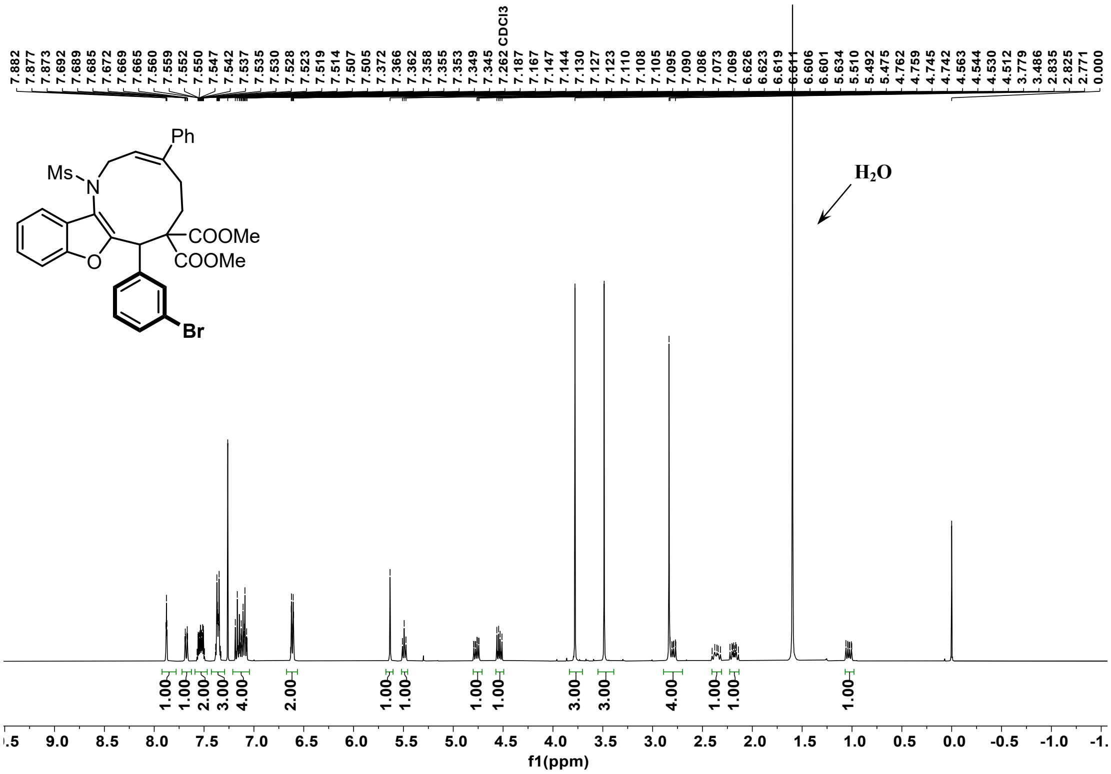
^{1}H NMR of **3ak** in $CDCl_3$ (400 MHz)



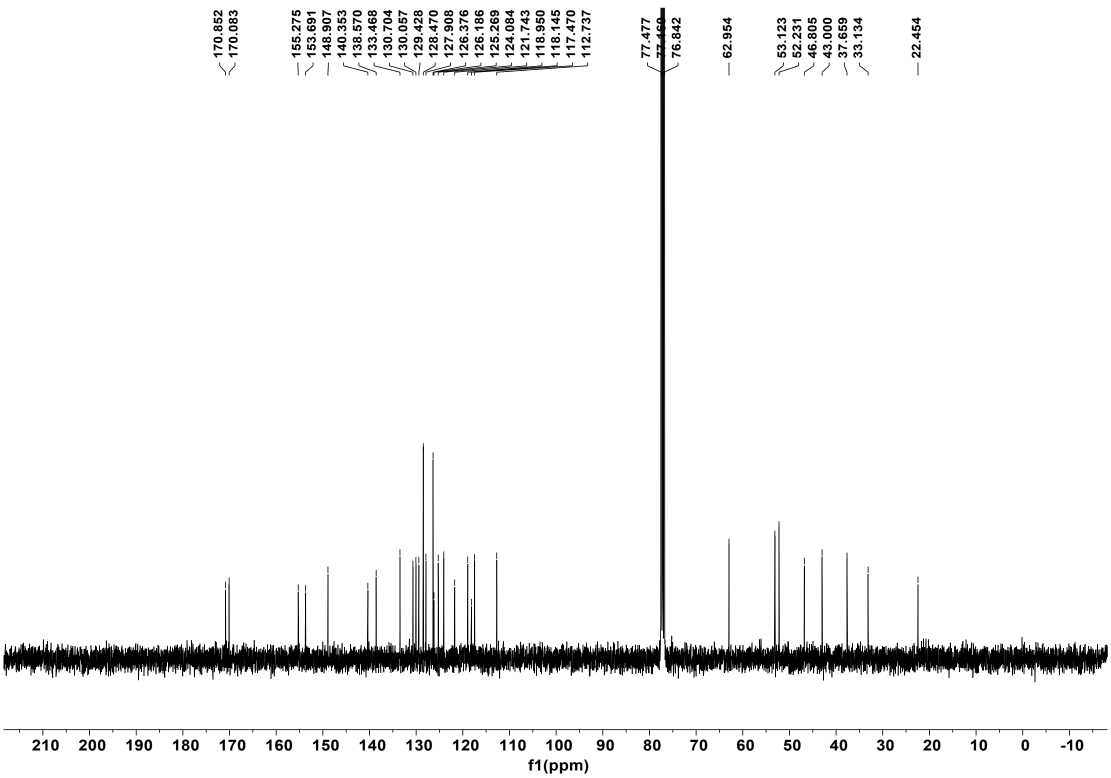
^{13}C NMR of **3ak** in $CDCl_3$ (101 MHz)



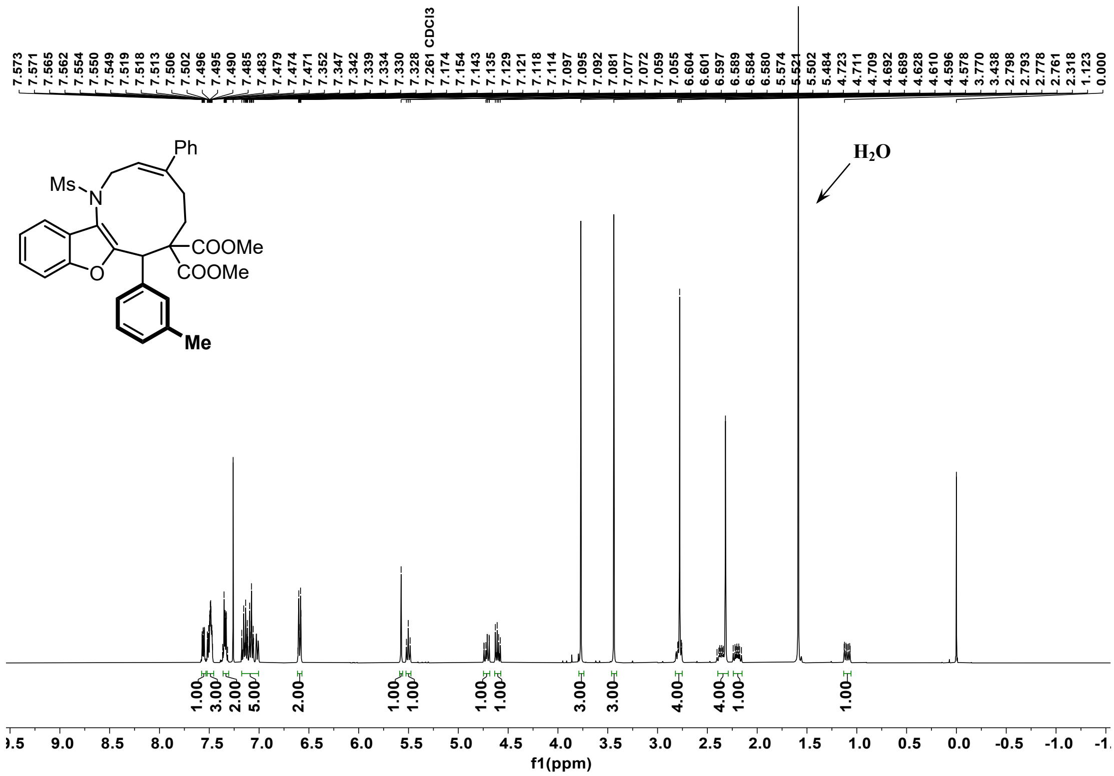
[1]H NMR of **3al** in $CDCl_3$ (400 MHz)



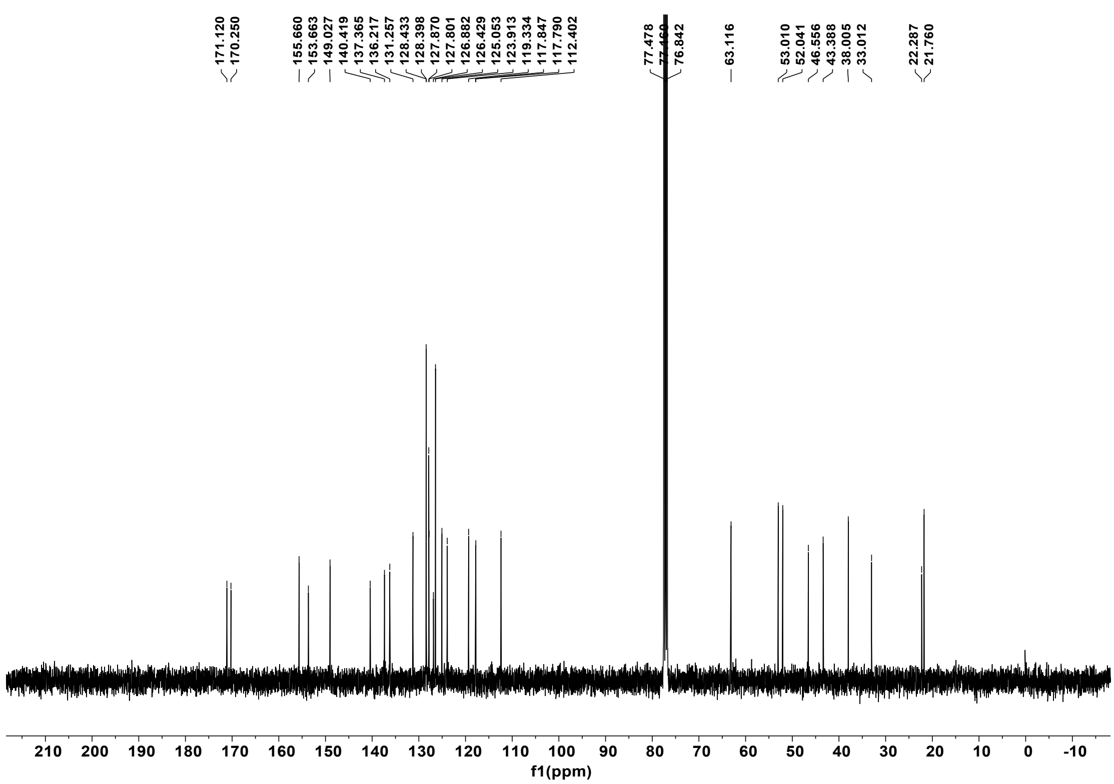
[13]C NMR of **3al** in $CDCl_3$ (101 MHz)



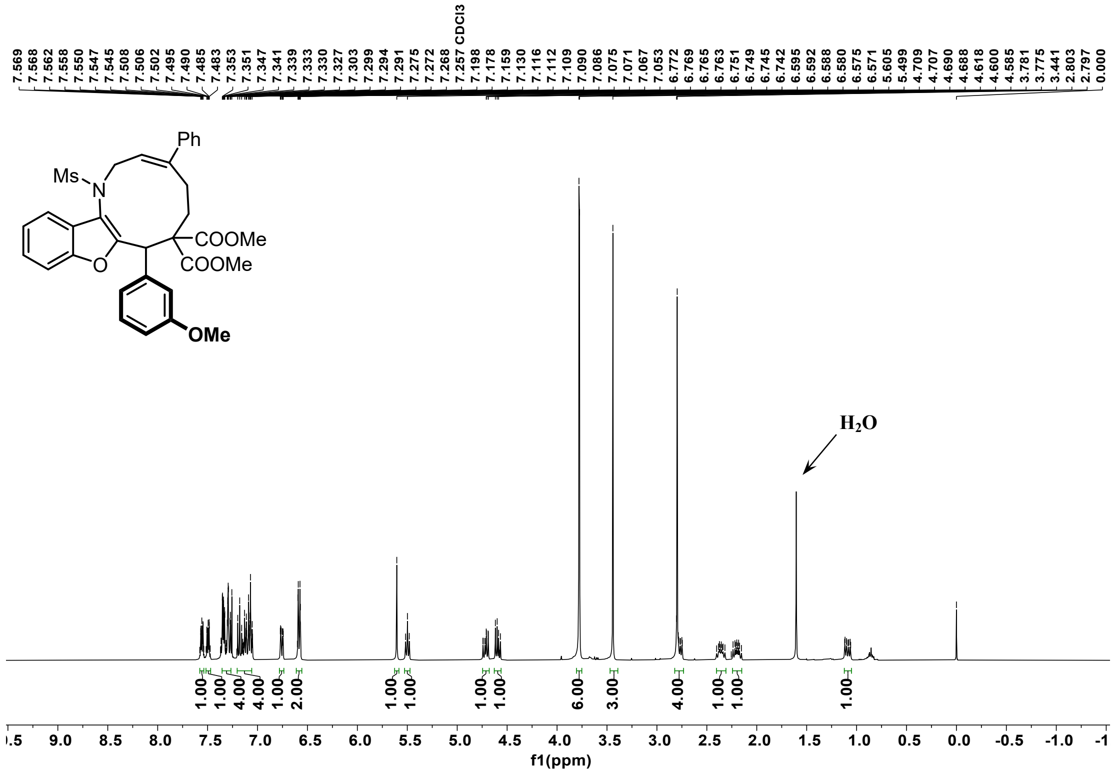
^{1}H NMR of **3am** in $CDCl_3$ (400 MHz)



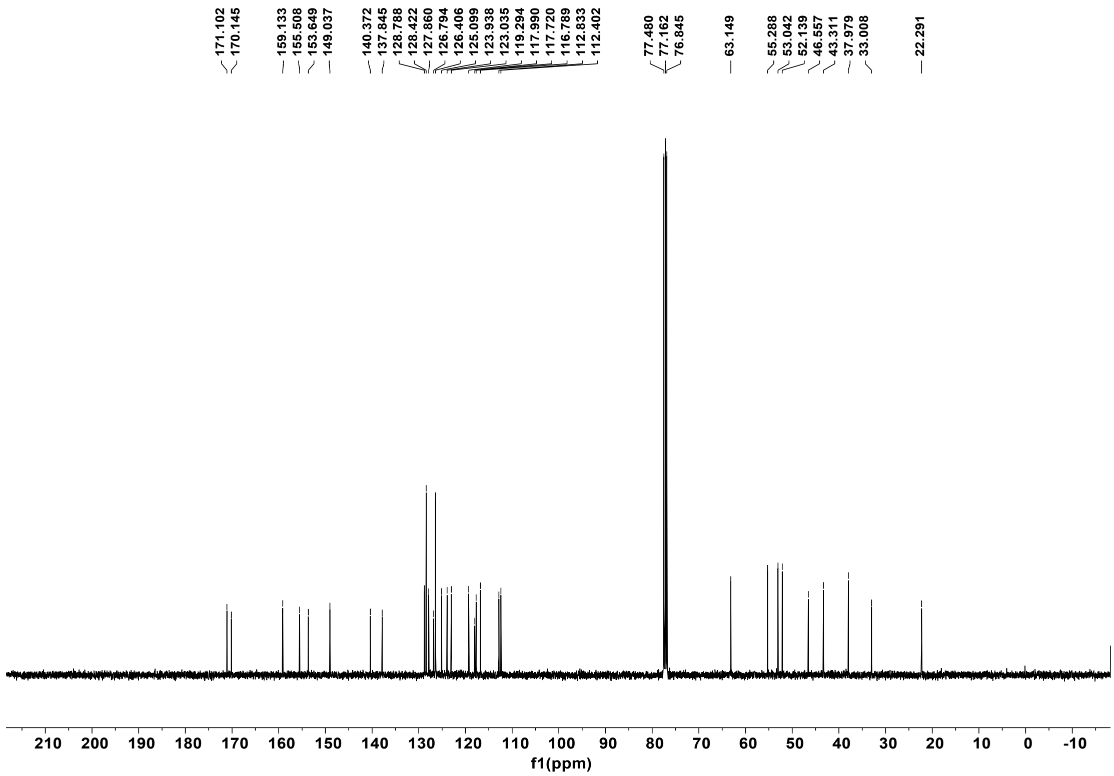
^{13}C NMR of **3am** in $CDCl_3$ (101 MHz)



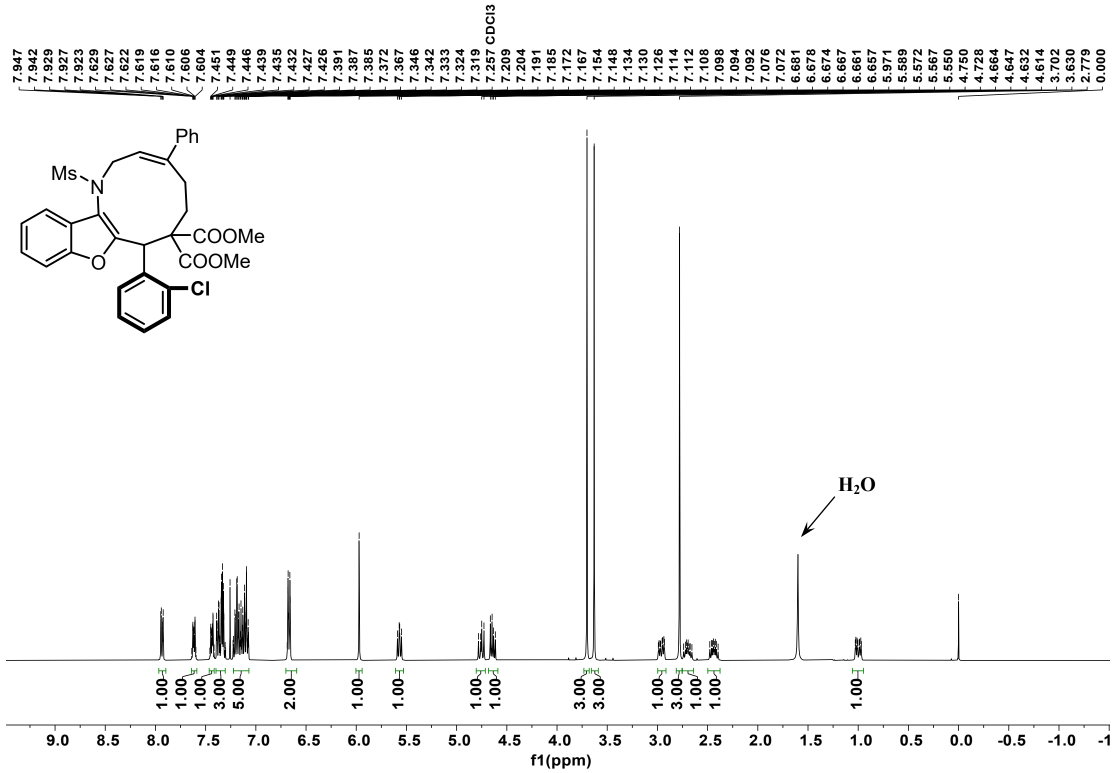
[1]H NMR of **3an** in $CDCl_3$ (400 MHz)



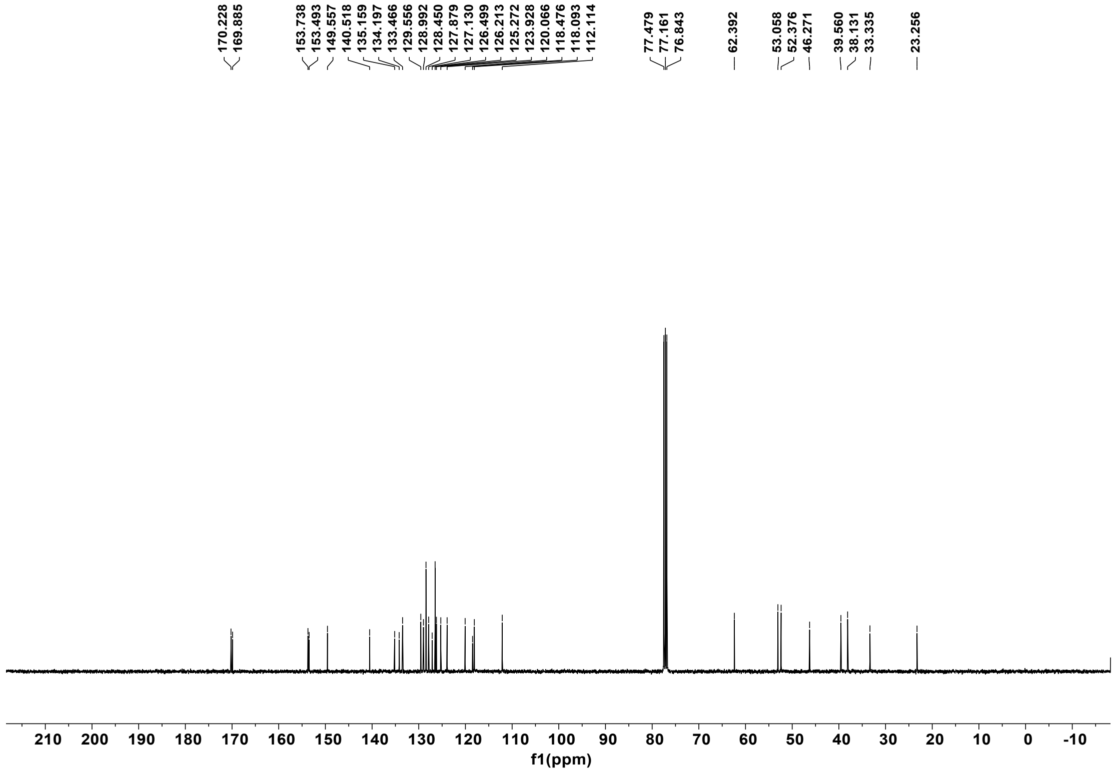
[13]C NMR of **3an** in $CDCl_3$ (101 MHz)



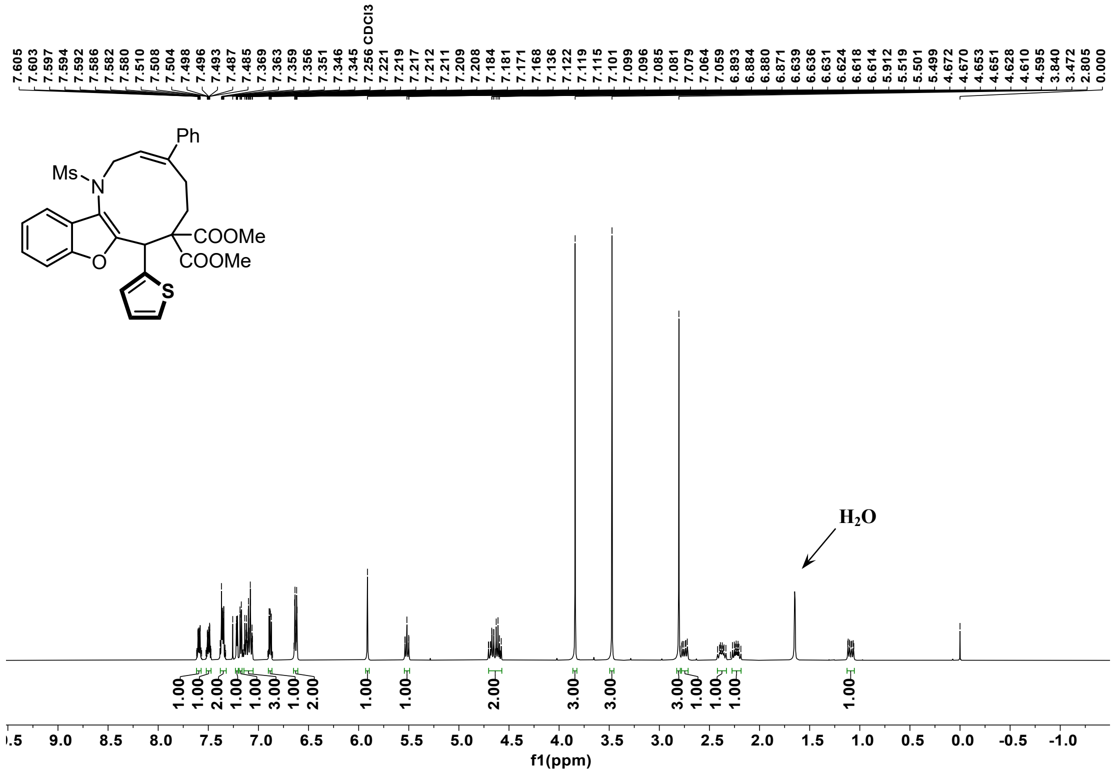
^{1}H NMR of **3ao** in $CDCl_3$ (400 MHz)



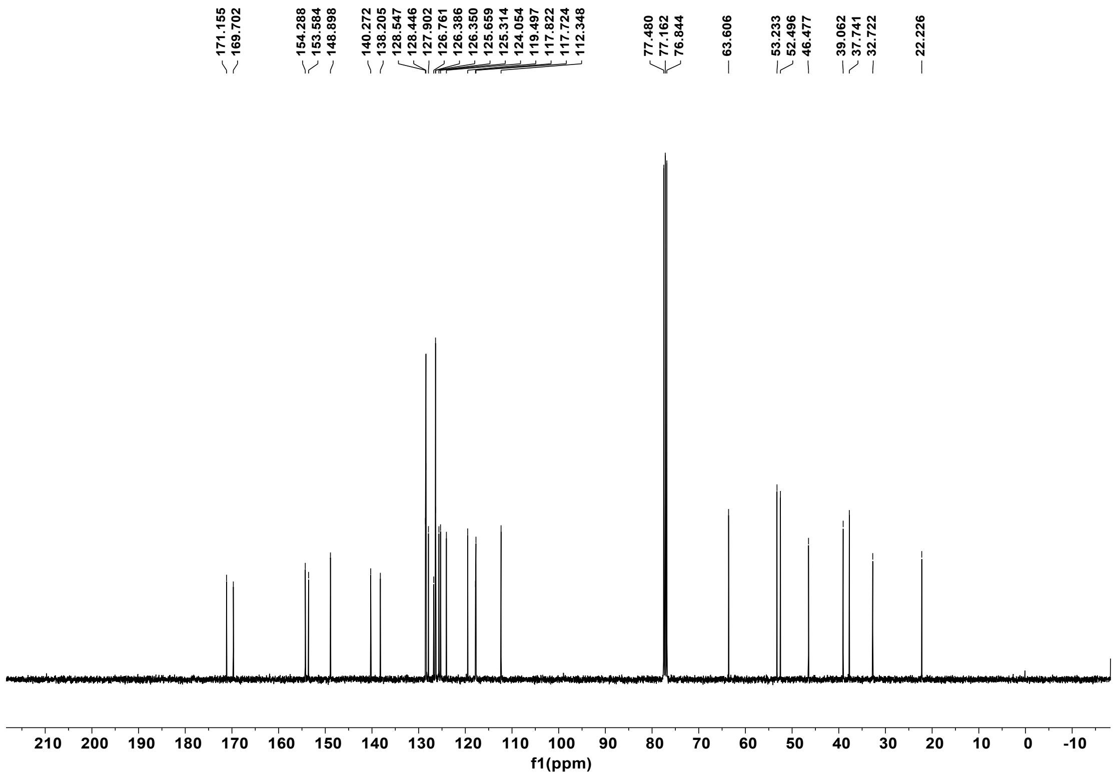
^{13}C NMR of **3ao** in $CDCl_3$ (101 MHz)



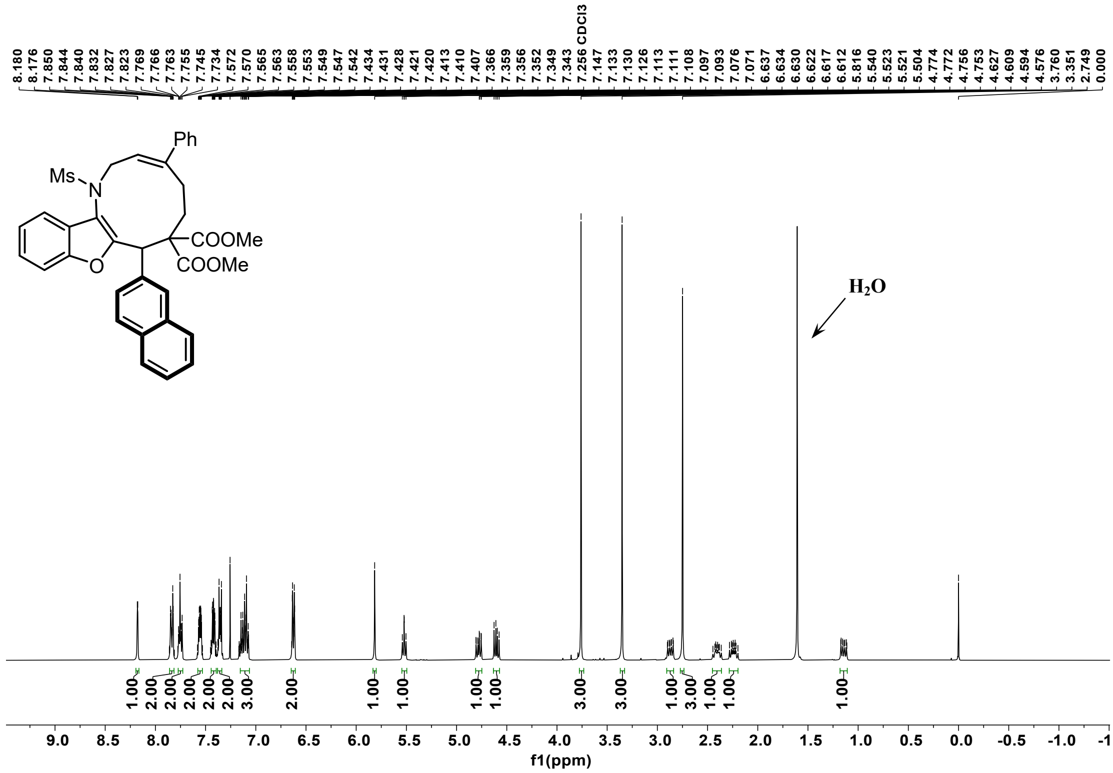
[1]H NMR of **3ap** in $CDCl_3$ (400 MHz)



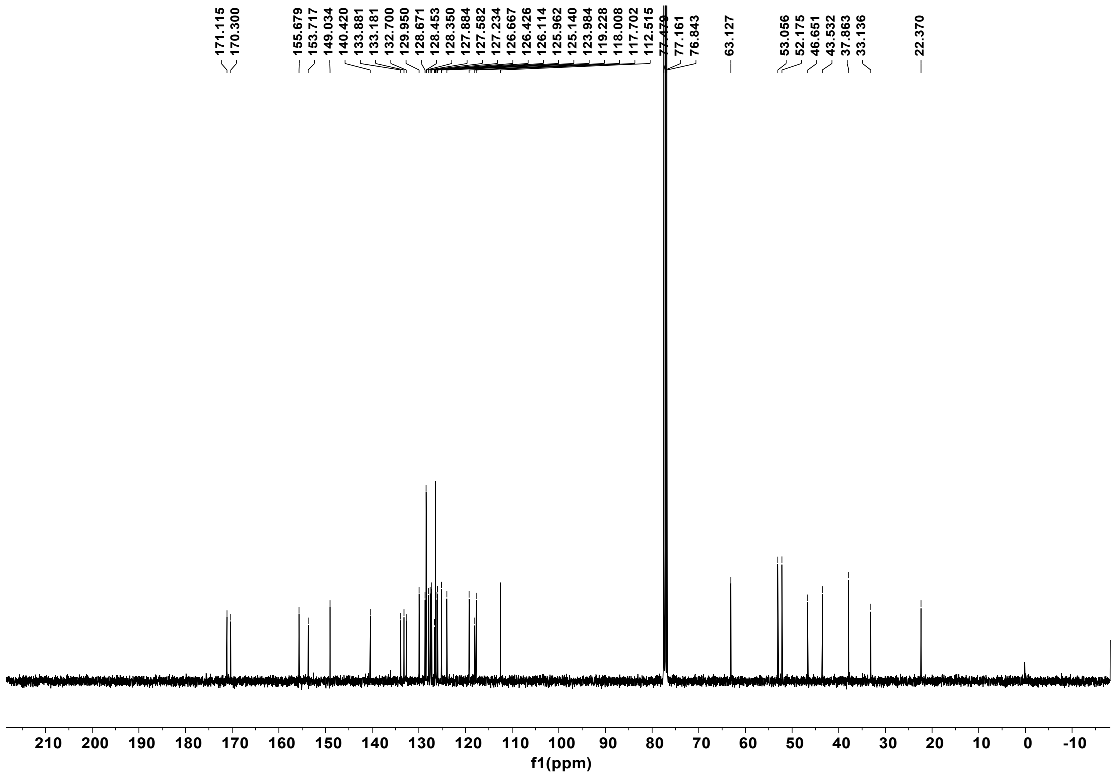
[13]C NMR of **3ap** in $CDCl_3$ (101 MHz)



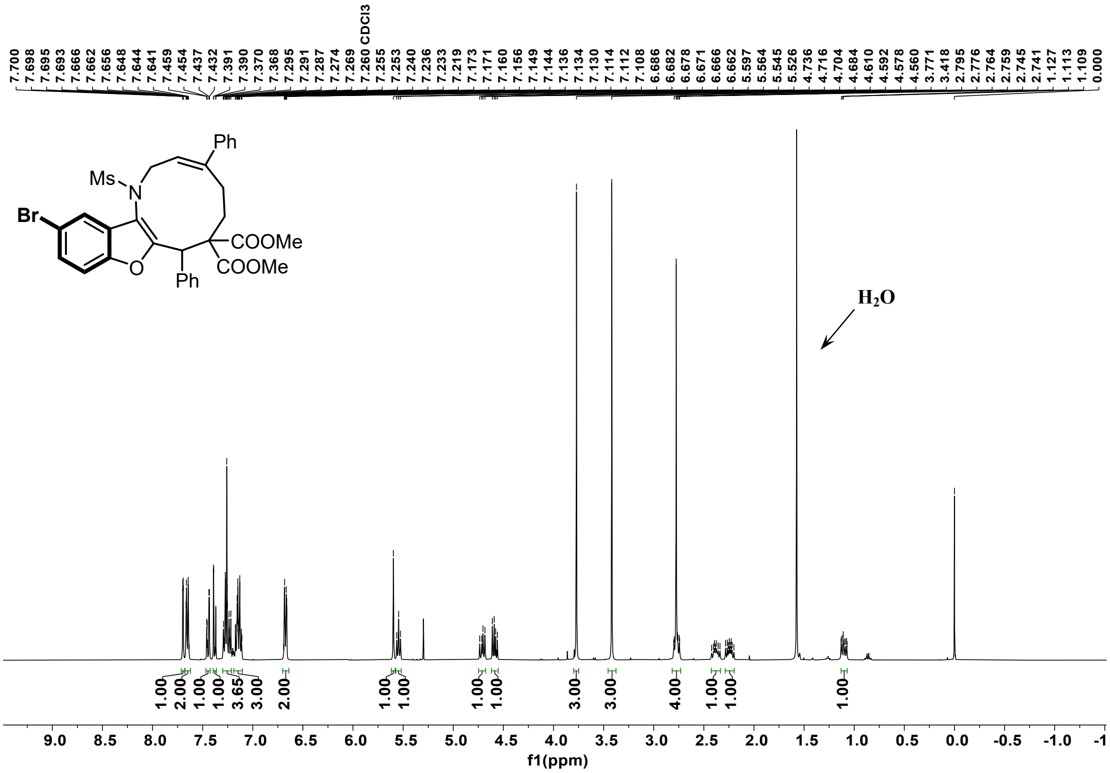
^{1}H NMR of **3aq** in $CDCl_3$ (400 MHz)



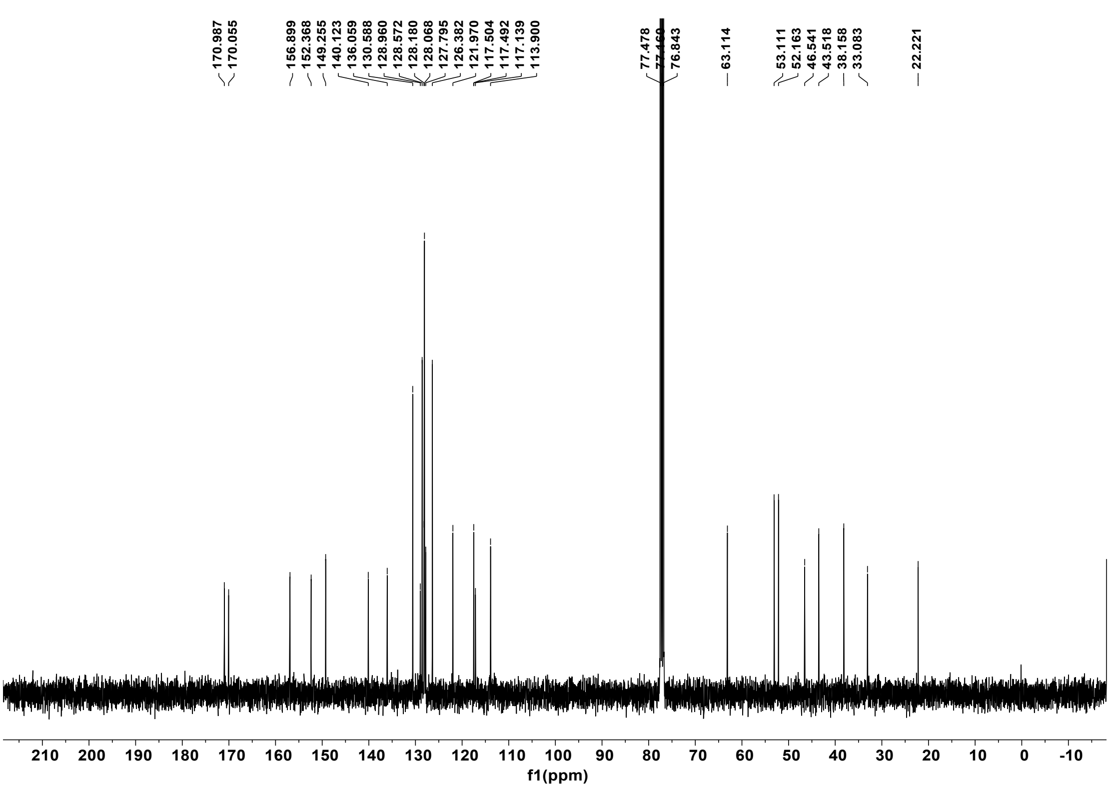
^{13}C NMR of **3aq** in $CDCl_3$ (101 MHz)



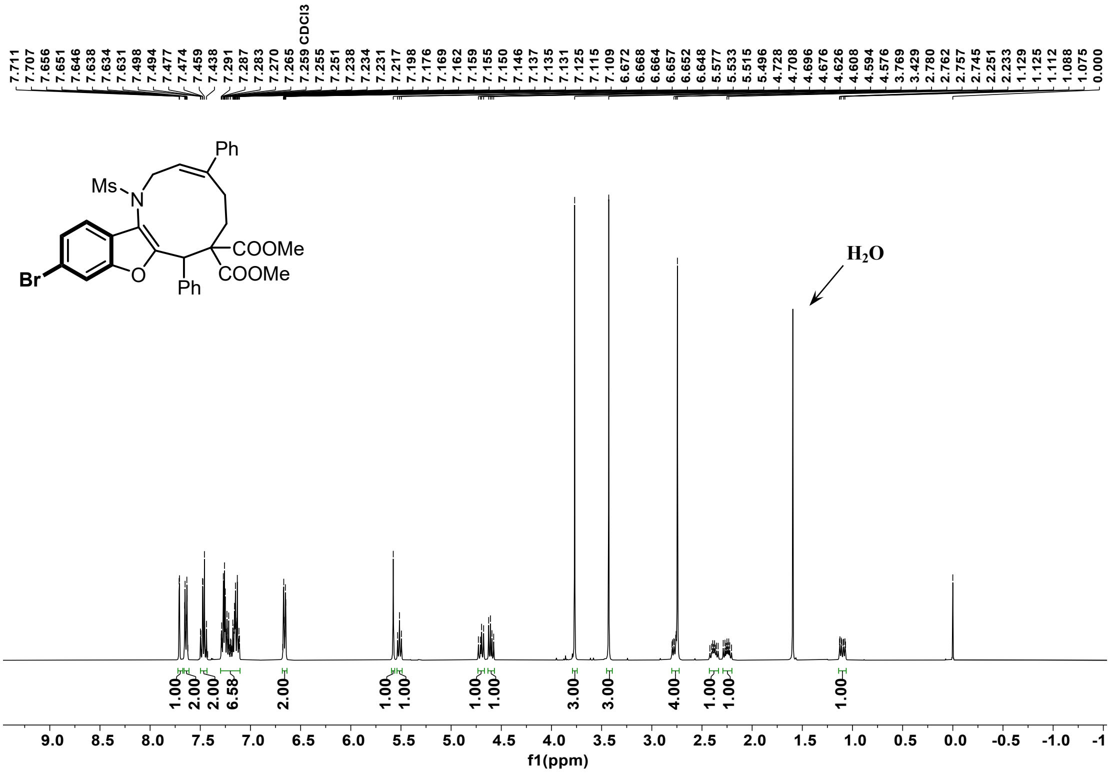
^{1}H NMR of **3ar** in $CDCl_3$ (400 MHz)



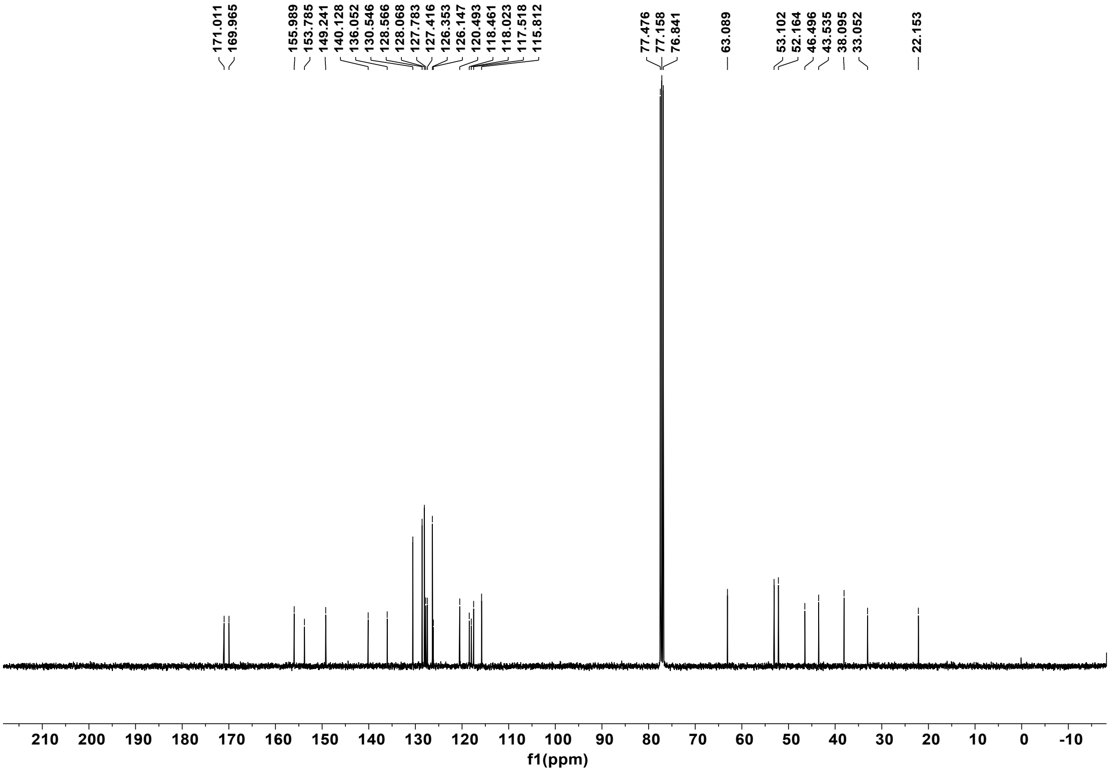
^{13}C NMR of **3ar** in $CDCl_3$ (101 MHz)



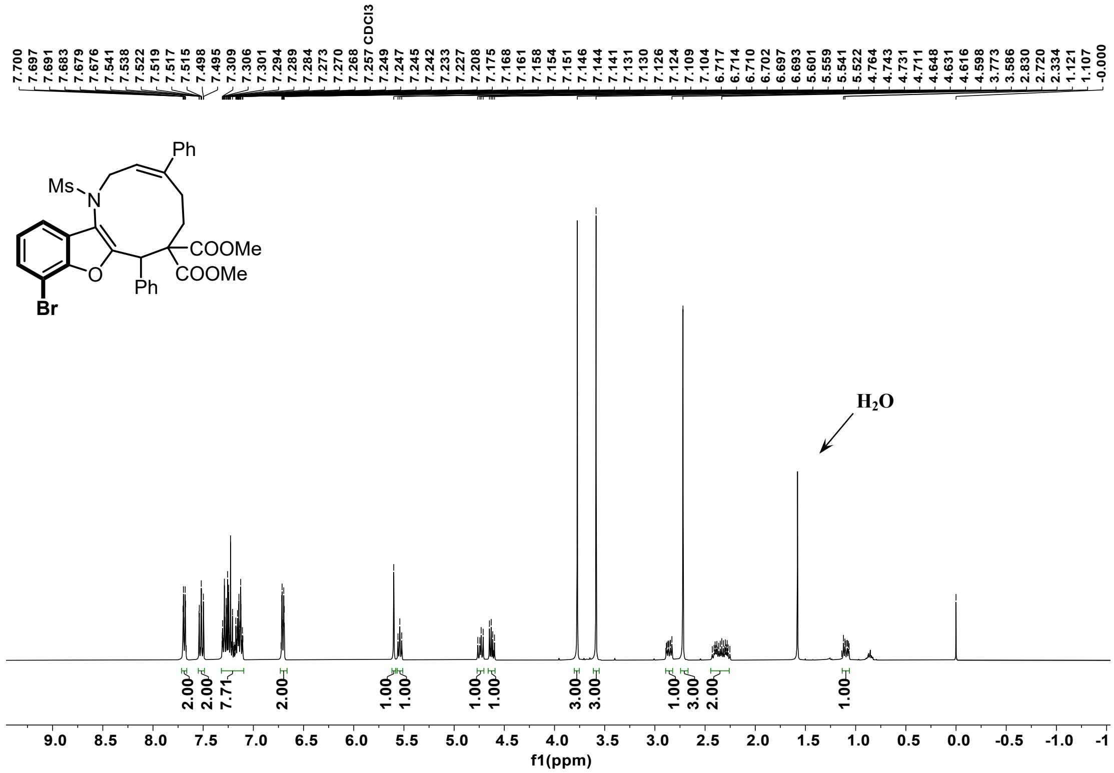
^{1}H NMR of **3as** in $CDCl_3$ (400 MHz)



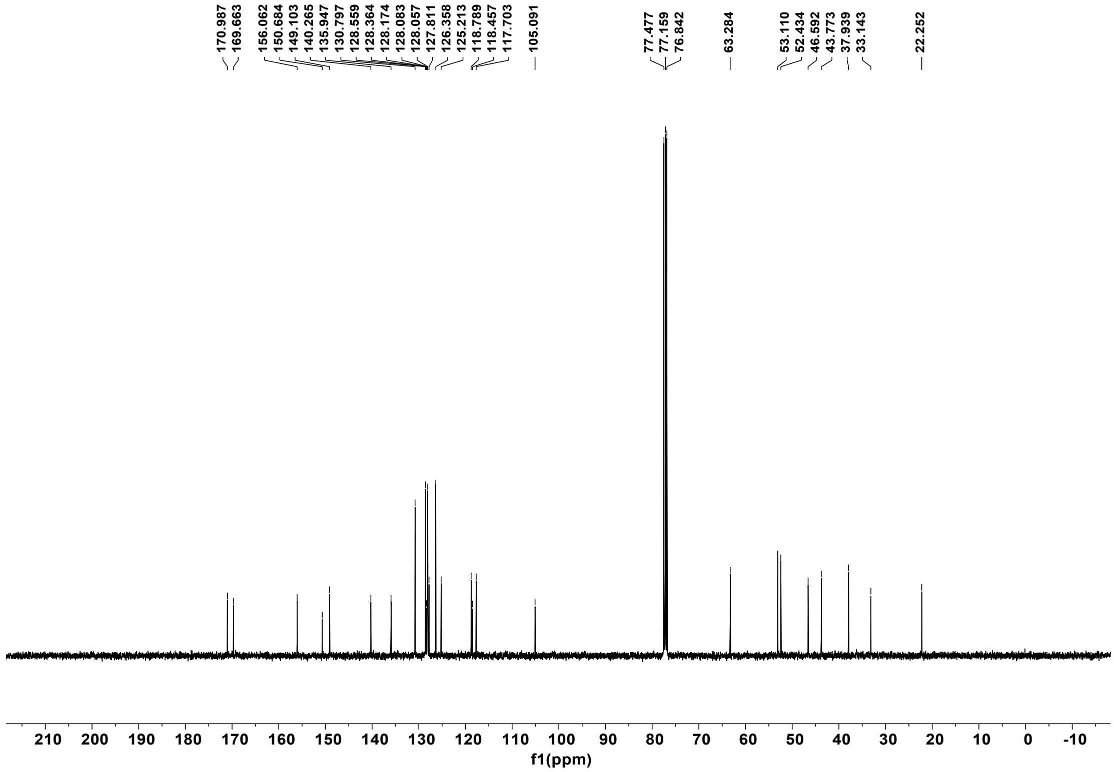
^{13}C NMR of **3as** in $CDCl_3$ (101 MHz)



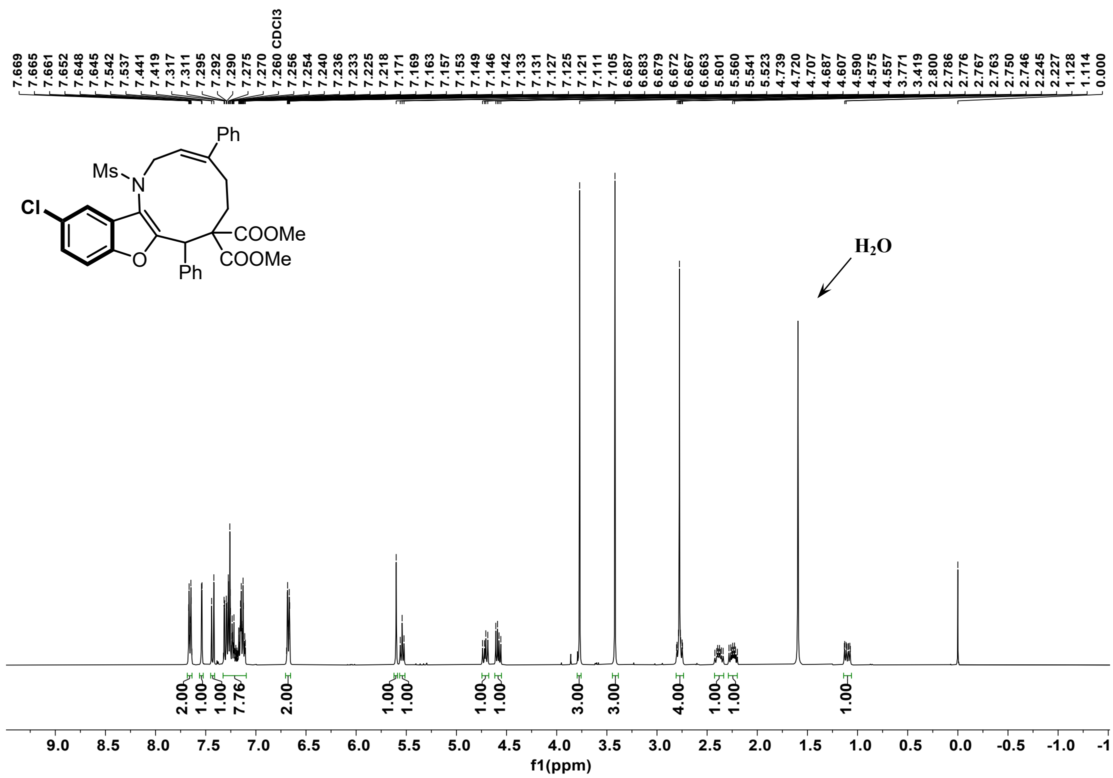
^{1}H NMR of **3at** in $CDCl_3$ (400 MHz)



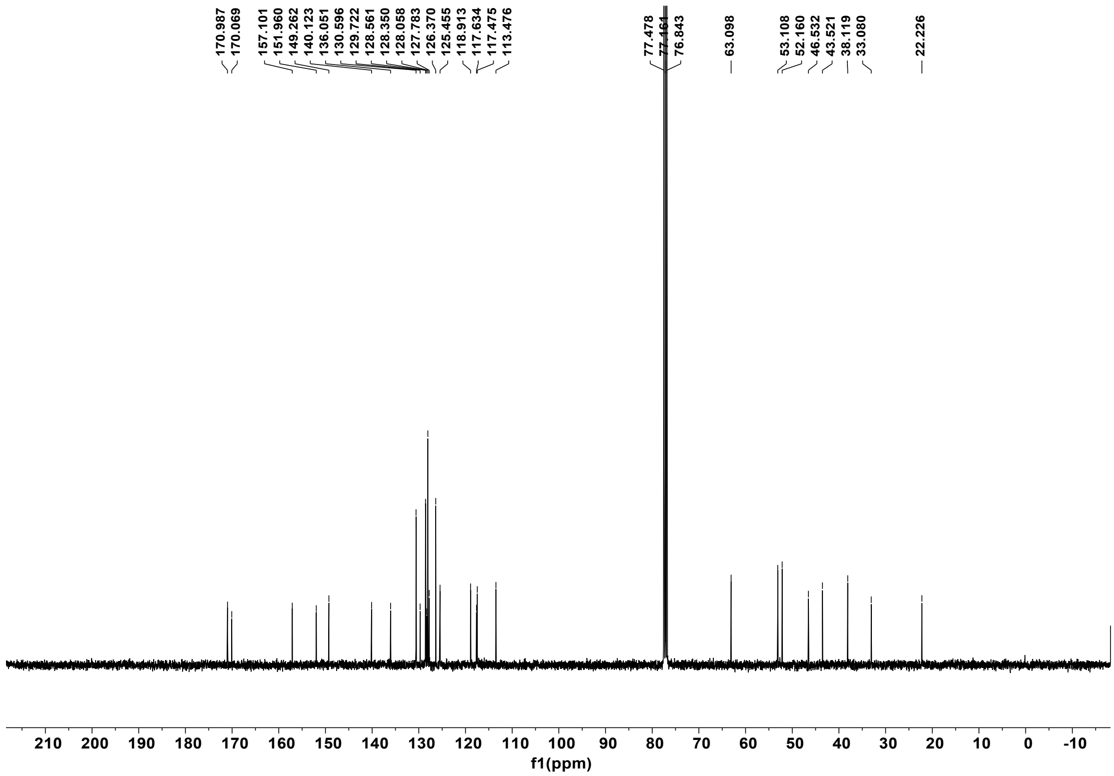
^{13}C NMR of **3at** in $CDCl_3$ (101 MHz)



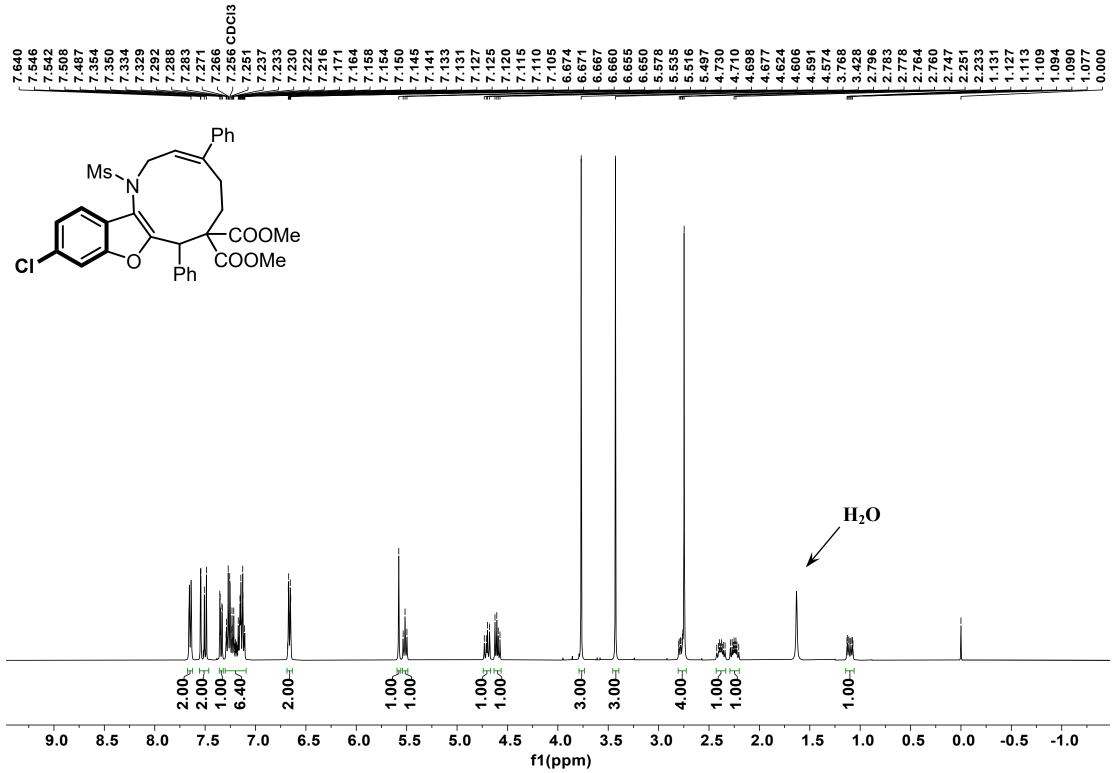
^1H NMR of **3au** in $CDCl_3$ (400 MHz)



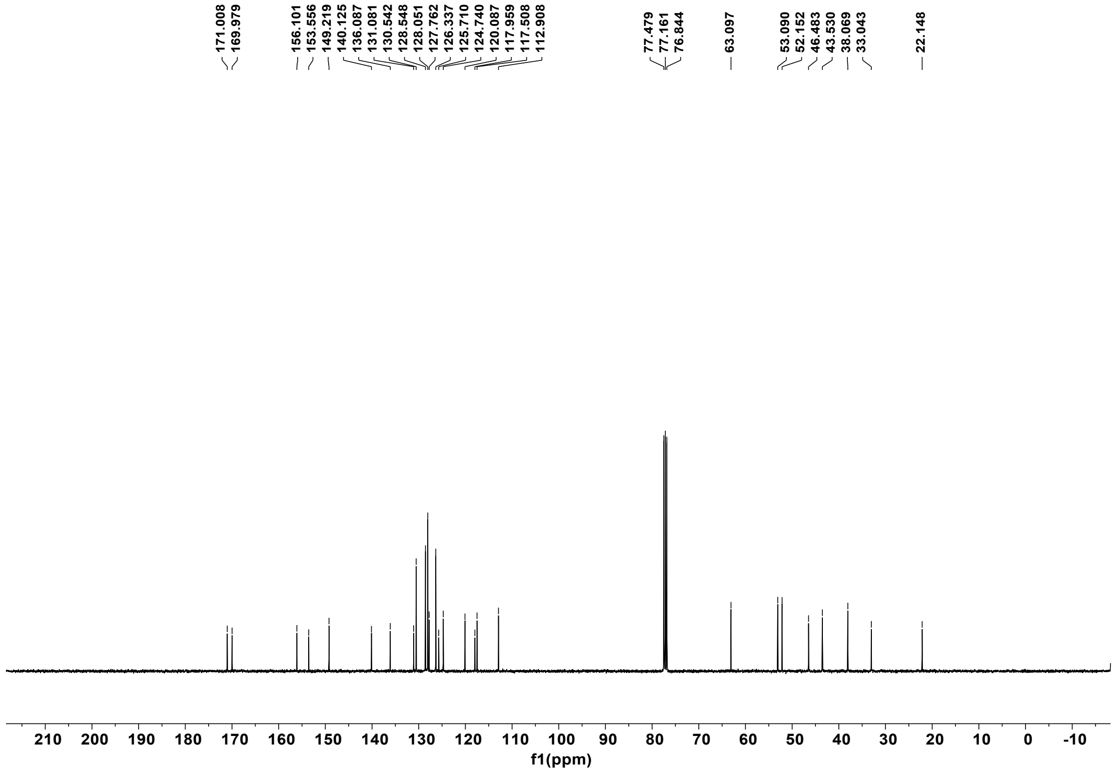
^{13}C NMR of **3au** in $CDCl_3$ (101 MHz)



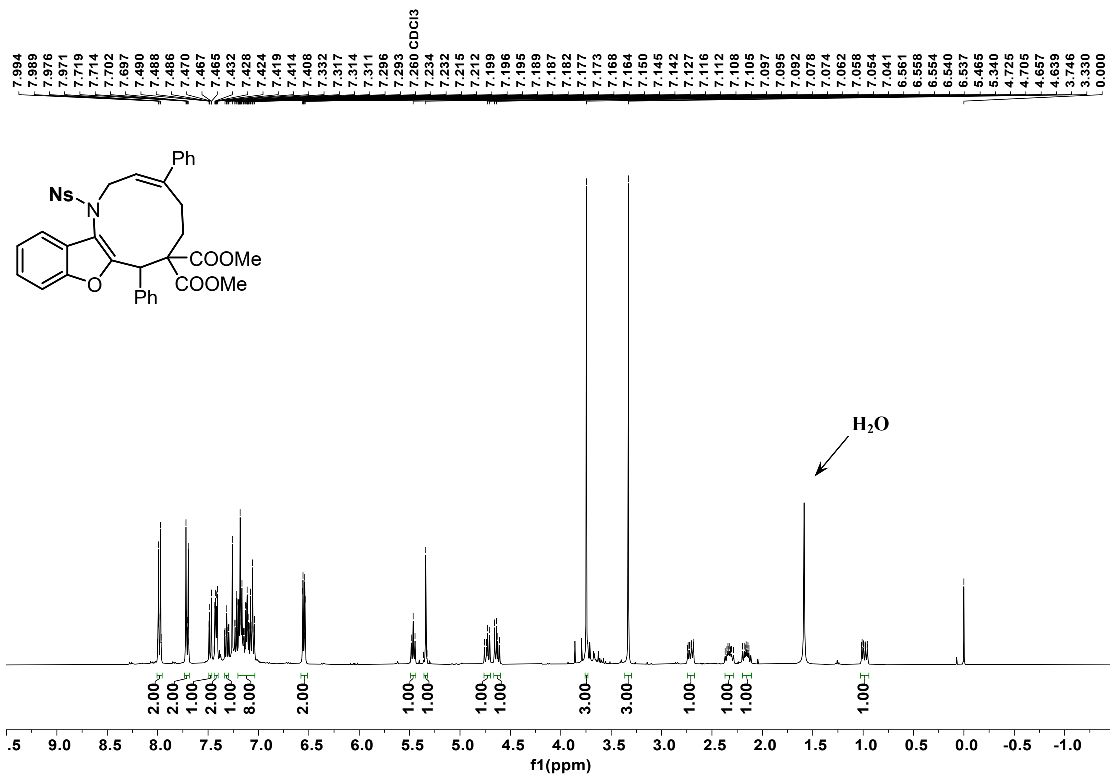
^{1}H NMR of **3av** in $CDCl_3$ (400 MHz)



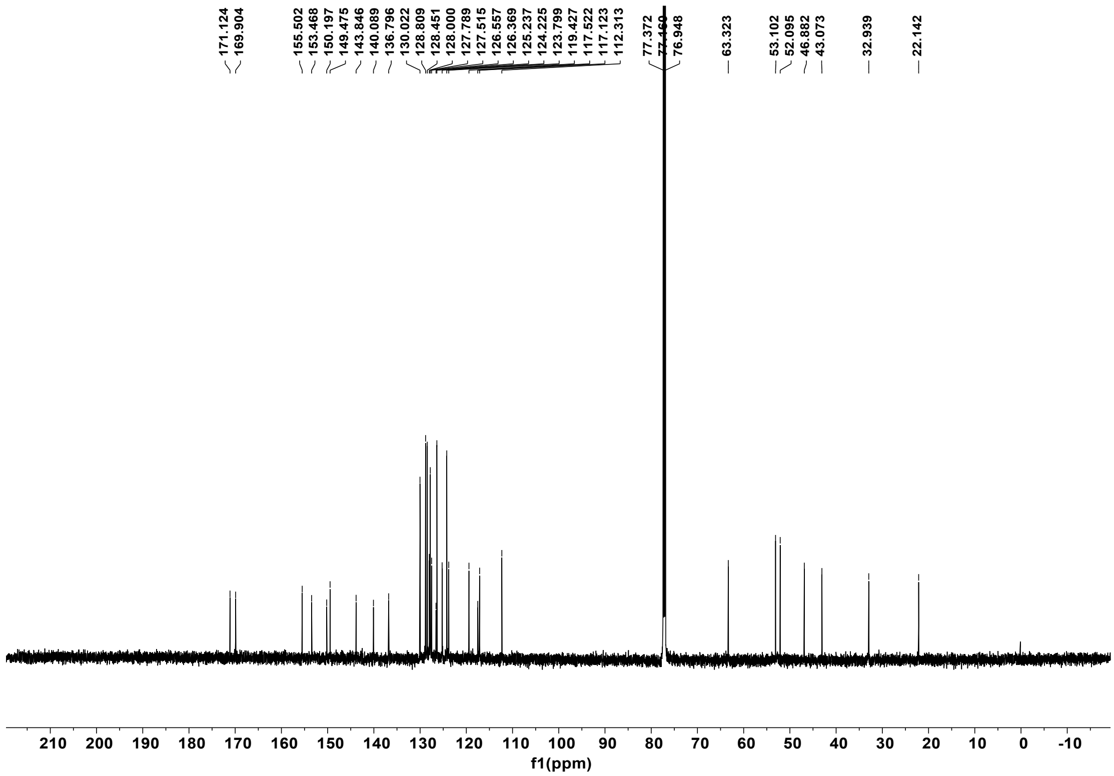
^{13}C NMR of **3av** in $CDCl_3$ (101 MHz)



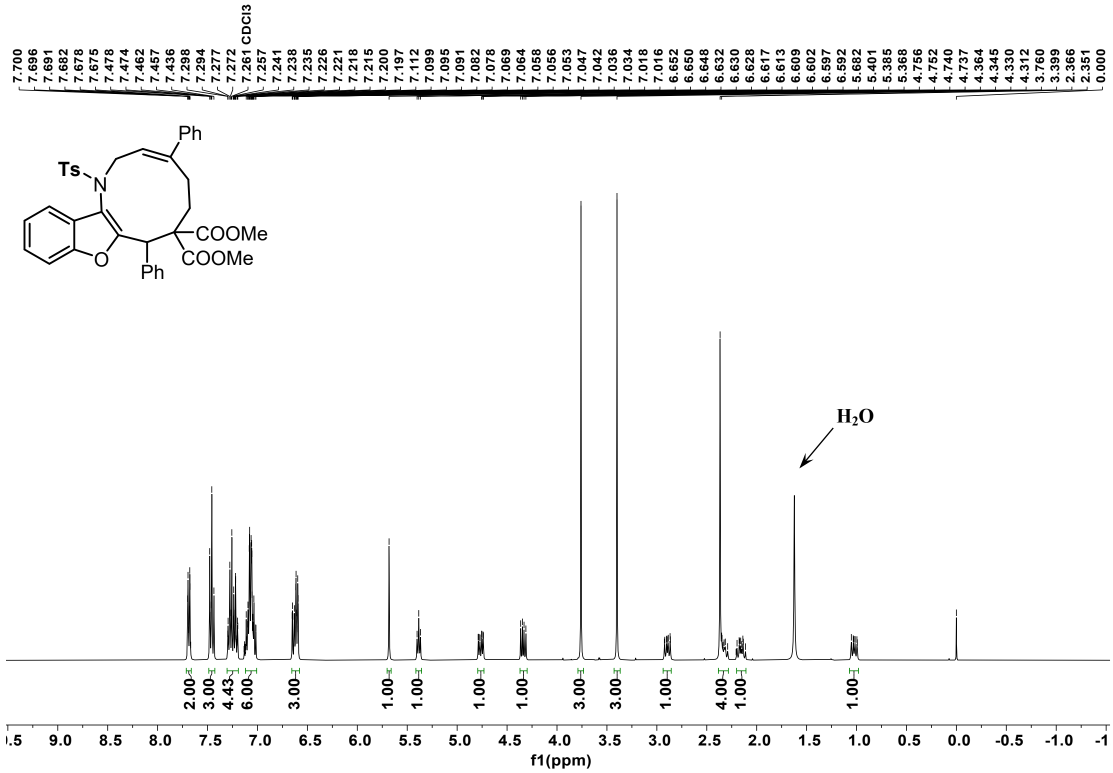
^{1}H NMR of **3aw** in $CDCl_3$ (400 MHz)



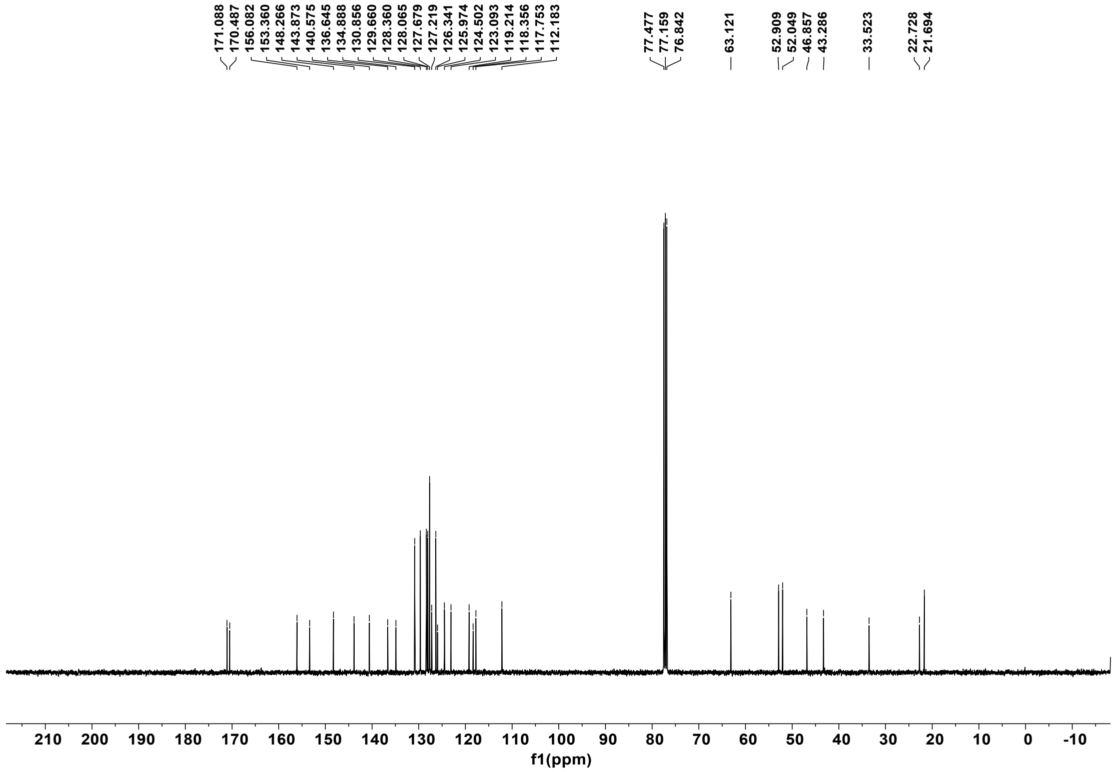
^{13}C NMR of **3aw** in $CDCl_3$ (101 MHz)



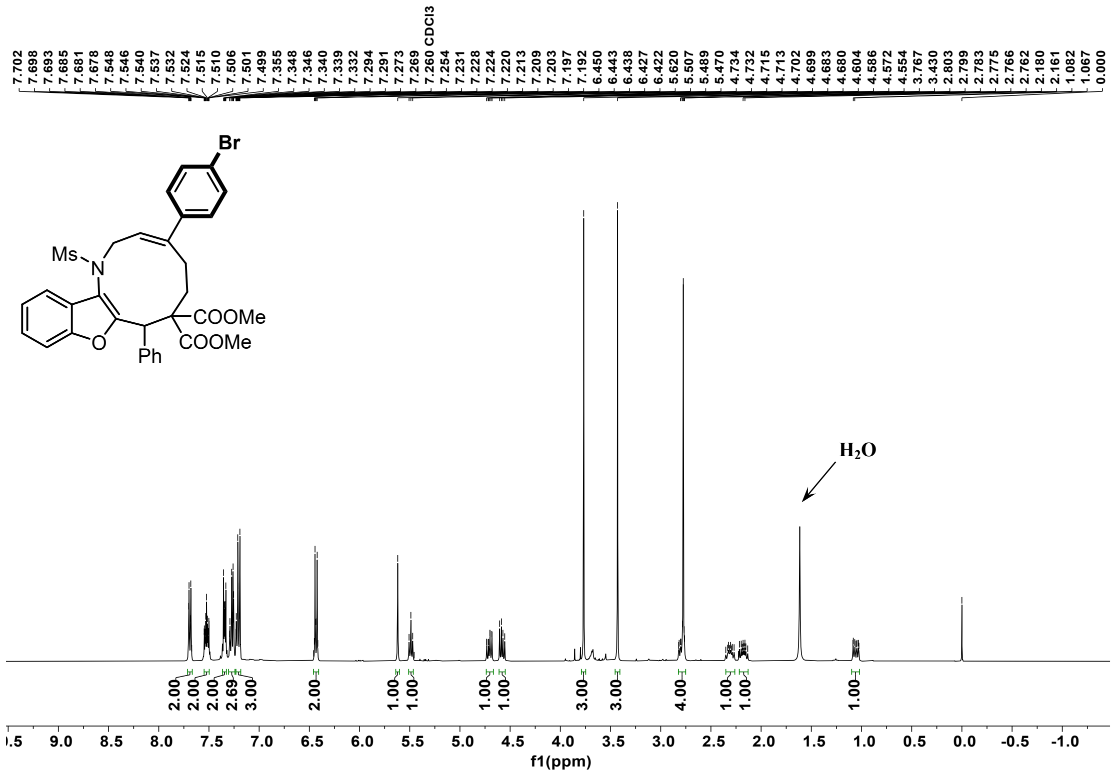
^{1}H NMR of **3ax** in $CDCl_3$ (400 MHz)



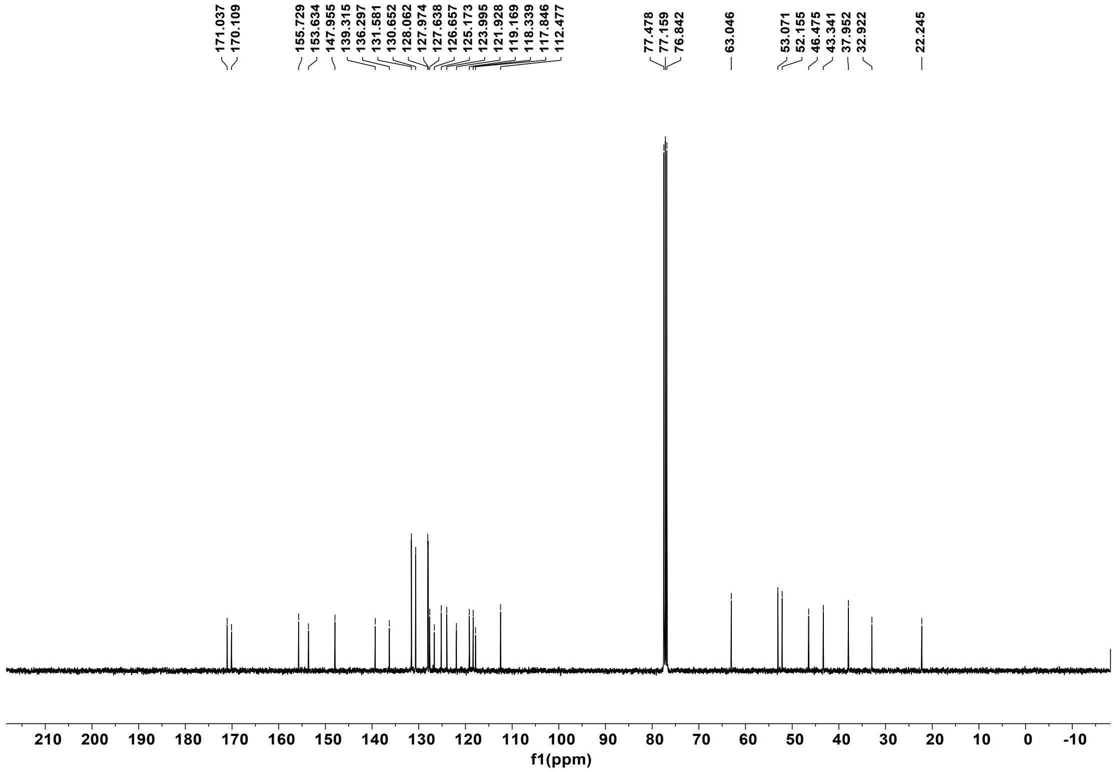
^{13}C NMR of **3ax** in $CDCl_3$ (101 MHz)



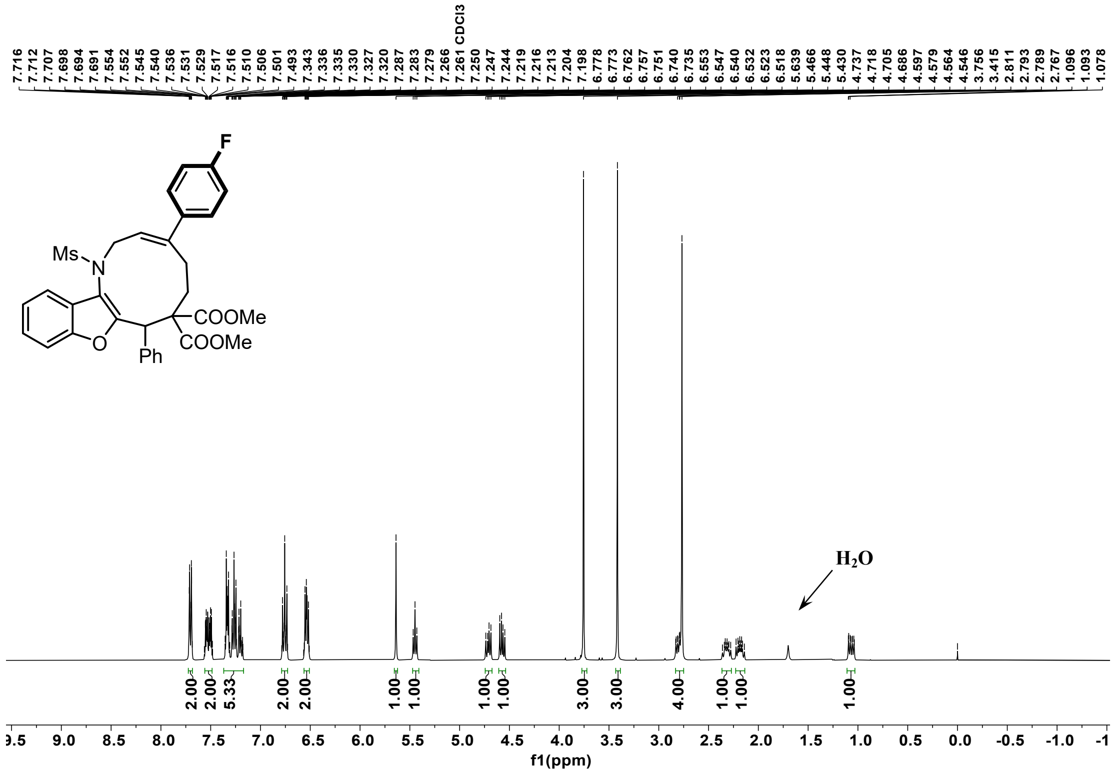
^{1}H NMR of **3ba** in $CDCl_3$ (400 MHz)



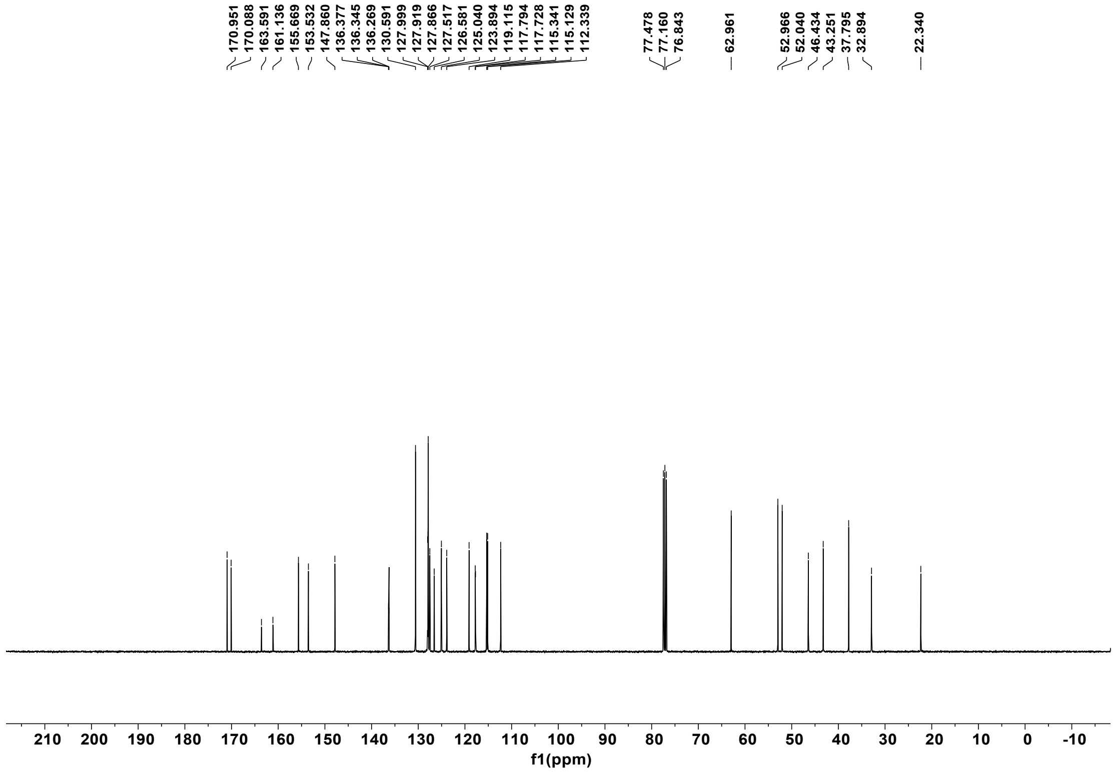
^{13}C NMR of **3ba** in $CDCl_3$ (101 MHz)



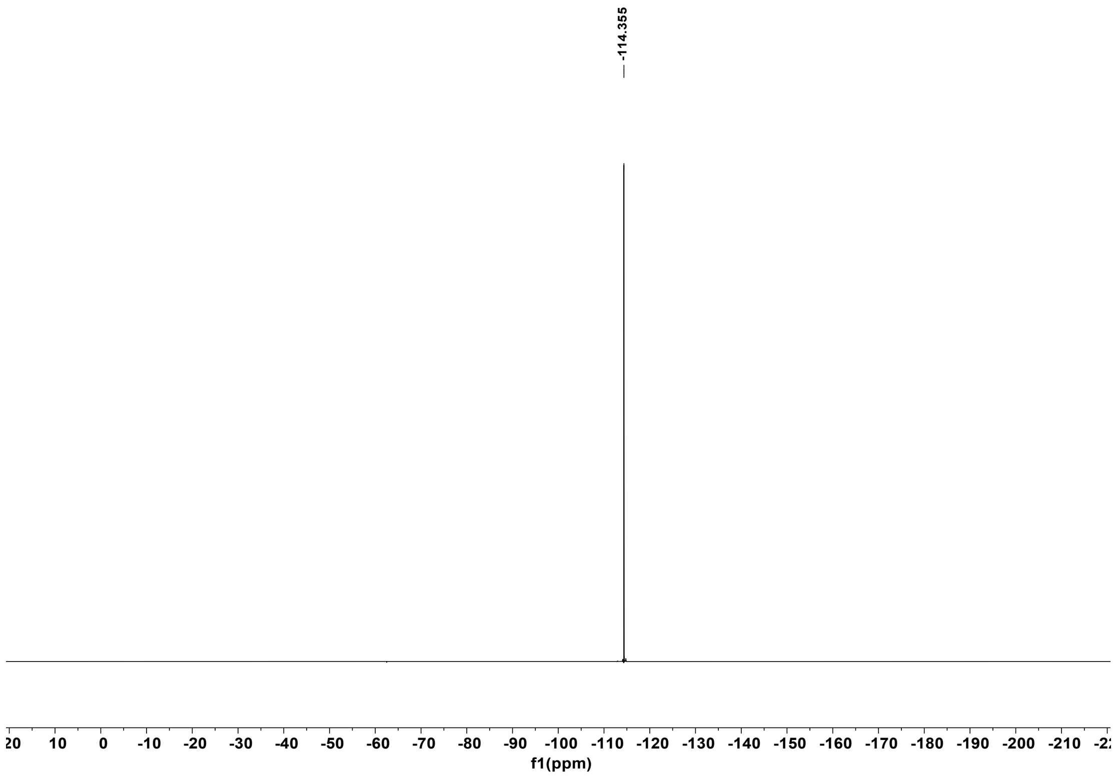
^{1}H NMR of **3ca** in $CDCl_3$ (400 MHz)



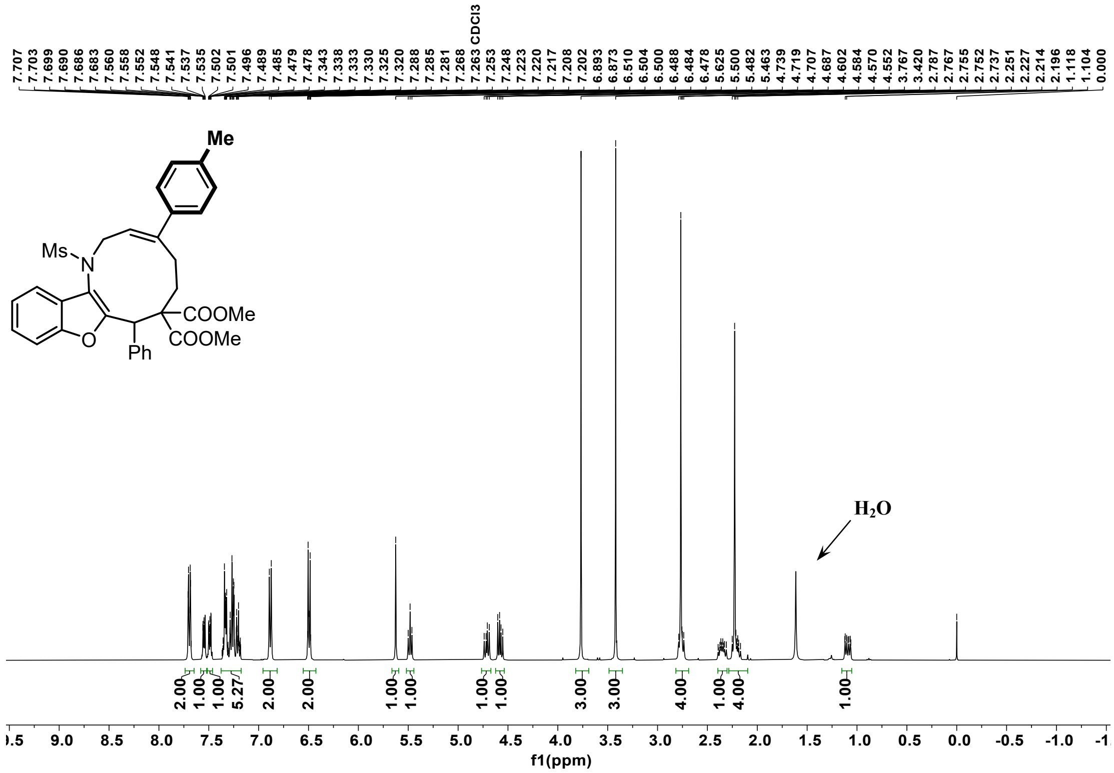
^{13}C NMR of **3ca** in $CDCl_3$ (101 MHz)



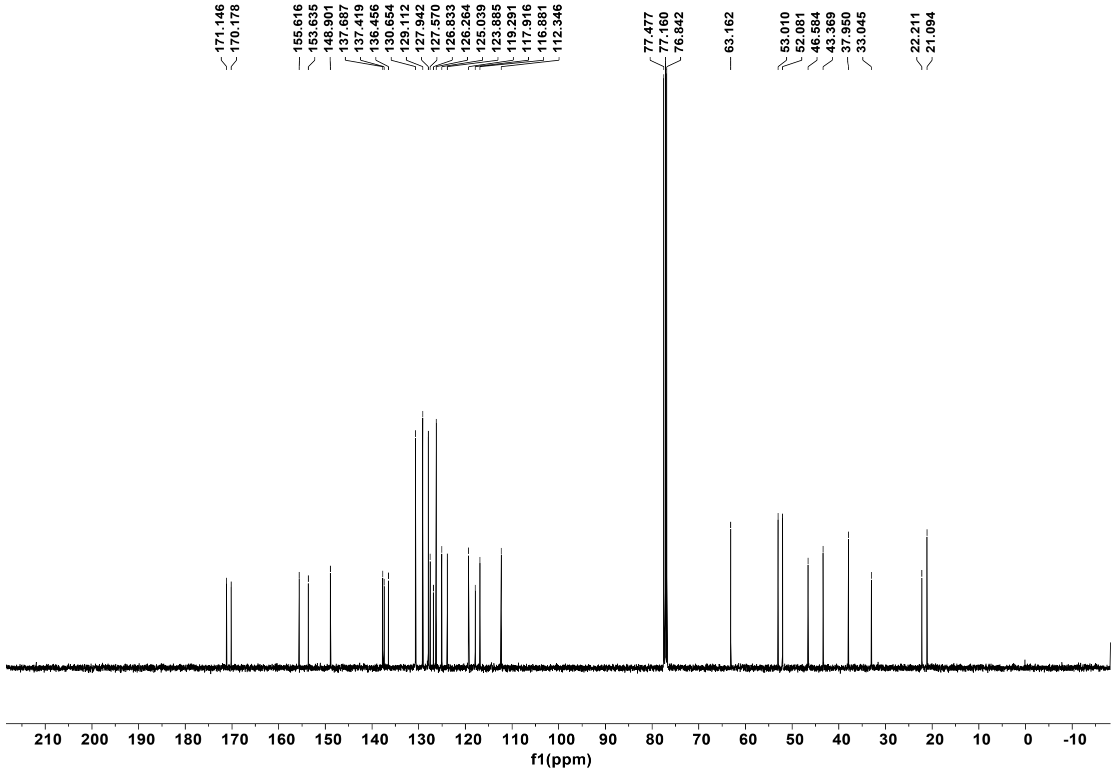
^{19}F NMR of **3ca** in $CDCl_3$ (377 MHz)



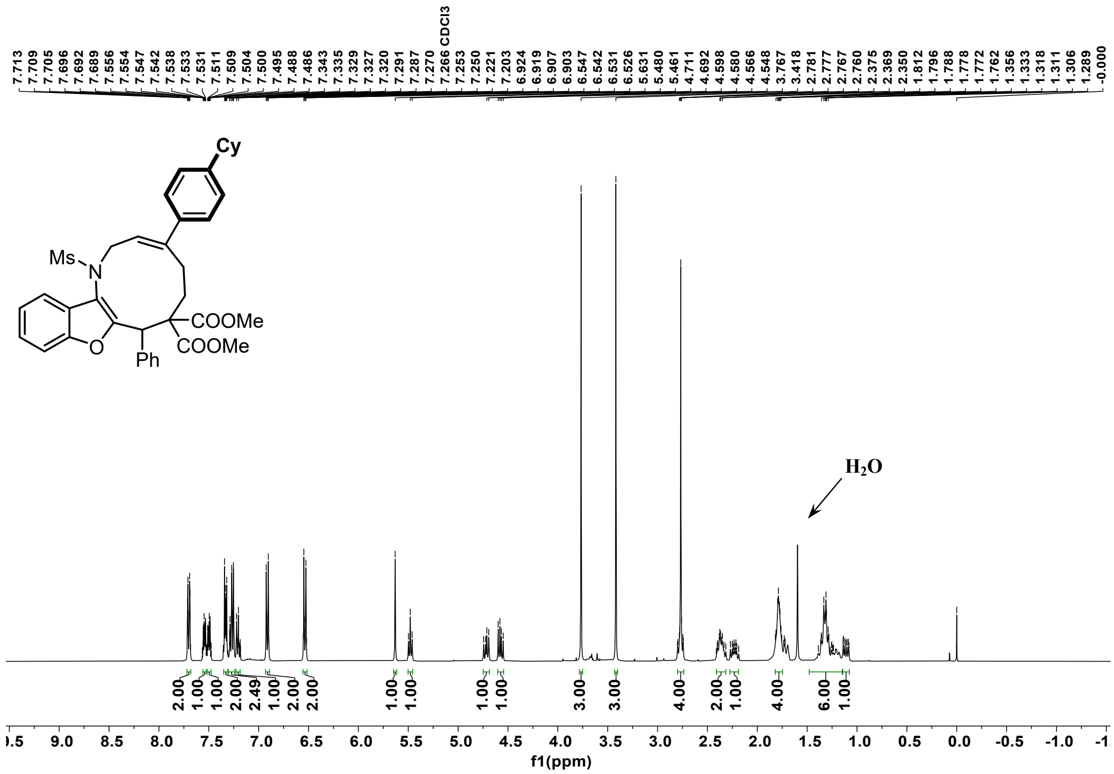
[1]H NMR of **3da** in $CDCl_3$ (400 MHz)



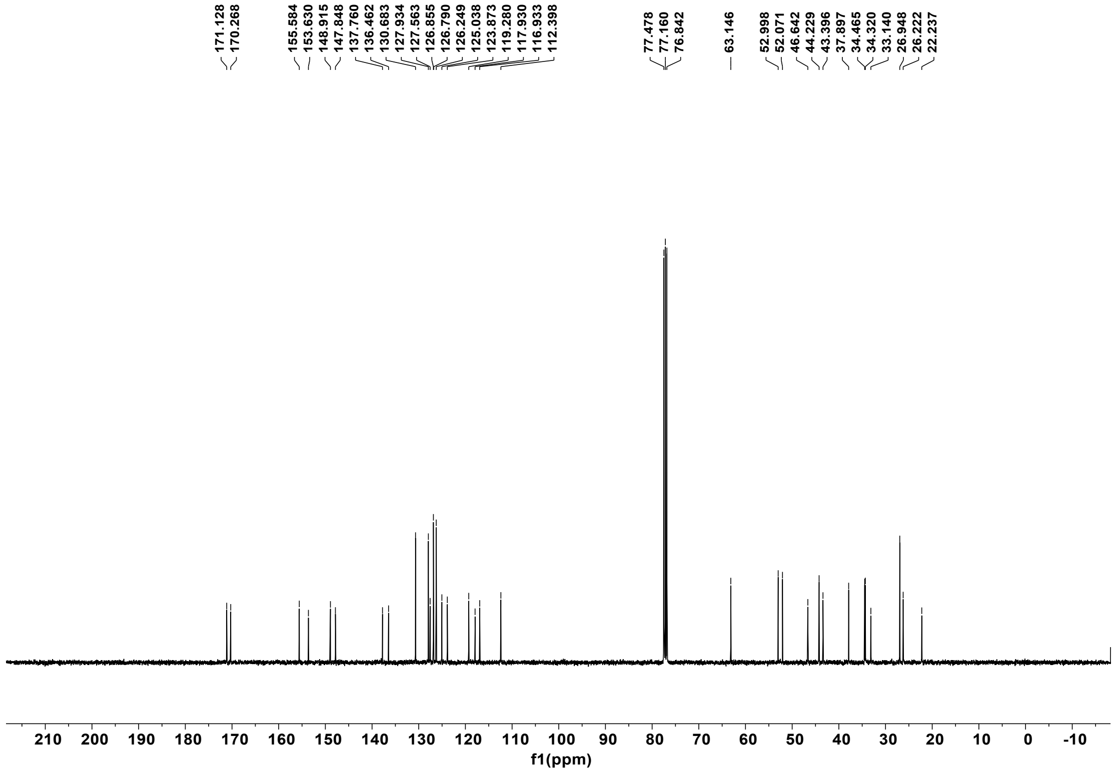
[13]C NMR of **3da** in $CDCl_3$ (101 MHz)



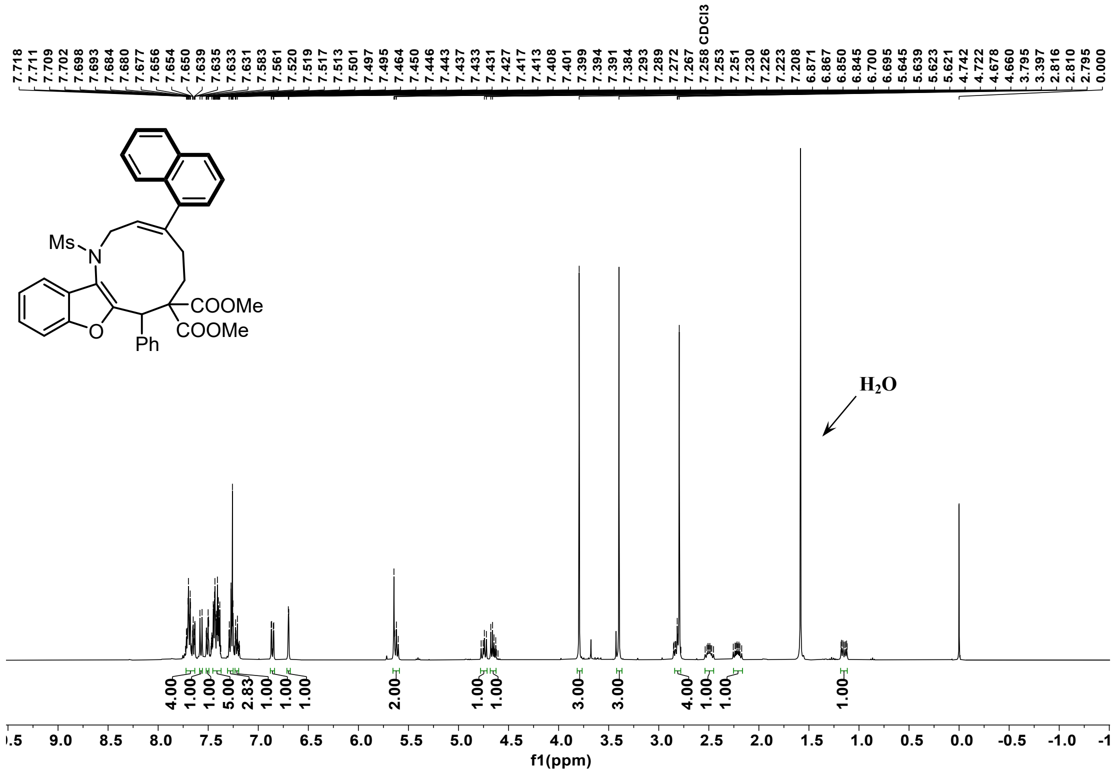
^{1}H NMR of **3ea** in $CDCl_3$ (400 MHz)



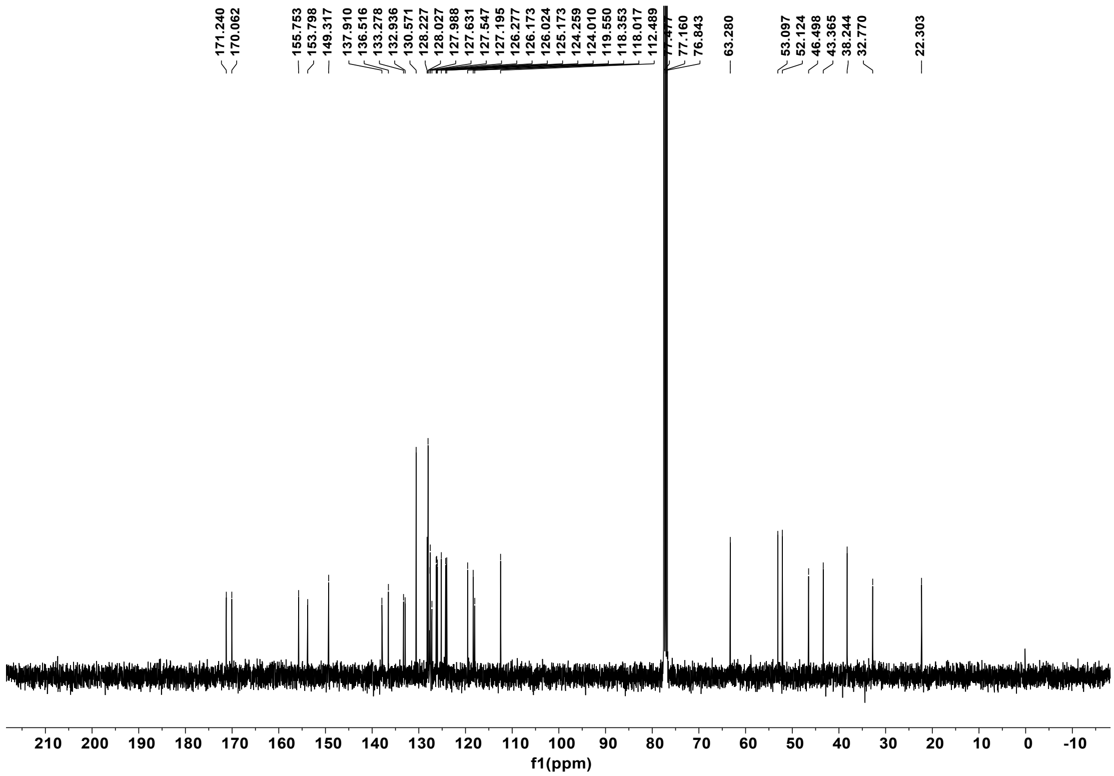
^{13}C NMR of **3ea** in $CDCl_3$ (101 MHz)



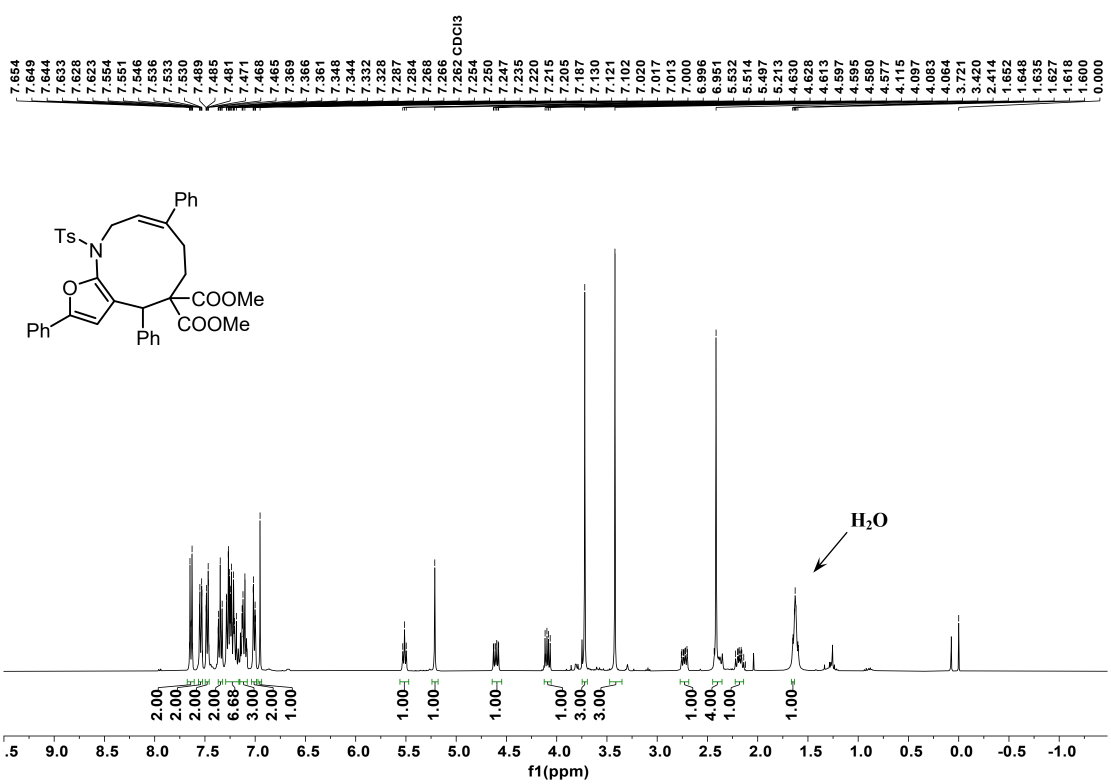
[1]H NMR of **3fa** in $CDCl_3$ (400 MHz)



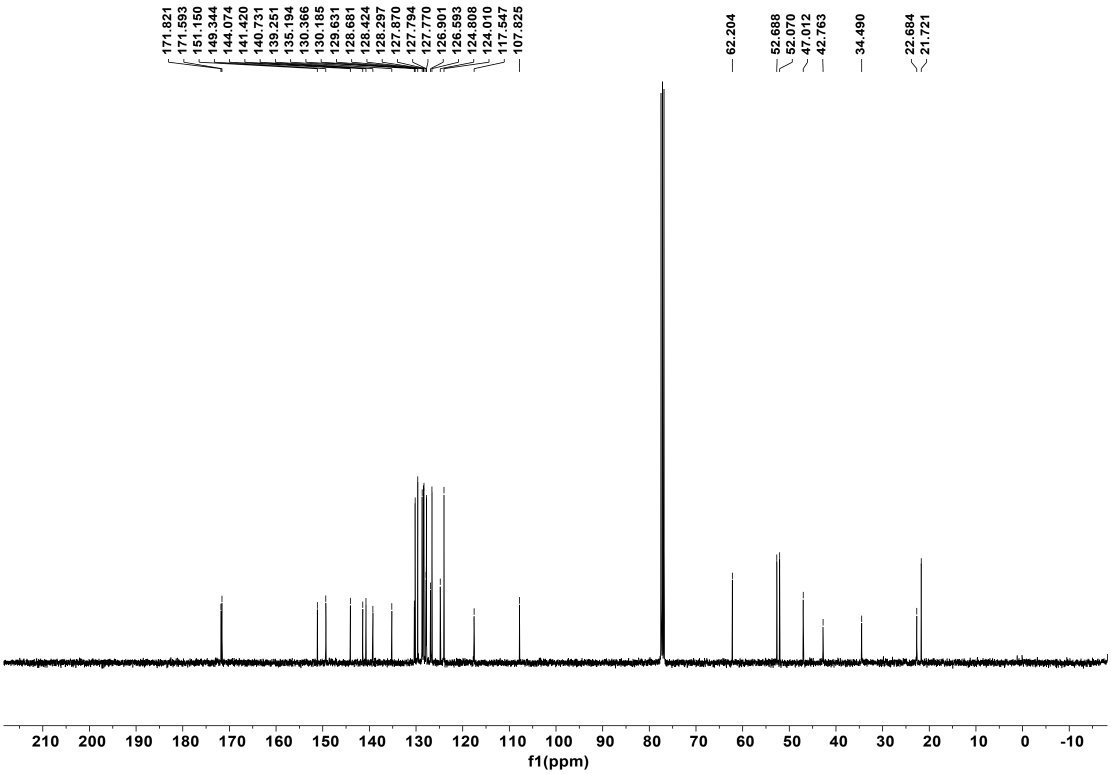
[13]C NMR of **3fa** in $CDCl_3$ (101 MHz)



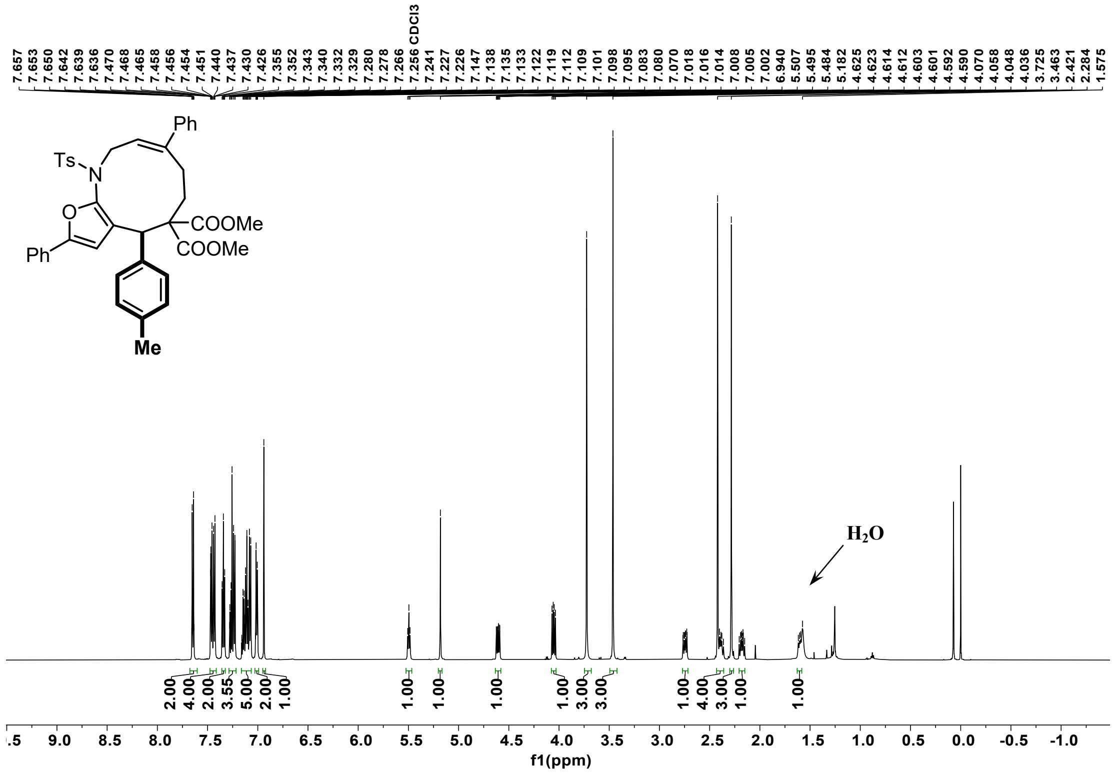
[1]H NMR of **5aa** in $CDCl_3$ (400 MHz)



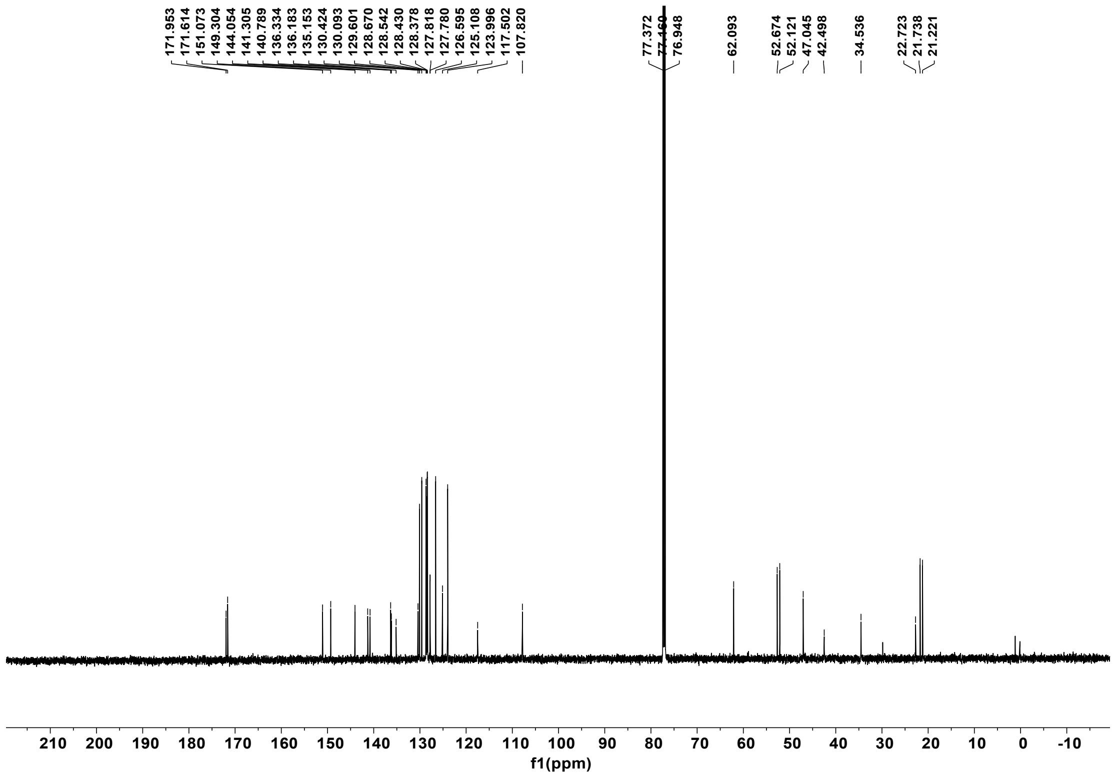
[13]C NMR of **5aa** in $CDCl_3$ (101 MHz)



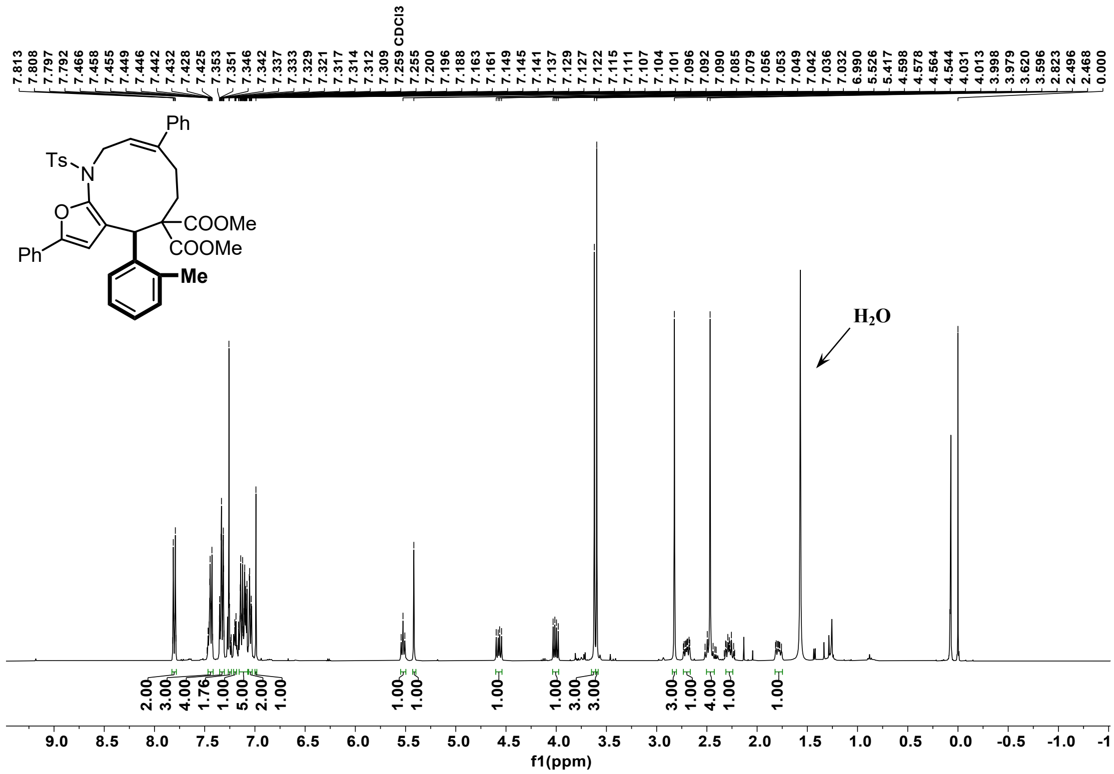
[1]H NMR of **5ab** in $CDCl_3$ (600 MHz)



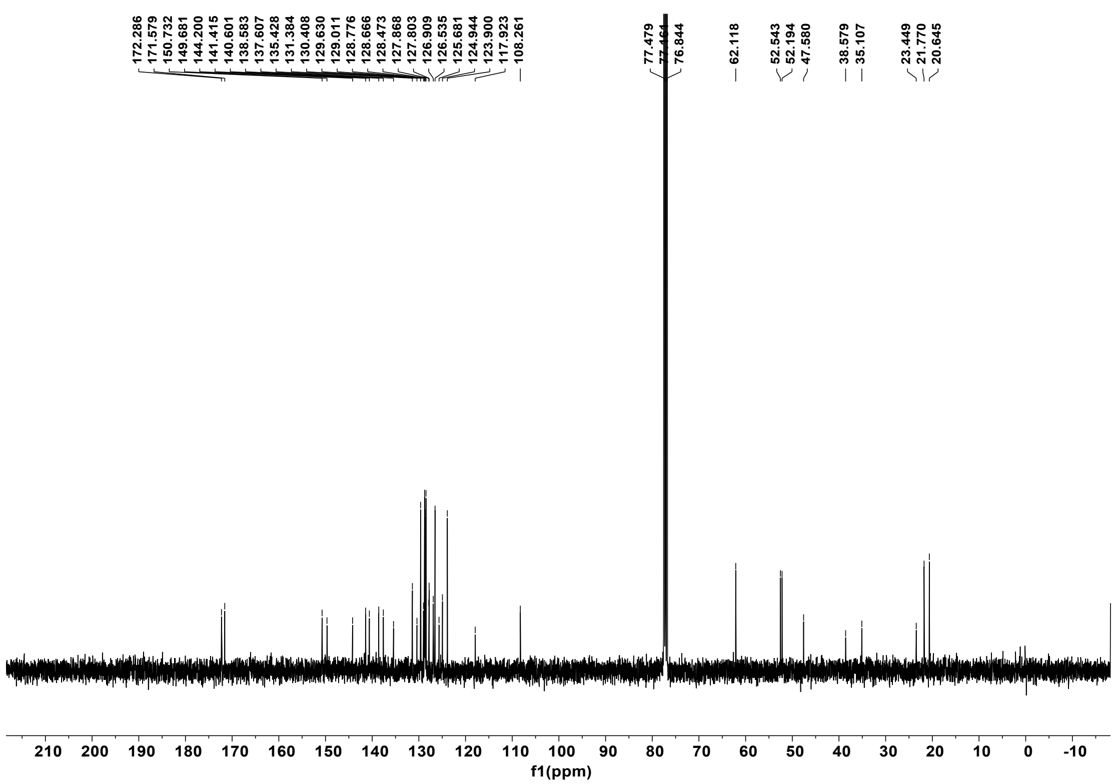
[13]C NMR of 5**ab** in $CDCl_3$ (151 MHz)



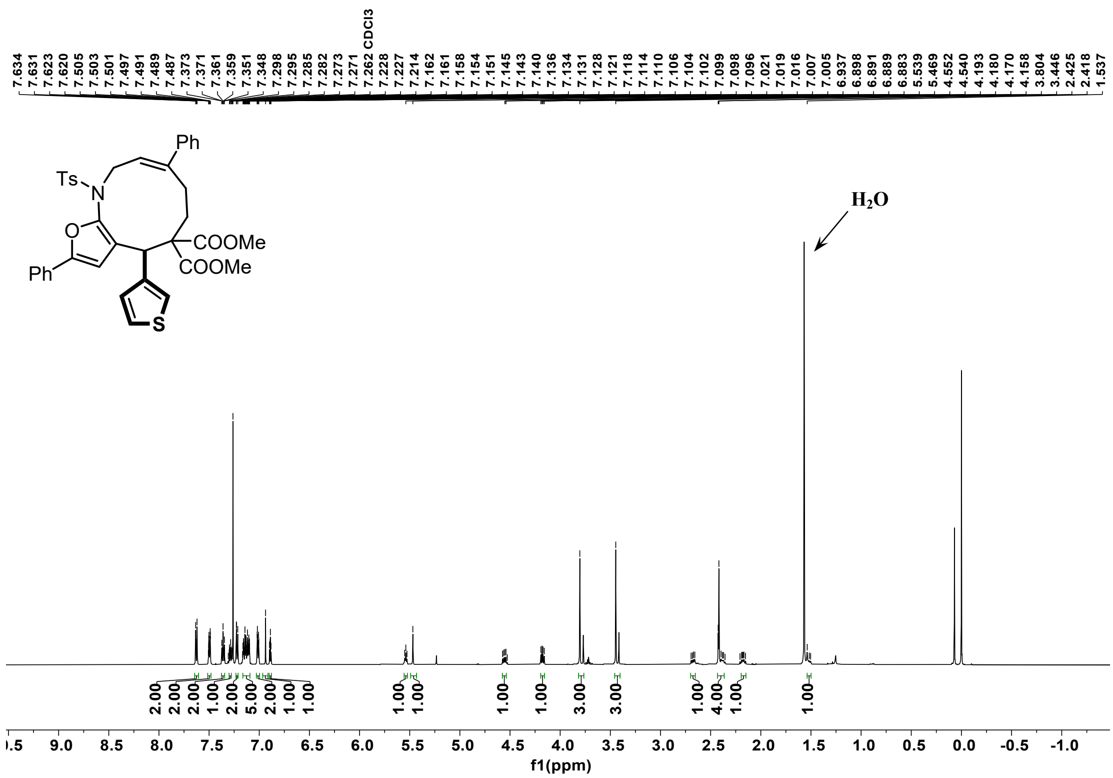
^{1}H NMR of **5ac** in $CDCl_3$ (400 MHz)



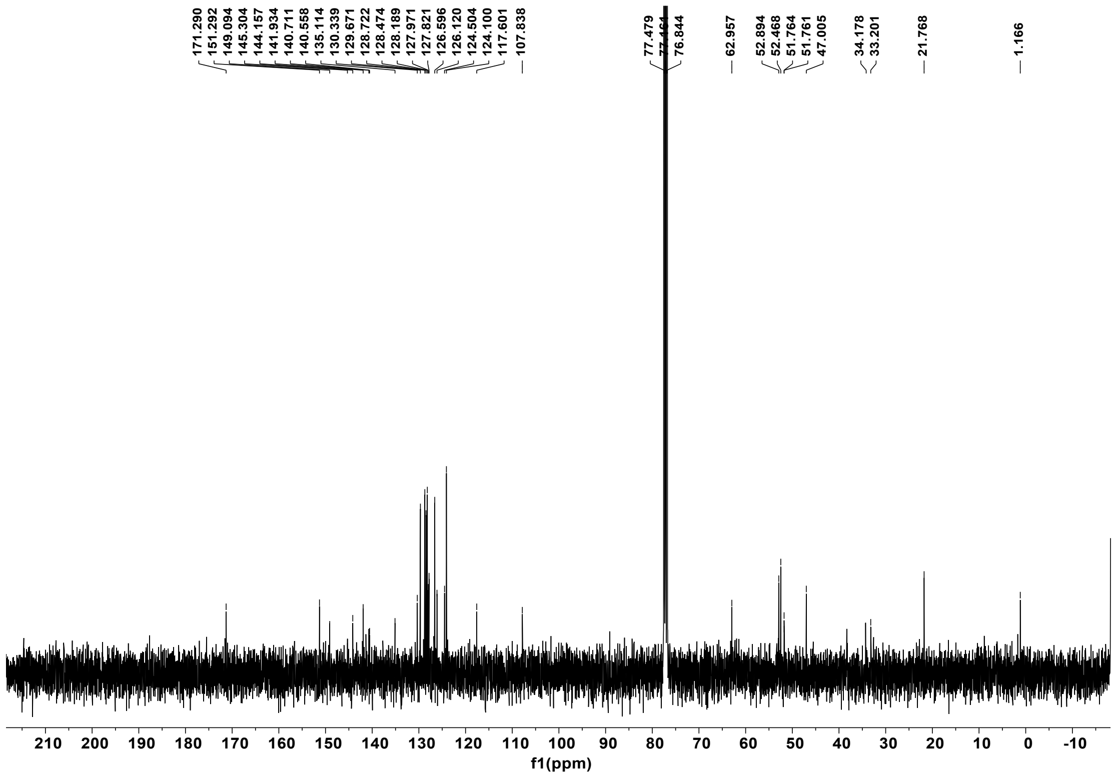
^{13}C NMR of **5ac** in $CDCl_3$ (101 MHz)



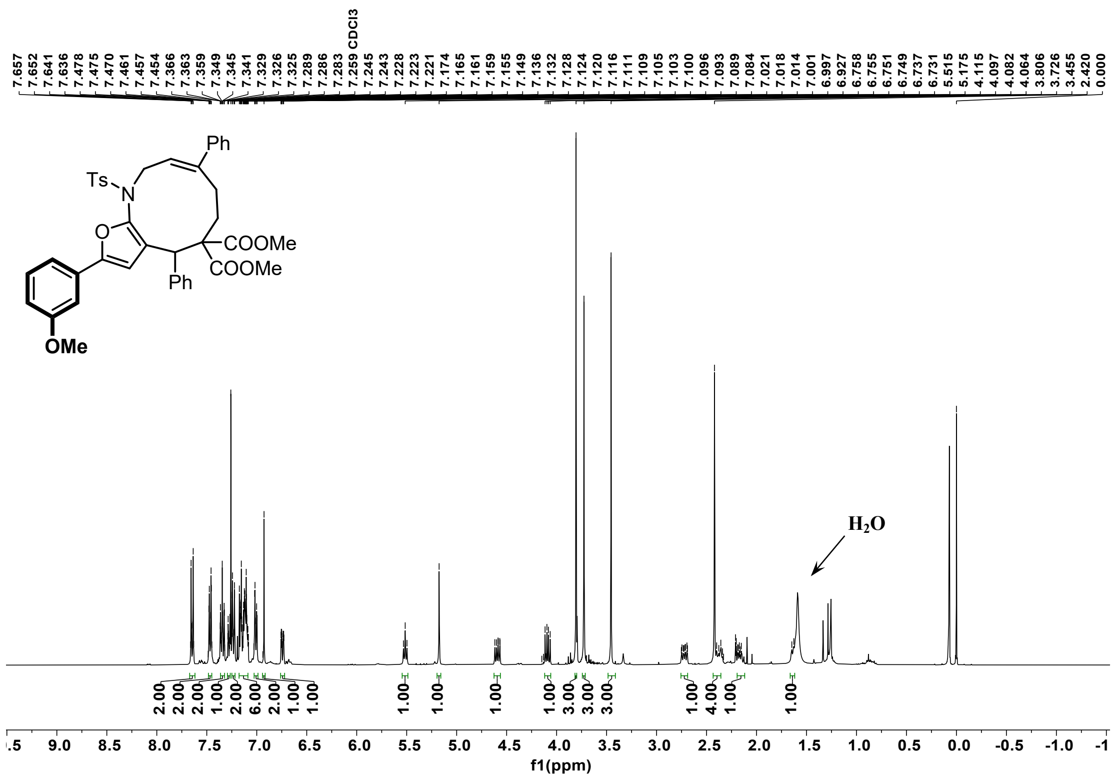
[1]H NMR of **5ad** in $CDCl_3$ (400 MHz)



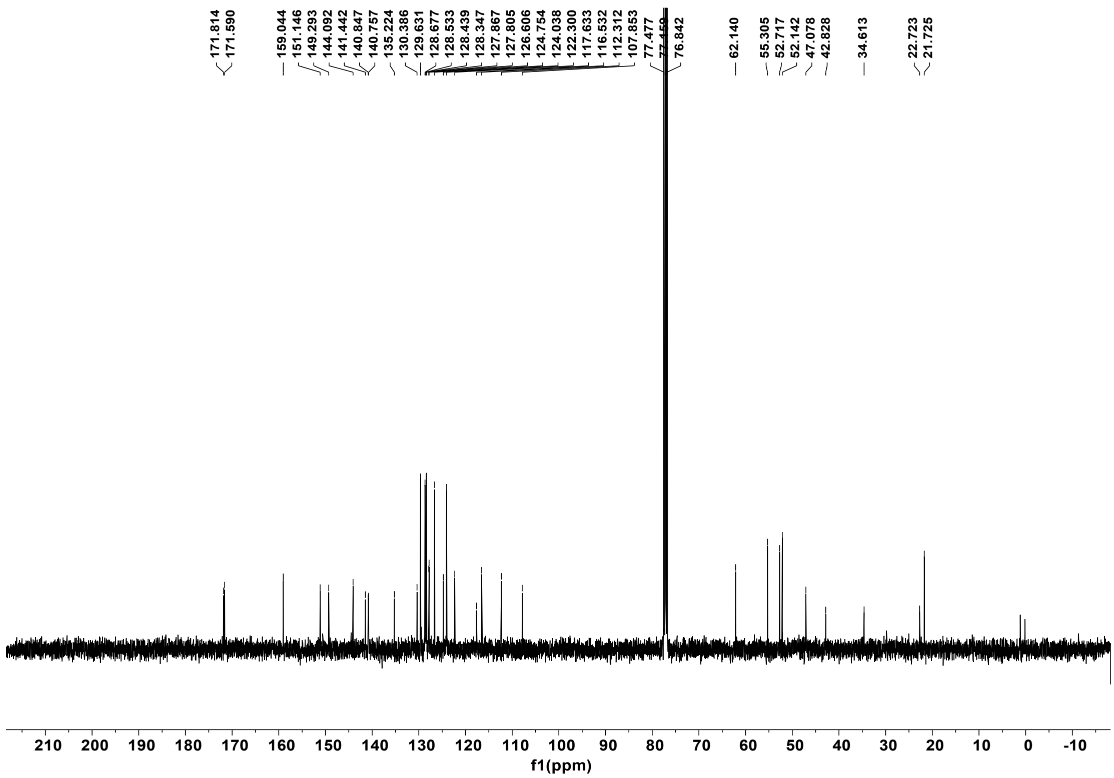
[13]C NMR of **5ad** in $CDCl_3$ (101 MHz)



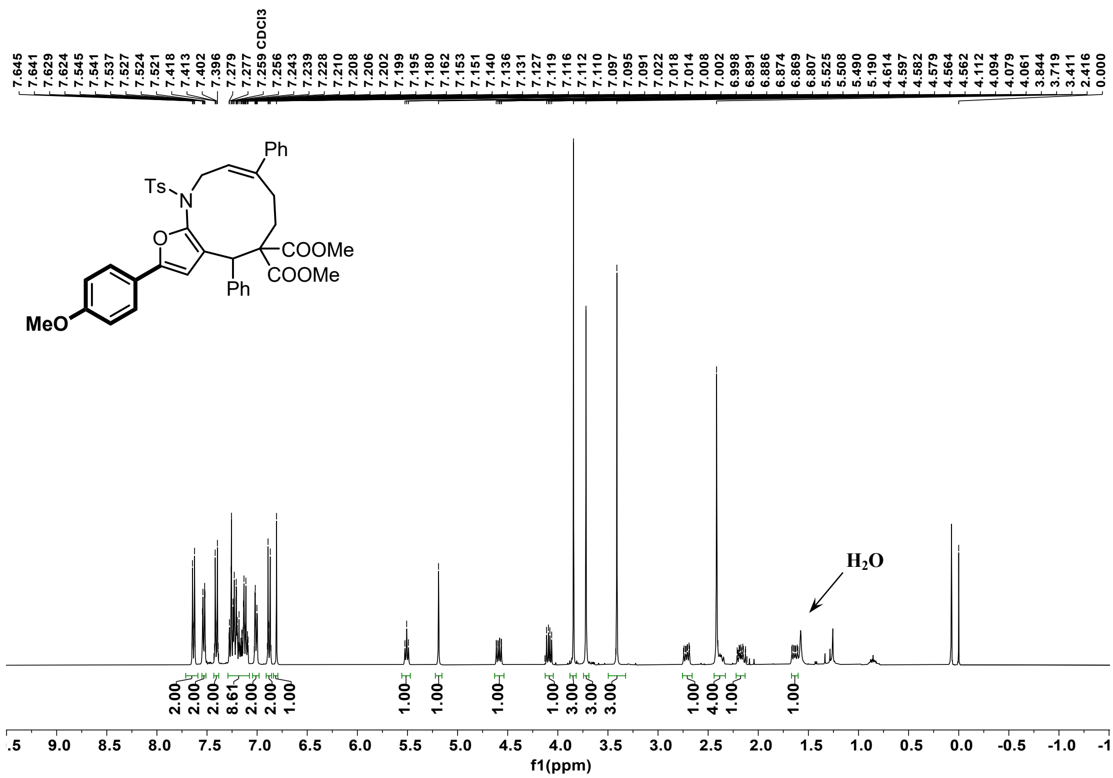
[1]H NMR of **5ae** in $CDCl_3$ (400 MHz)



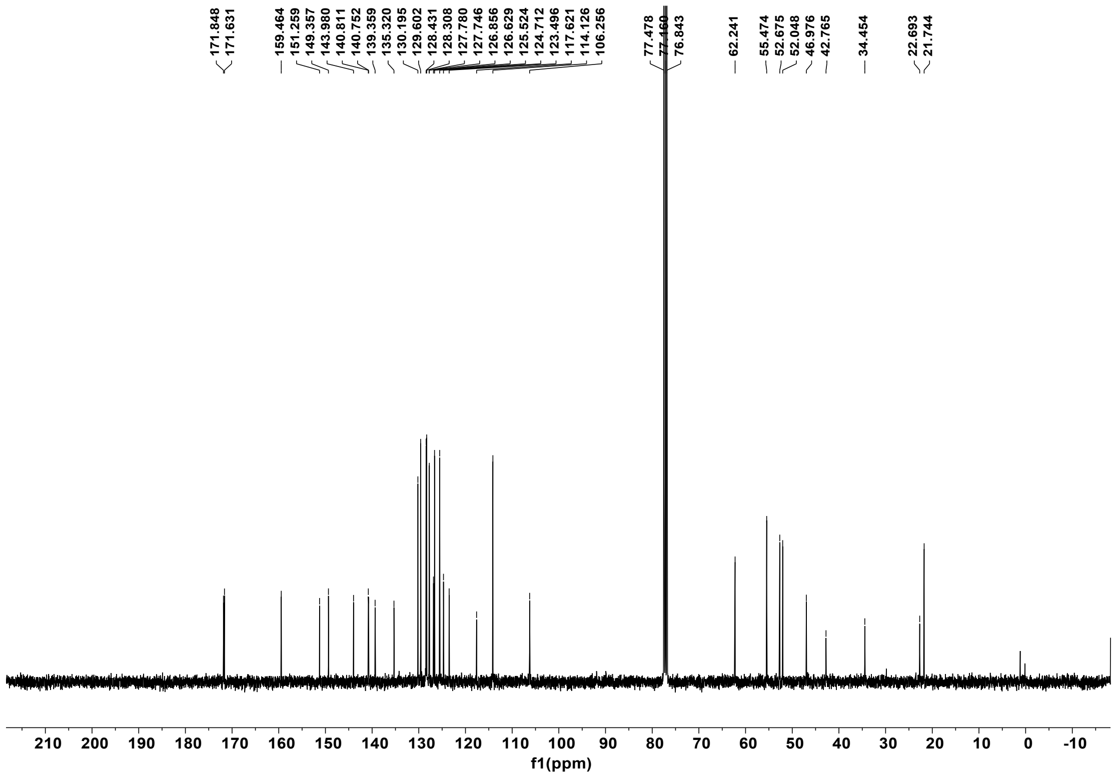
[13]C NMR of **5ae** in $CDCl_3$ (101 MHz)



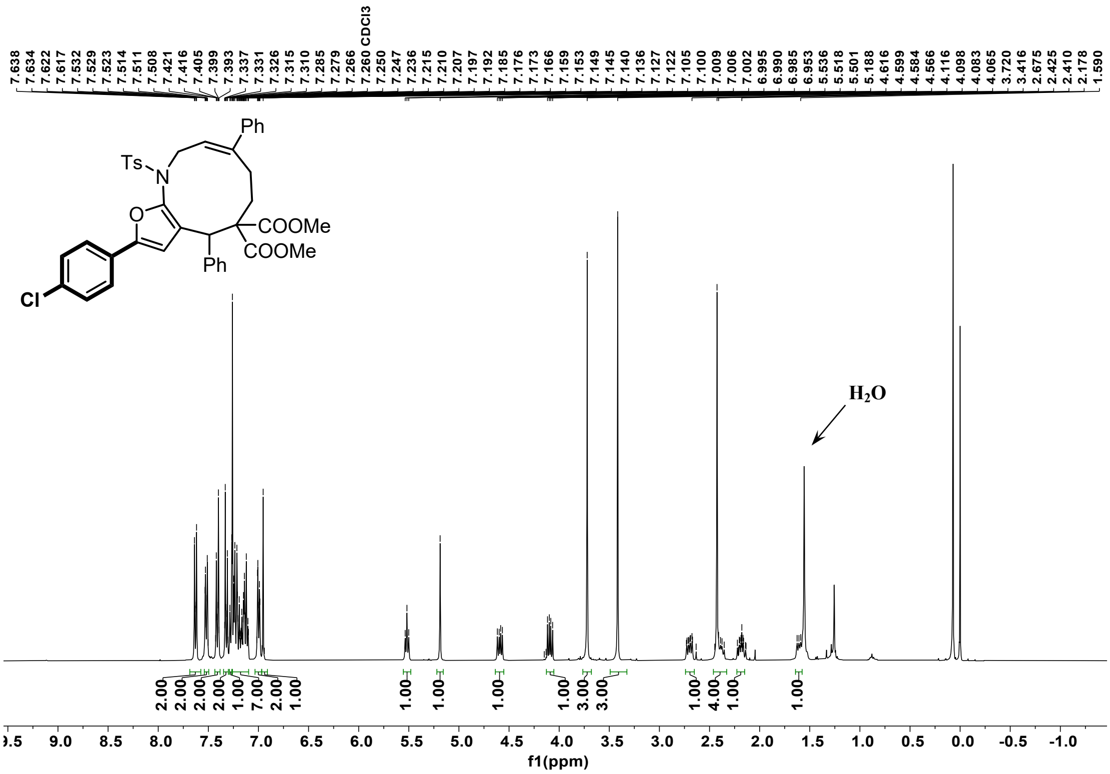
^{1}H NMR of **5af** in $CDCl_3$ (400 MHz)



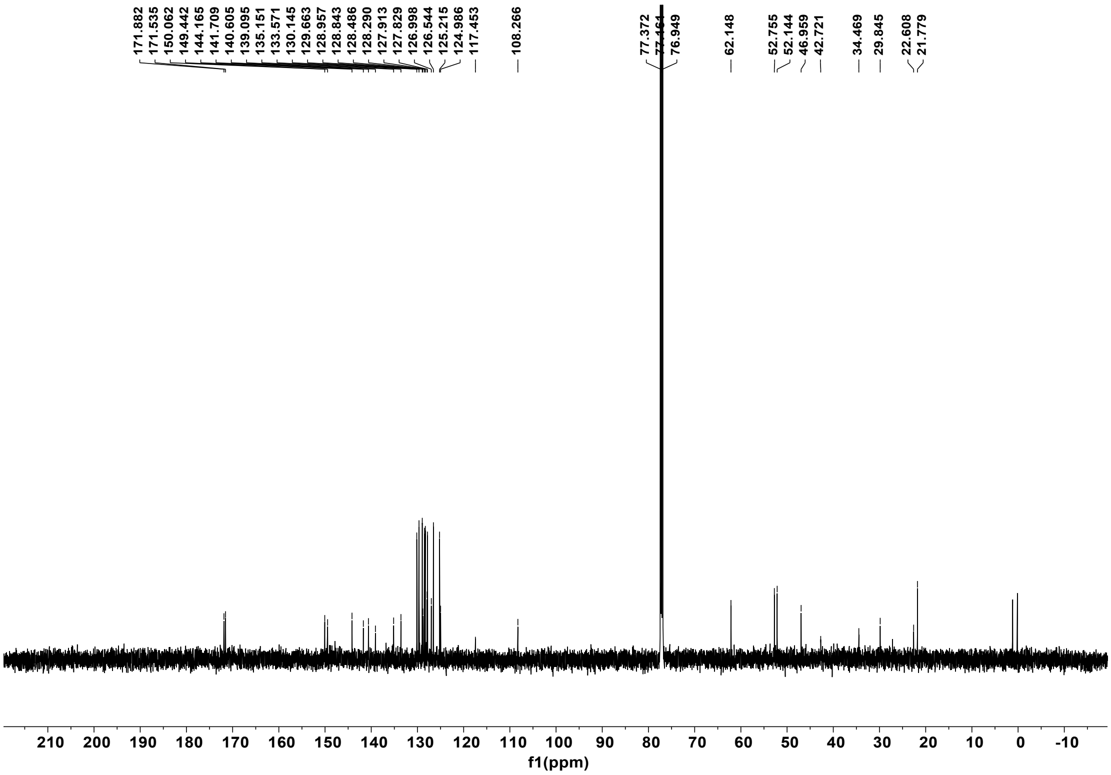
^{13}C NMR of **5af** in $CDCl_3$ (101 MHz)



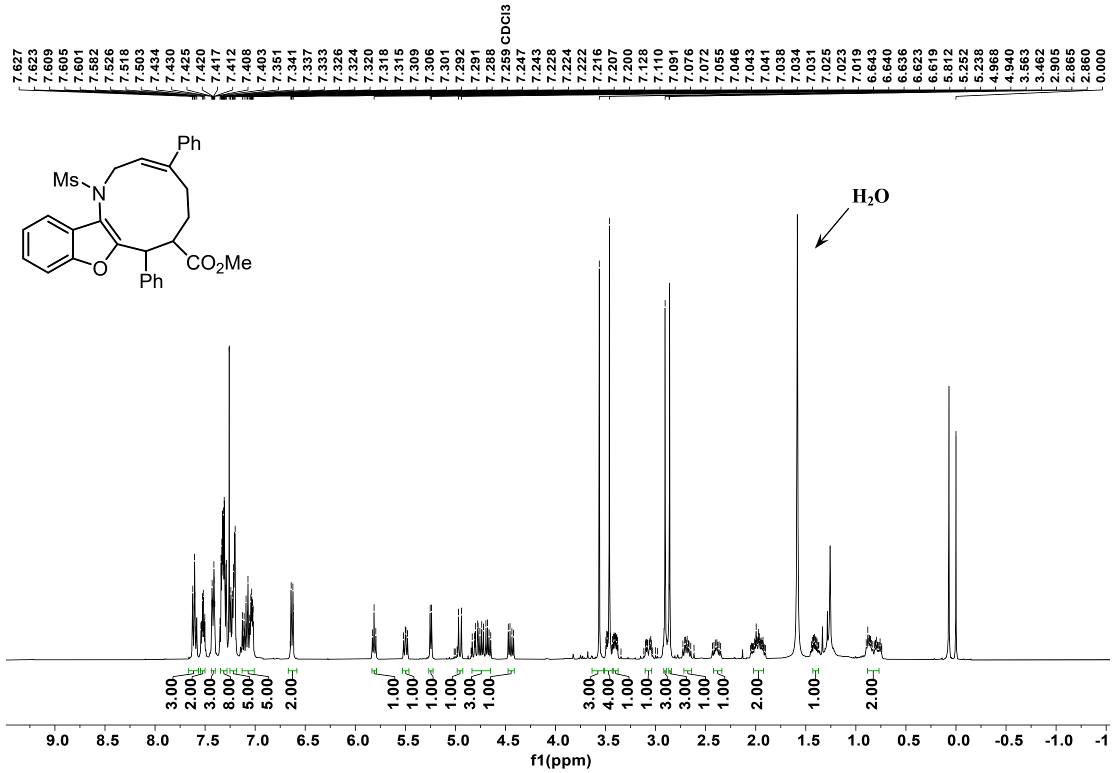
[1]H NMR of **5ag** in $CDCl_3$ (600 MHz)



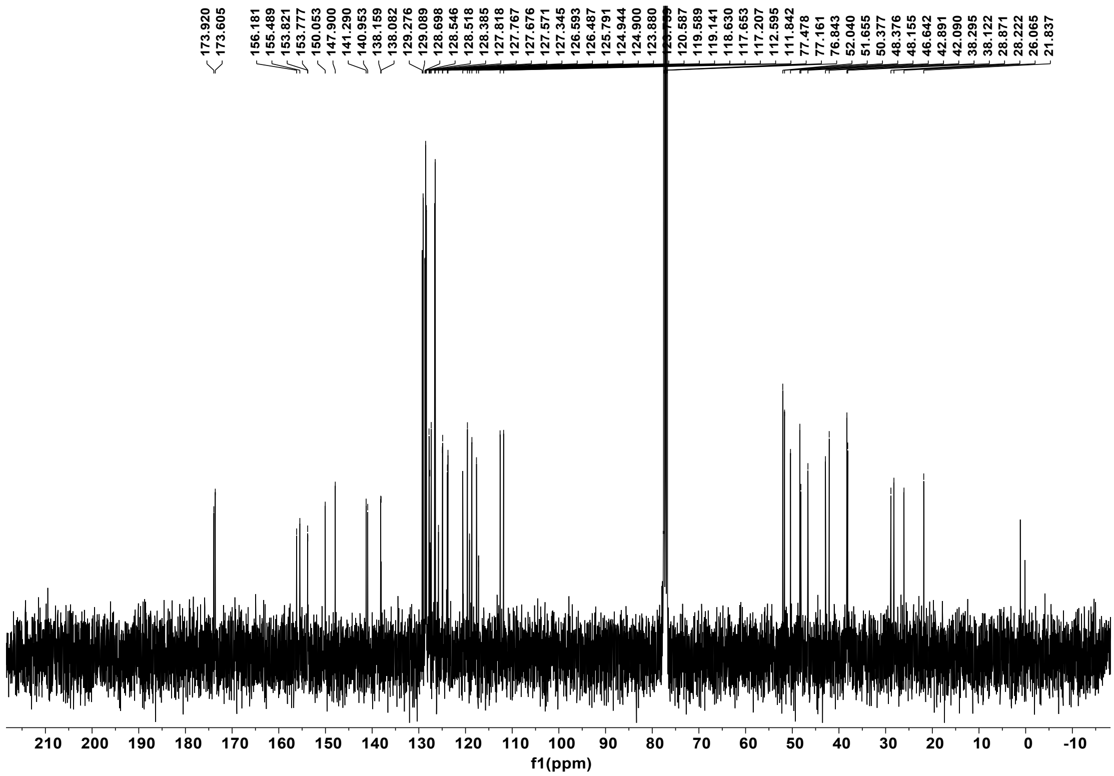
[13]C NMR of **5ag** in $CDCl_3$ (151 MHz)



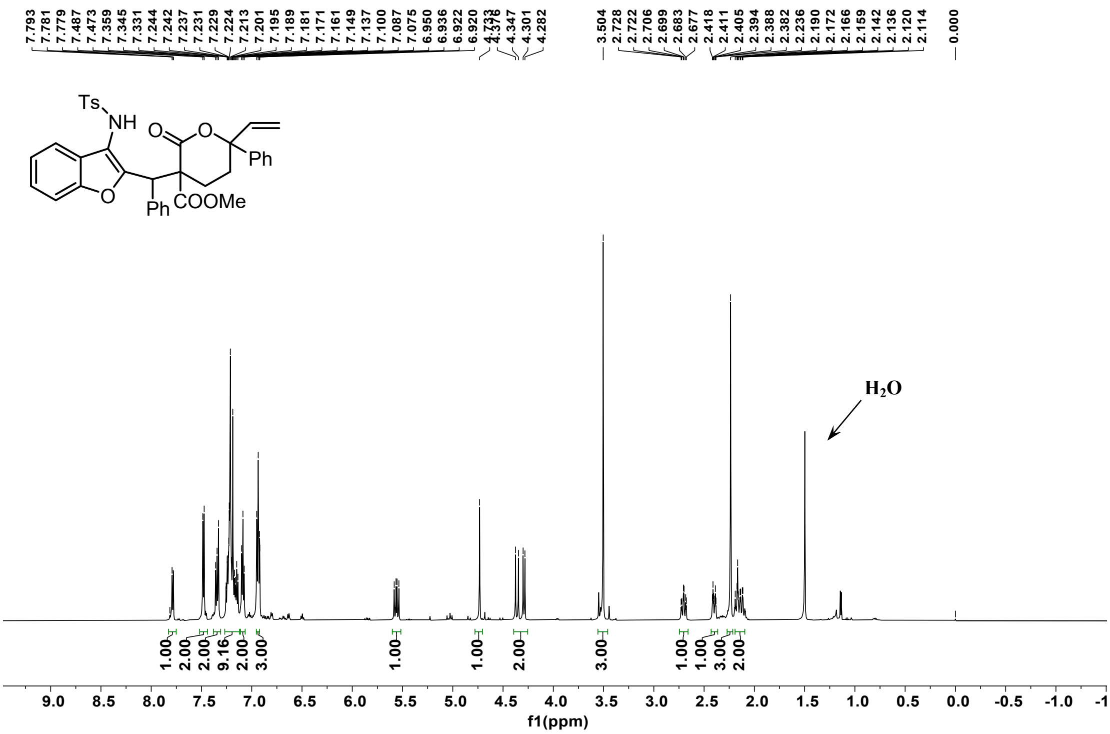
^{1}H NMR of **7aa** in $CDCl_3$ (400 MHz)



^{13}C NMR of **7aa** in $CDCl_3$ (101 MHz)



^{1}H NMR of **8ax** in $CDCl_3$ (600 MHz)



^{13}C NMR of **8ax** in $CDCl_3$ (151 MHz)