Supporting Information

Recyclable Nickel-Catalyzed C−H/O−H Dual Functionalization of Phenols with Mandelic Acids for the Synthesis of 3-Aryl Benzofuran-2(*3H*)-ones under Solvent-Free Condition†

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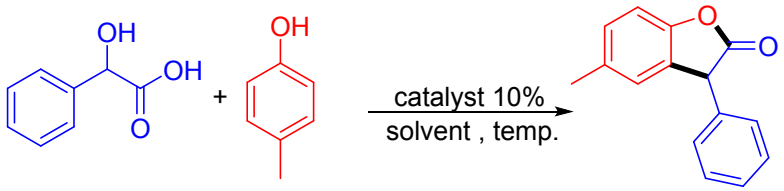
S1. Condition optimization

At first, we used the reaction of mandelic acid (1a) with 4-methylphenol (2a) as model reaction for condition optimization (Table S1). Four Lewis acid catalysts, $AlCl_3$, $Bi(OTf)_3$, $Cu(OTf)_2$ and $Ni(OTf)_2$ (10 mol%), were screened under solvent-free condition at 160 °C (entries 1−4). Among them, only $Ni(OTf)_2$ gives the target product 3-aryl benzofuran-2(*3H*)-one (3a) in 88% yield. The use of the other Ni catalysts resulted in lower yields (entries 5−10). The effects of solvent, reaction temperature, and catalyst amount were also investigated. The reaction proceeded sluggishly in organic solvents (entries 11−16). With the decrease of reaction temperature, there is lowering of product yield (entries 17−19). When the amount of catalyst decreased from 10 mol% to 5.0 and 1.0 mol%, the yield of 3a decreased from 88% to 72% and 34%, respectively (entries 20−21).

Table S1. Survey on condition for 3a formation [a]

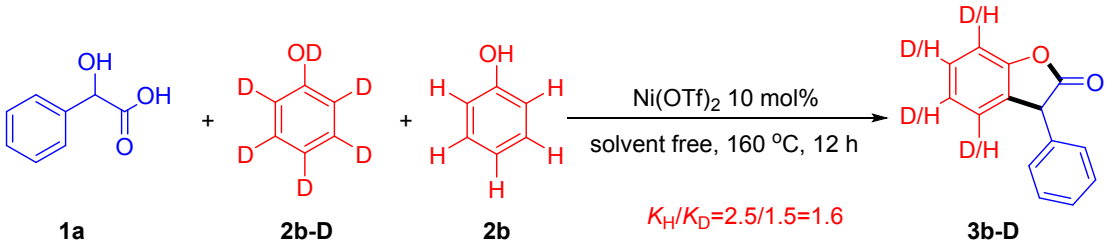


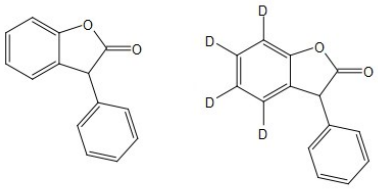
1a **2a** **3a**

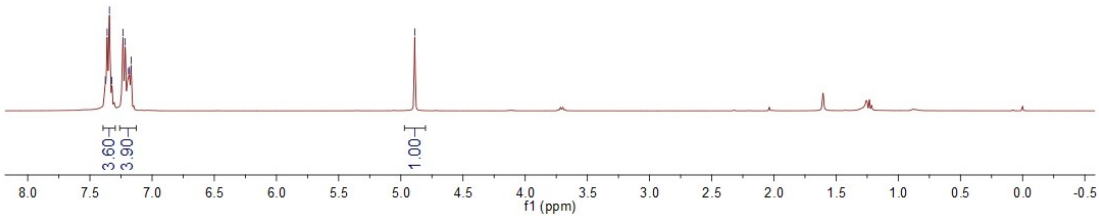
entry	catalyst	solvent	temperature (^{o}C)	yield[b] (%)
1	$AlCl_3$ 100%	–	160	10
2	$Cu(OTf)_2$ 10%	–	160	11
3	$Bi(OTf)_3$ 10%	–	160	13
4	$Ni(OTf)_2$ 10%	–	160	88
5	dppe Ni 10%	–	160	trace
6	$NiCl_2$ 10%	–	160	23
7	NiF_2 10%	–	160	36
8	$Ni(acac)_2$ 10%	–	160	19
9	$Ni(OAc)_2$ 10%	–	160	trace
10	$NiCl(PPh_3)_2$ 10%	–	160	trace
11	$Ni(OTf)_2$ 10%	DMF	160	trace
12	$Ni(OTf)_2$ 10%	DMSO	160	trace
13	$Ni(OTf)_2$ 10%	THF	160	trace
14	$Ni(OTf)_2$ 10%	1,4-dioxane	160	trace
15	$Ni(OTf)_2$ 10%	toluene	160	13
16	$Ni(OTf)_2$ 10%	cyclohexane	160	15
17	$Ni(OTf)_2$ 10%	–	140	67
18	$Ni(OTf)_2$ 10%	–	120	45
19	$Ni(OTf)_2$ 10%	–	100	23
20	$Ni(OTf)_2$ 5%	–	160	72
21	$Ni(OTf)_2$ 1%	–	160	34

[a] Mandelic acid 1a (0.5 mmol), 4-methylphenol 2a (1.0 mmol), under air condition, sealed tube, [b] isolated yield.

S2. Deuterium Labeling Experiment



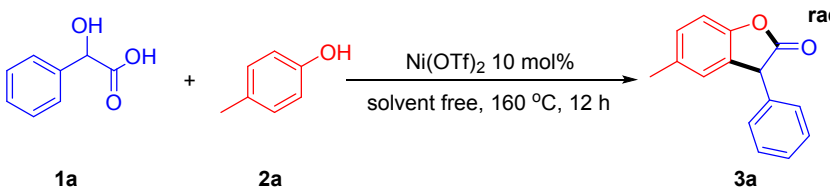




To a 10 mL oven-dried Schlenk tube equipped with a magnetic stirring bar was added mandelic acid 1a (1 mmol，2.0 equiv, 152 mg), phenol 2b (0.25 mmol, 0.5 equiv, 23.5 mg), phen-2,3,4,5,6-d5-ol-d 2b-D (0.25 mmol, 0.5 equiv, 25 mg), and $Ni(OTf)_2$ (0.05 mmol, 10 mol%, 18 mg), and the mixture was vigorously stirred at 160 °C for 12 h under vacuum. Then the mixture was cooled to room temperature, followed by the addition of water (15 mL), and extraction with EtOAc (15 mL×3). The combined organic phases were dried over anhydrous Na_2SO_4, filtered and concentrated in vacuo. Further purification by flash column chromatography on silica gel (eluting with petroleum ether/ethyl acetate) provided the product 3b and 3b-D. The ratio of 3b and 3b-D was determined by ^1H NMR.

The mixture of 3a and 1D-3a: ^1H NMR (400 MHz, $CDCl_3$) δ 7.39–7.30 (m, 3.6H), 7.26–7.13 (m, 3.9H), 4.89 (s, 1H).

Radical Trapping Experiment



radical scavenger(1 eq)	yield
none	88%
TEMPO	85%
BQ	81%

To a Schlenk tube of 10 mL was charged with 1a (152 mg, 1 mmol), 2a (50.4 mg, 0.50 mmol) TEMPO (78 mg, 0.5 mmol, 1.0 equiv) or 1,4-benzoquinone (54 mg, 0.5 mmol, 1.0 equiv) under standard reaction conditions. The vial was evacuated and then filled with N_2, and stirred at 160 °C for 12 h. The as-resulted mixture was cooled to room temperature, diluted with CH_2Cl_2 (2 mL), filtered through a celite pad and concentrated in vacuo. The residue was purified by flash column chromatography on silica gel, eluting with EtOAc/hexane (1:20, v/v), to afford the product 3a (yield = 81% to 85%).

S3. X-ray Crystallographic Data

Compounds 3a was collected at 100 K on a Rigaku Oxford Diffraction Supernova Dual Source, Cu at Zero equipped with an AtlasS2 CCD using Cu Kα radiation. Data reduction was carried out with the diffractometer software. [a] The structures were solved by direct methods using Olex2 software[b] and the non-hydrogen atoms were located from the trial structure and then refined anisotropically with SHELXL-2014[c] using a full-matrix least squares procedure based on F2. The weighted R factor, wR and goodness-of-fit S values were obtained based on F2.The hydrogen atom positions were fixed geometrically at the calculated distances and allowed to ride on their parent atoms. Crystallographic data for the structure reported in this paper have been deposited at the Cambridge Crystallographic Data Center and allocated with the deposition numbers: CCDC 1854879 for 3a.

Figure S1. ORTEP drawing of 3a

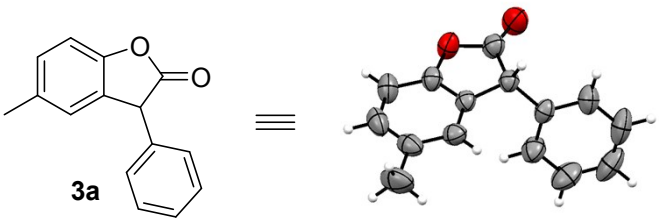


Table S1. Crystal data and structure refinement for 3a.

Empirical formula	$C_{15}H_{12}O_2$
Formula weight	224.25
Temperature/K	296.15

Crystal system	monoclinic
Space group	$P2_1/n$
a/Å	9.6376(9)
b/Å	8.3094(8)
c/Å	14.8885(14)
α/°	90.00
β/°	92.0420(10)
γ/°	90.00
Volume/Å^3	1191.6(2)
Z	4
ρ_{calc}g/cm^3	1.250
μ/mm^{-1}	0.082
F(000)	472.0
Crystal size/mm^3	0.23 × 0.21 × 0.2
Radiation	MoKα (λ = 0.71073)
2Θ range for data collection/°	4.96 to 49.98
Index ranges	-11 ≤ h ≤ 9, -9 ≤ k ≤ 8, -13 ≤ l ≤ 17
Reflections collected	5269
Independent reflections	2065 [R_{int} = 0.0140, R_{sigma} = 0.0150]
Data/restraints/parameters	2065/0/155
Goodness-of-fit on F^2	1.071
Final R indexes [I>=2σ (I)]	R_1 = 0.0407, wR_2 = 0.1062
Final R indexes [all data]	R_1 = 0.0481, wR_2 = 0.1111
Largest diff. peak/hole / e Å^{-3}	0.14/-0.17

Crystal structure determination of 3a

Crystal Data for $C_{15}H_{12}O_2$ (*M* = 224.25 g/mol): monoclinic, space group $P2_1/n$ (no. 14), *a* = 9.6376(9) Å, *b* = 8.3094(8) Å, *c* = 14.8885(14) Å, *β* = 92.0420(10), *V* = 1191.6(2) Å^3, *Z* = 4, *T* = 296.15 K, μ(MoKα) = 0.082 mm^{-1}, *Dcalc* = 1.250 g/cm^3, 5269 reflections measured (4.96° ≤ 2Θ ≤ 49.98°), 2065 unique (R_{int} = 0.0140, R_{sigma} =

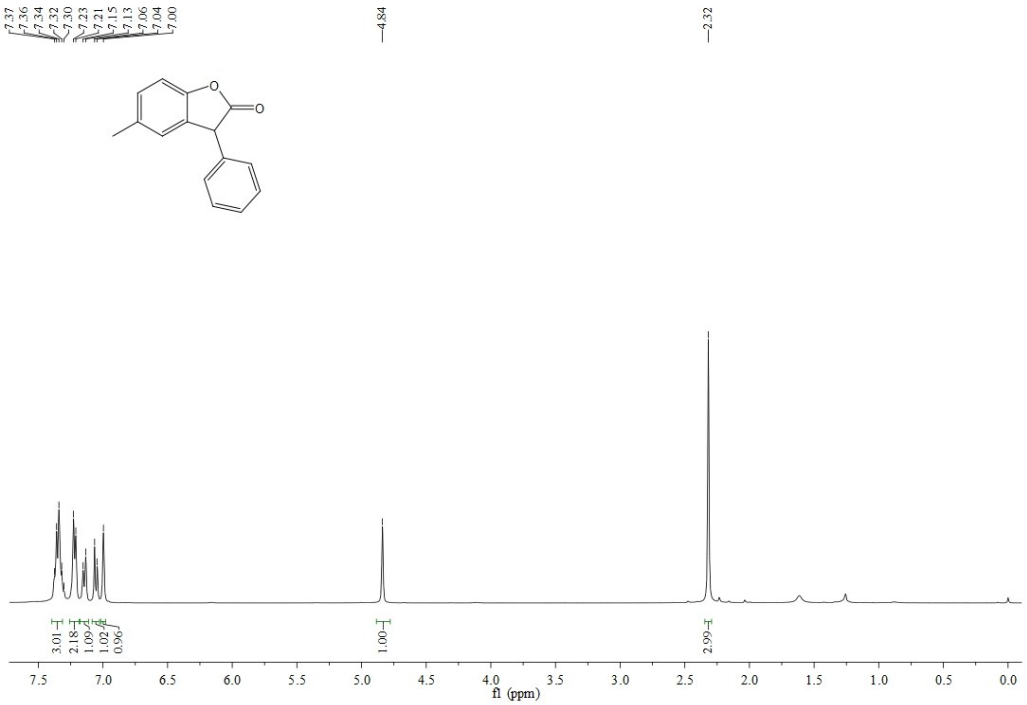
0.0150) which were used in all calculations. The final R_1 was 0.0407 (>2sigma(I)) and wR_2 was 0.1111 (all data).

References

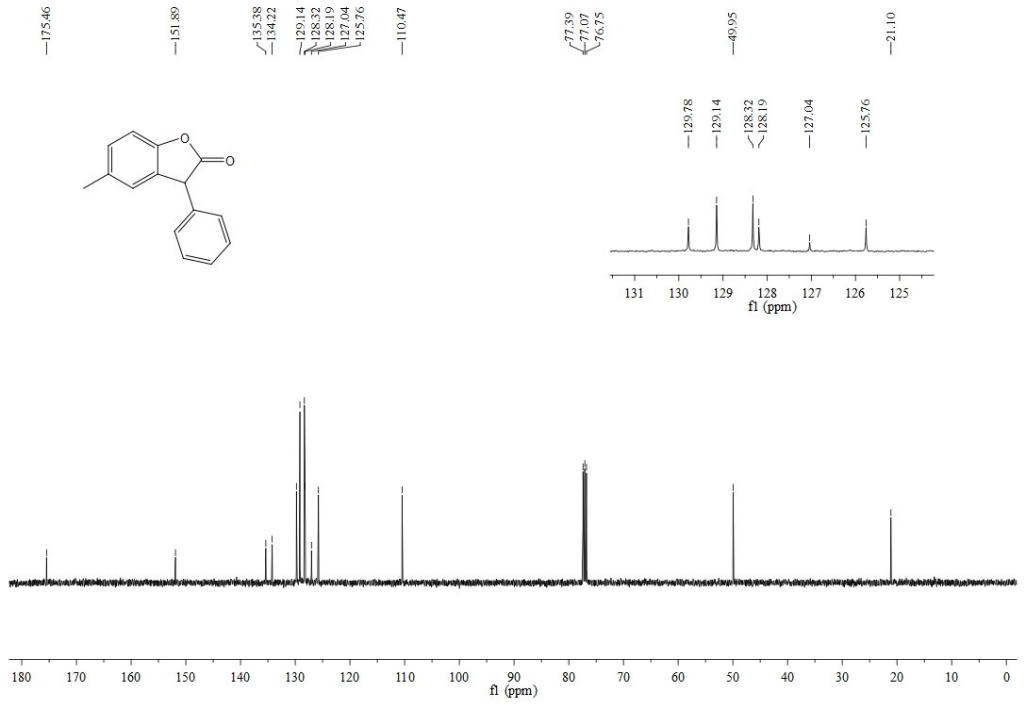
(a) Agilent Technologies, CrysAlisPRO, Version 1.171.36.28, 2013.
(b) Dolomanov, O. V.; Bourhis, L. J.; Gildea, R. J. *J. Appl. Cryst*. 2009, *42*, 339.
(c) Kratzert, D.; Holstein, J. J.; Krossing, I. *J. Appl. Cryst*. 2015, *48*, 933.

S4. NMR spectra of all compounds

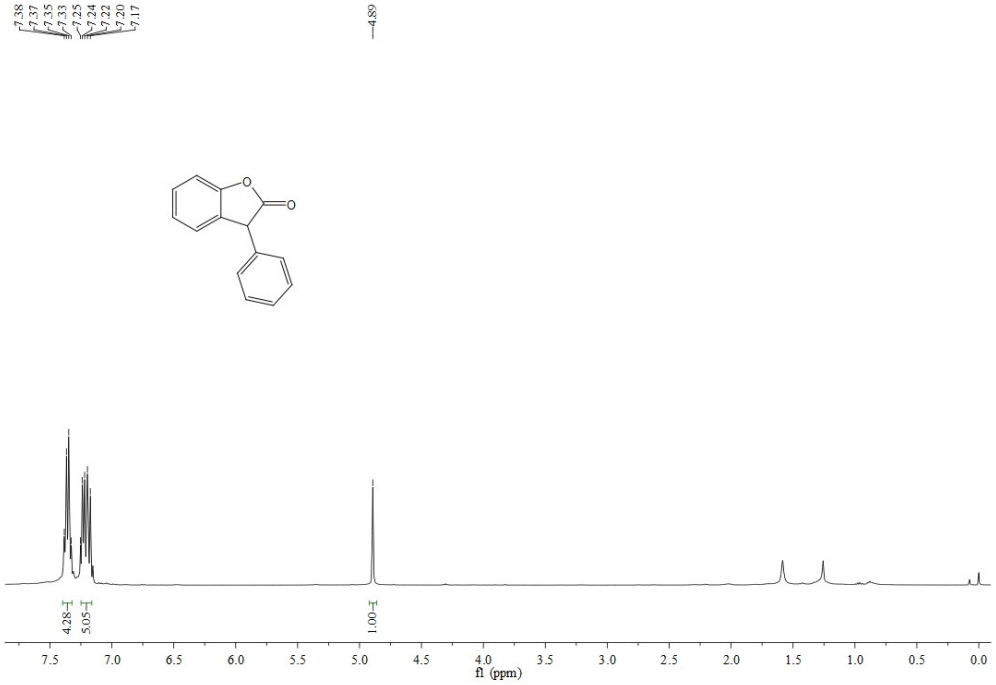
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3a



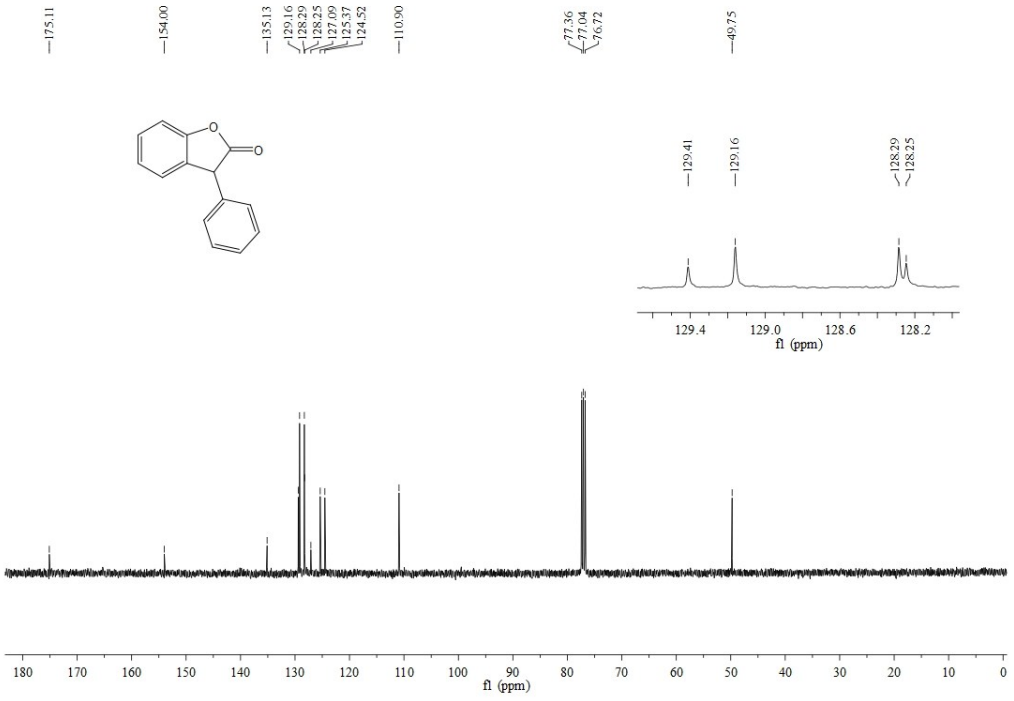
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3a



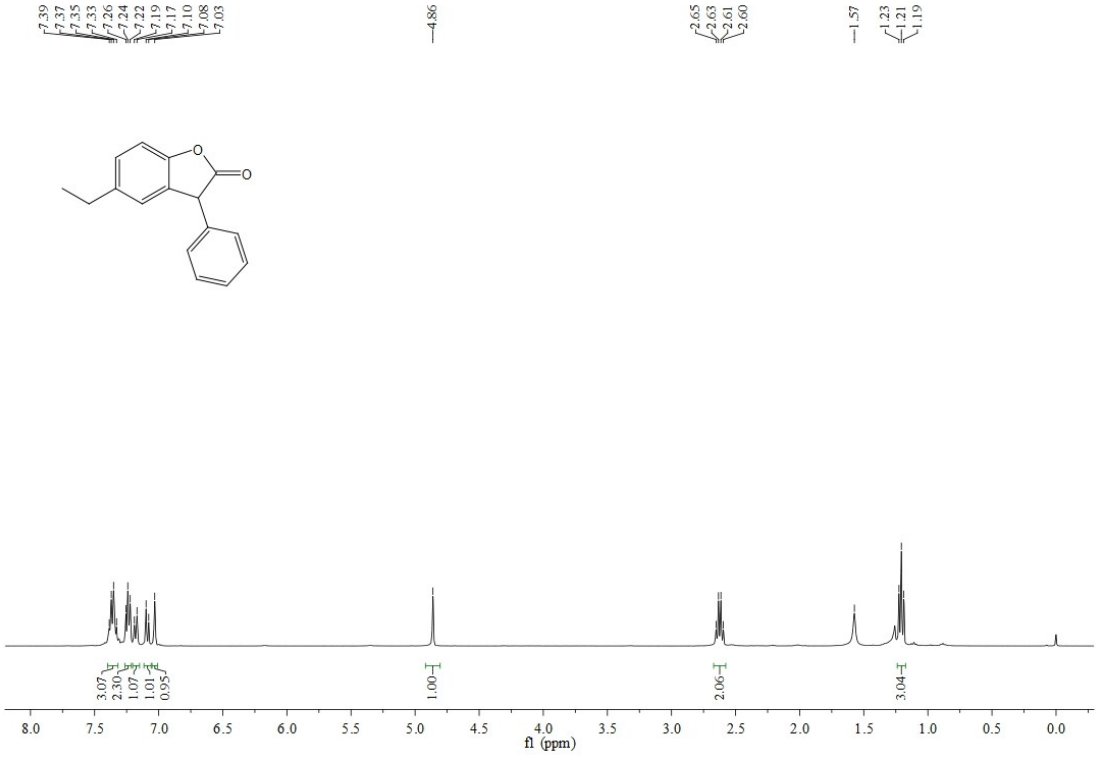
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3b



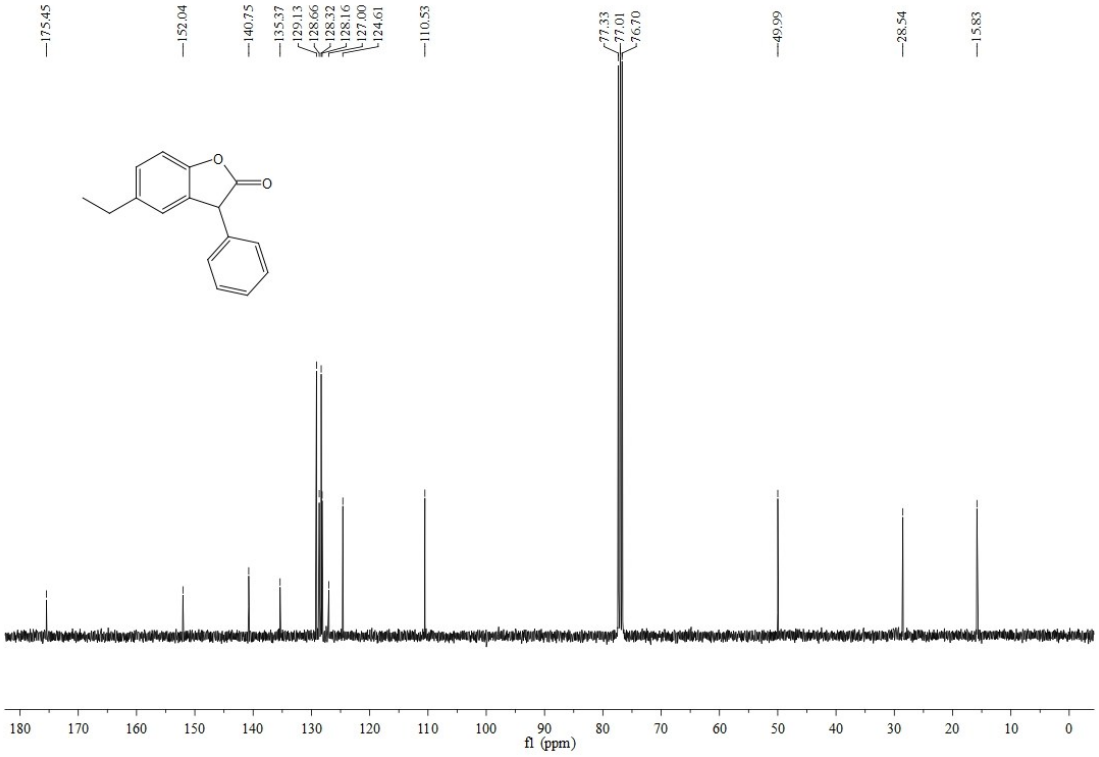
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3b



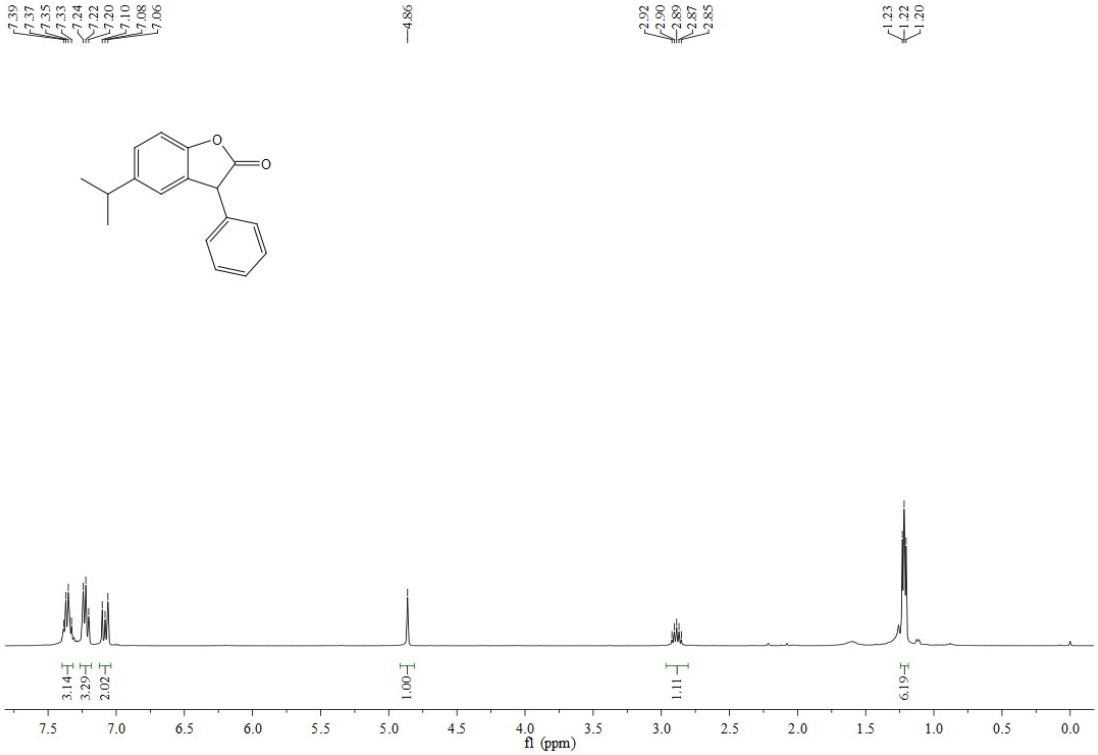
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3c



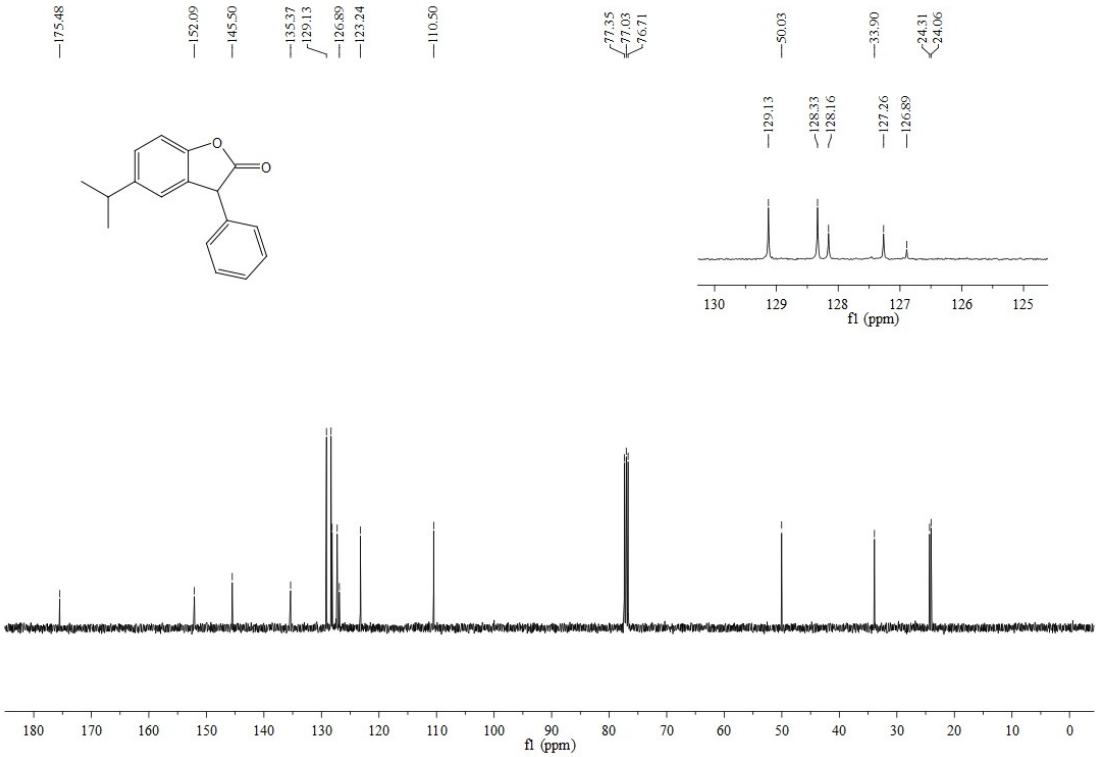
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3c



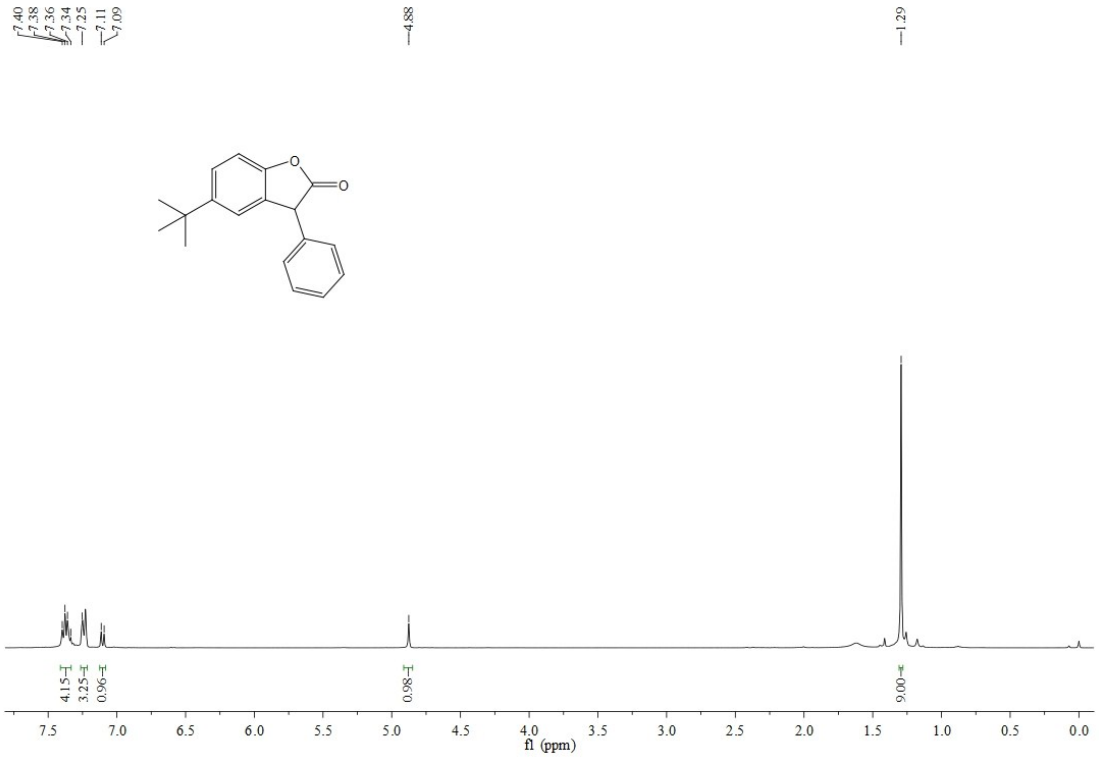
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3d



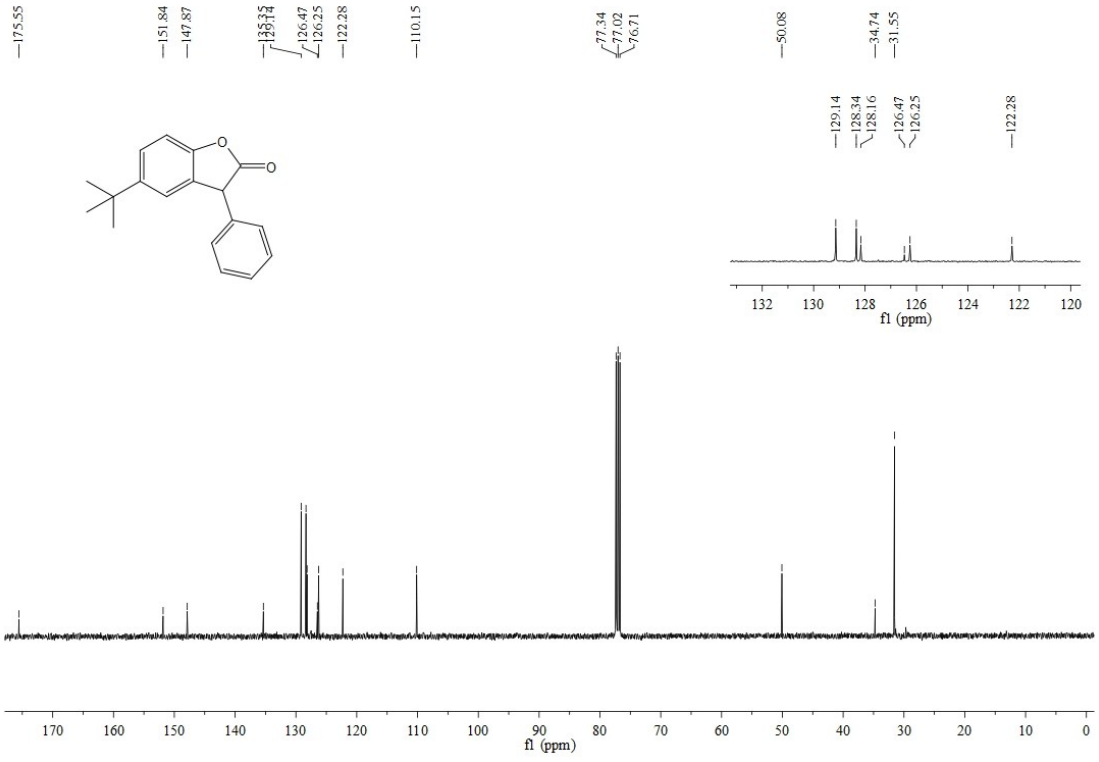
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3c



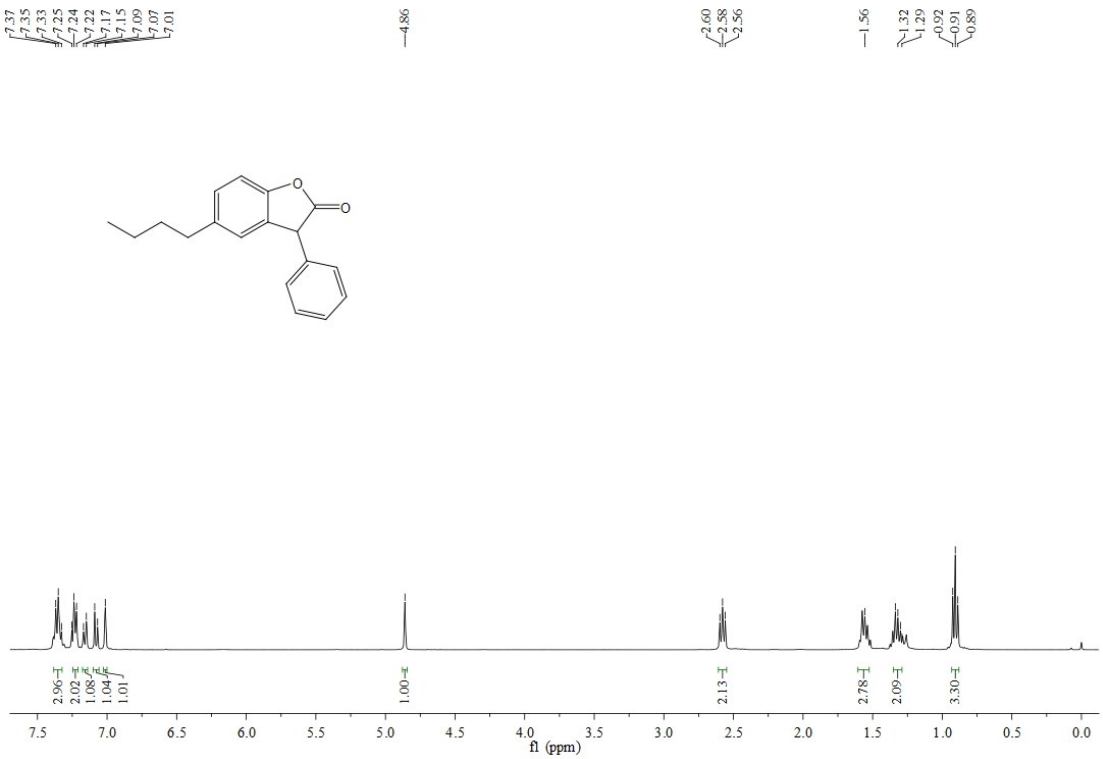
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3e



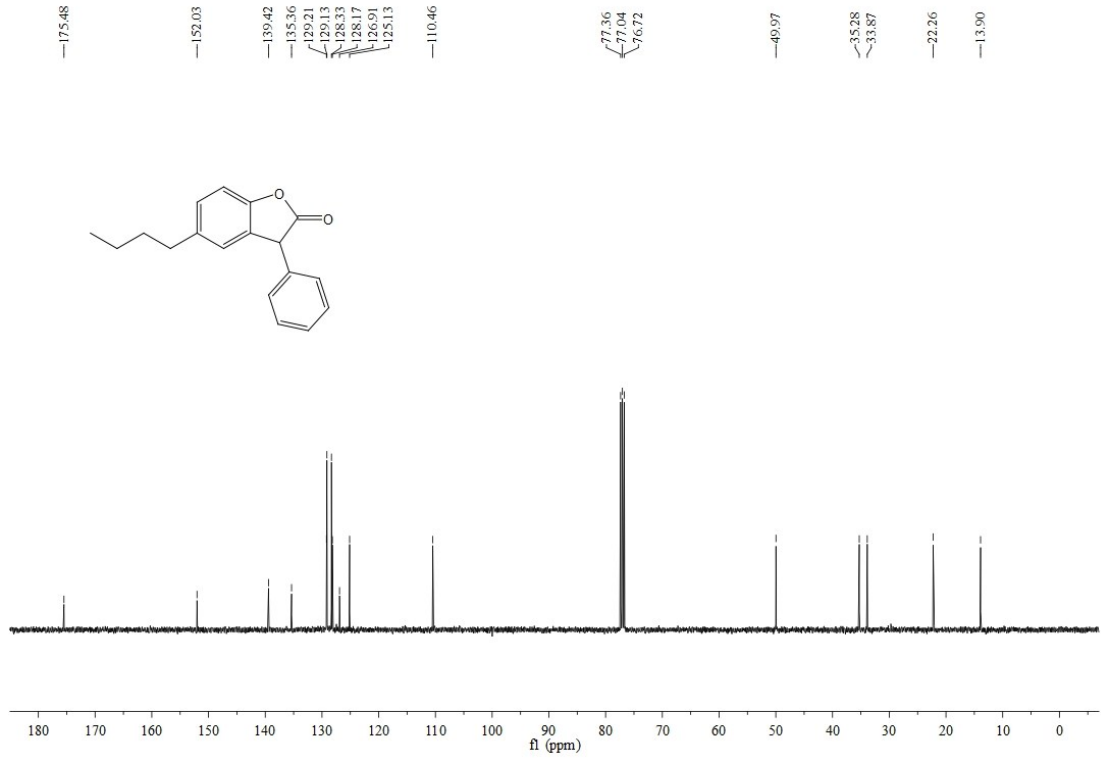
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3e



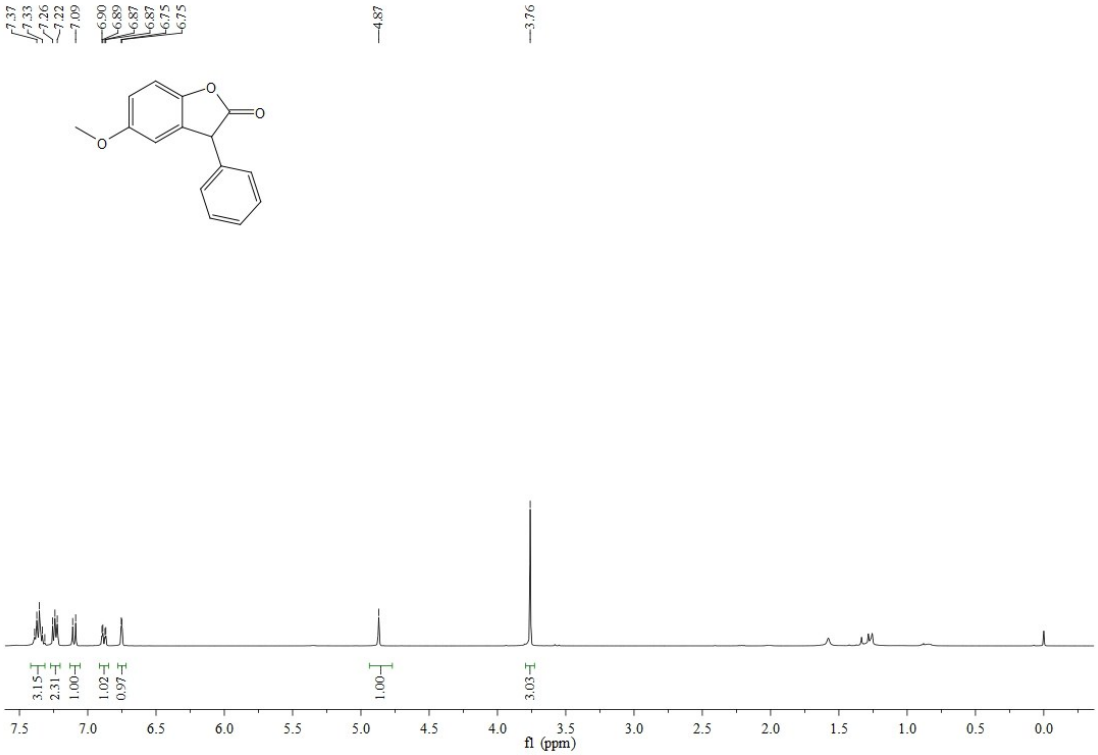
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3f



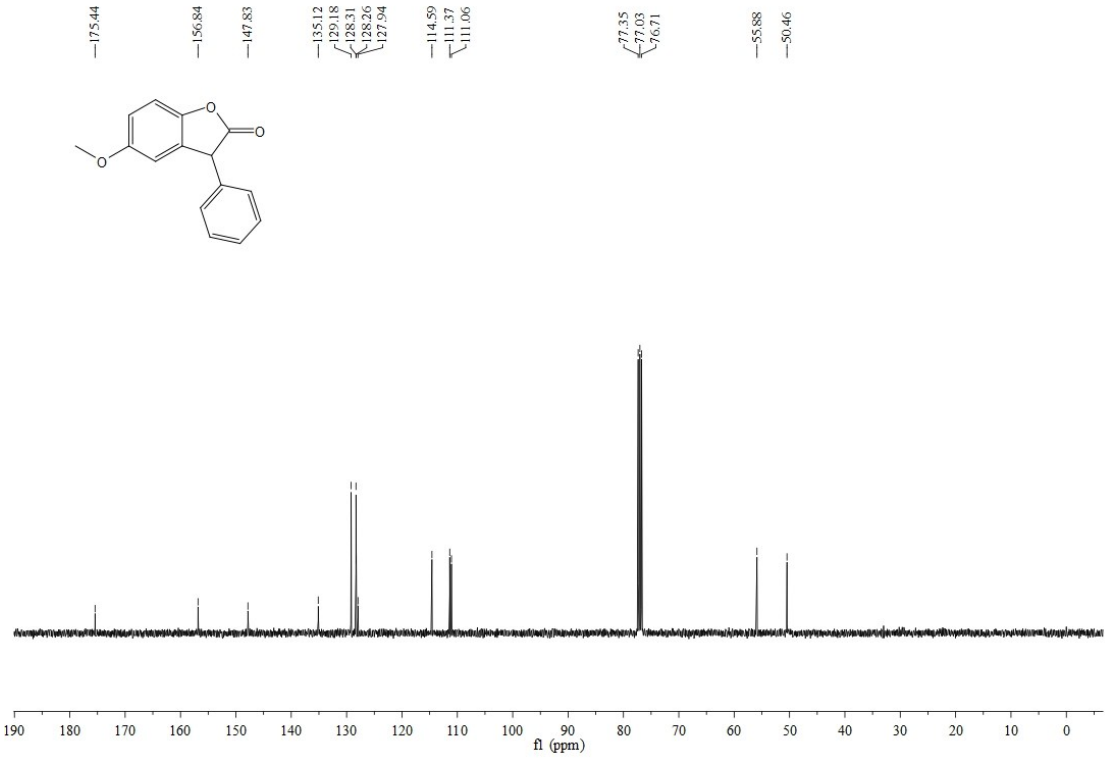
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3f



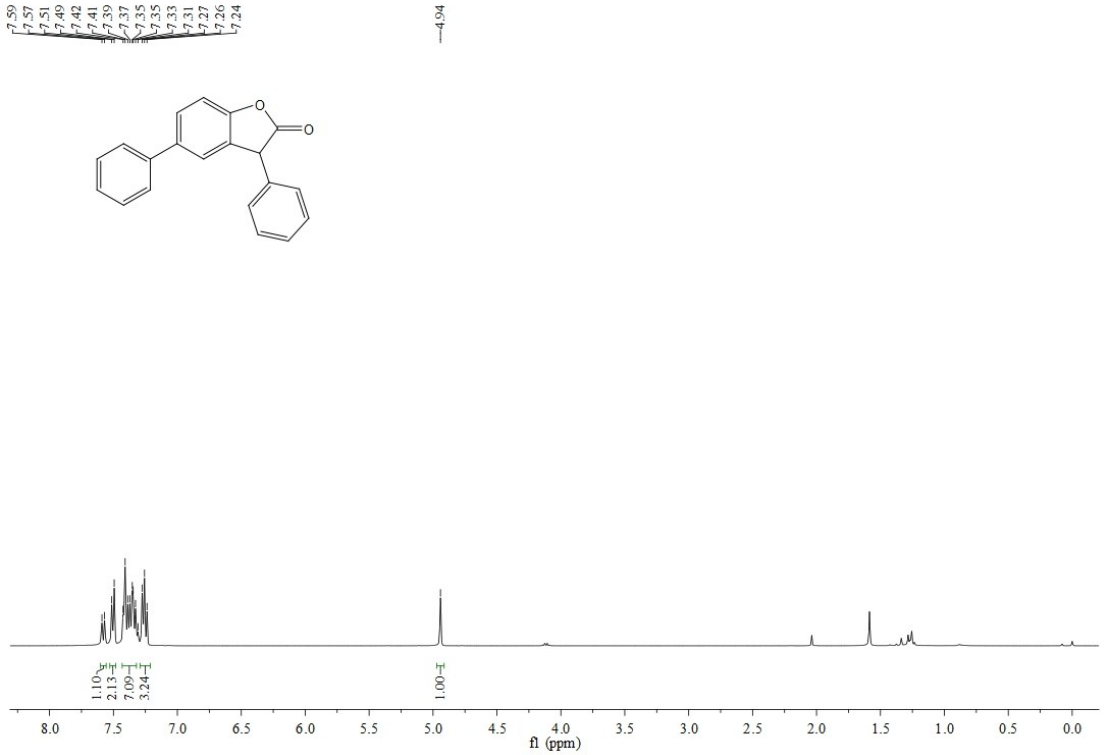
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3g



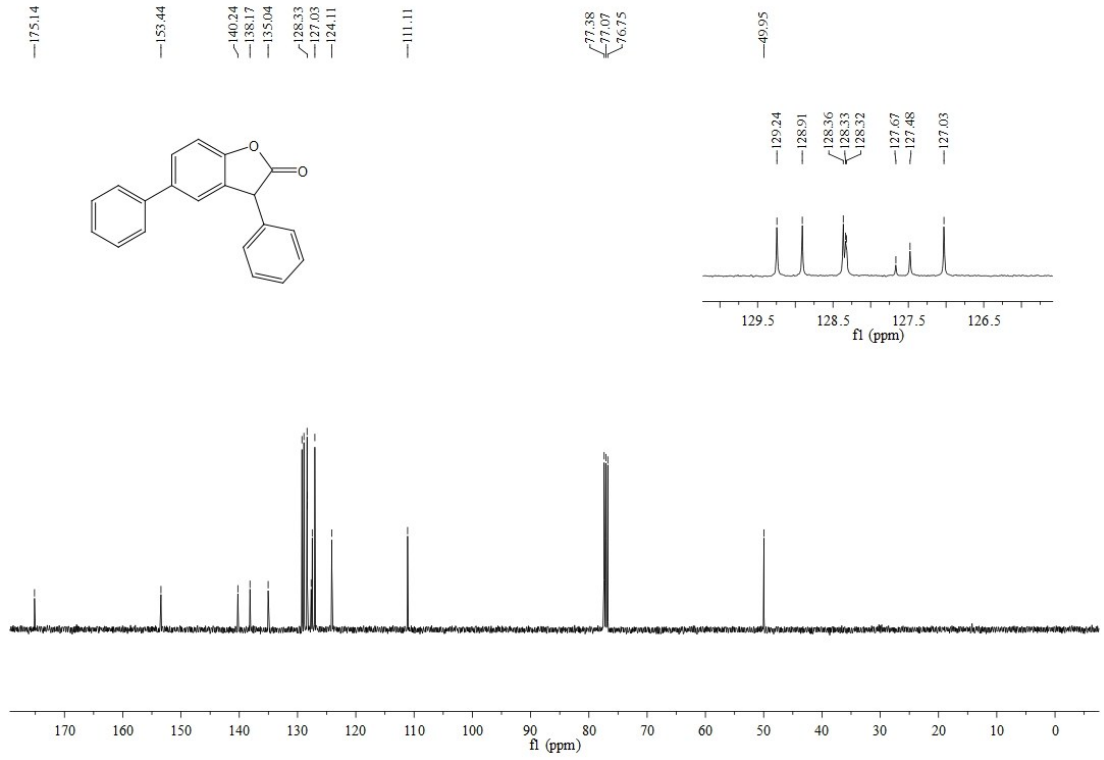
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3g



^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3h



^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3h



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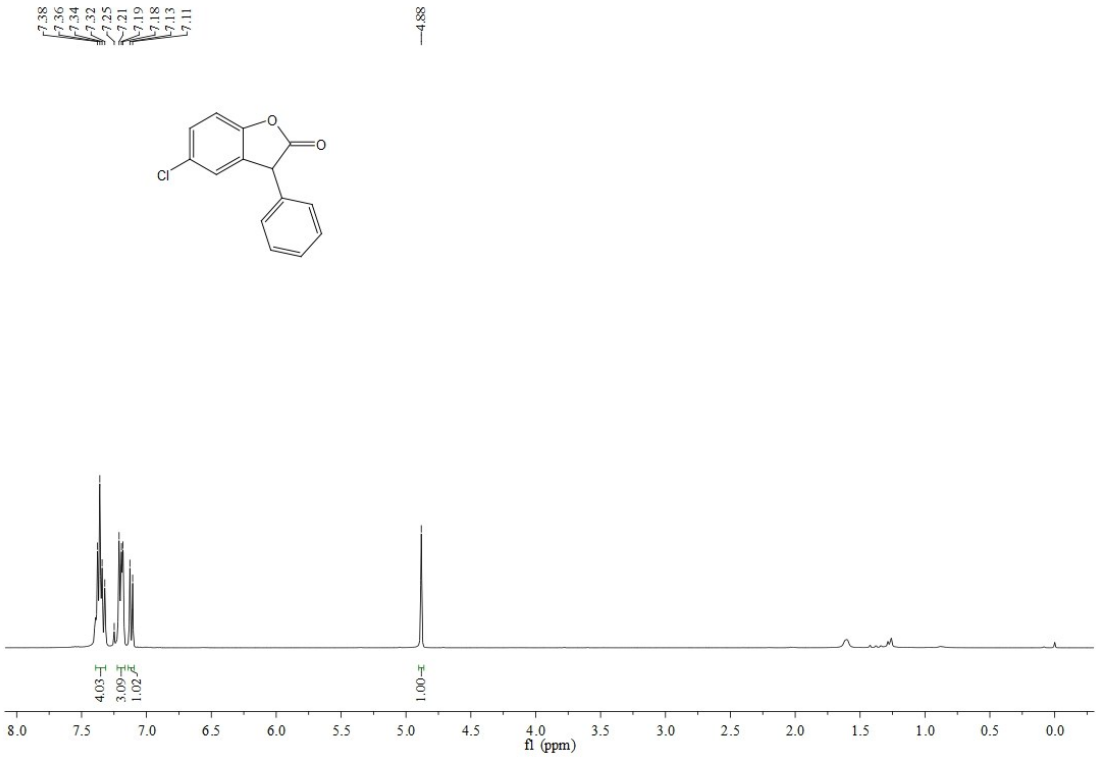
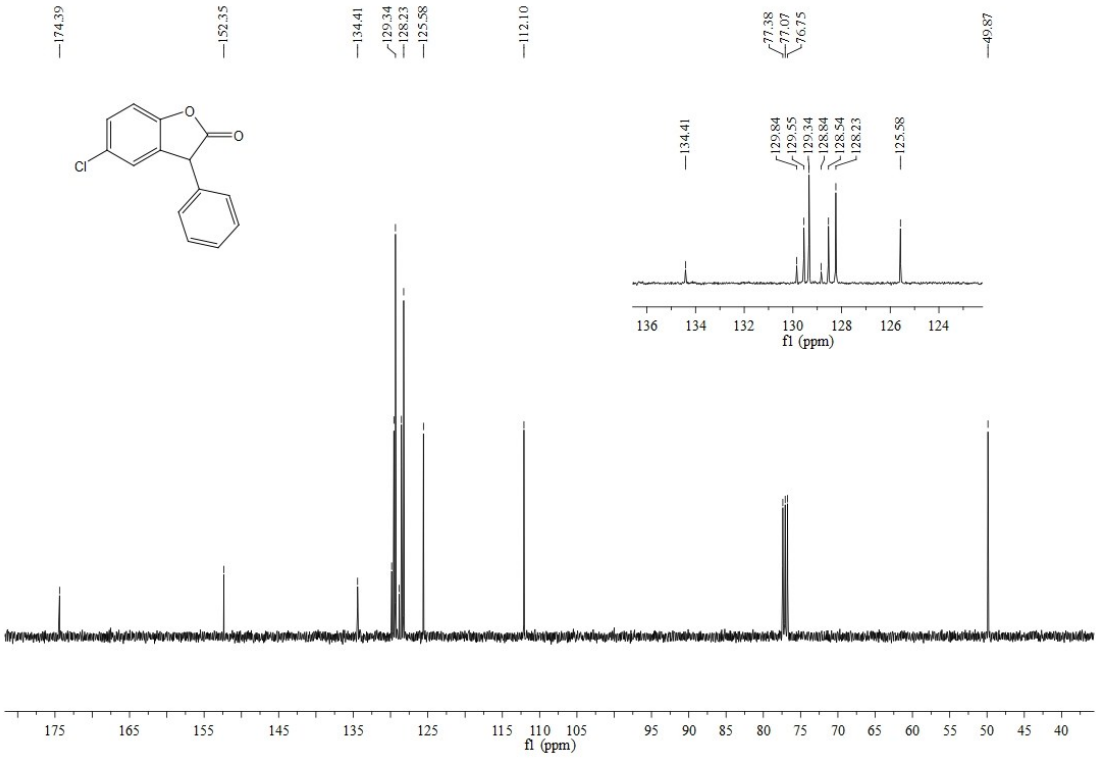
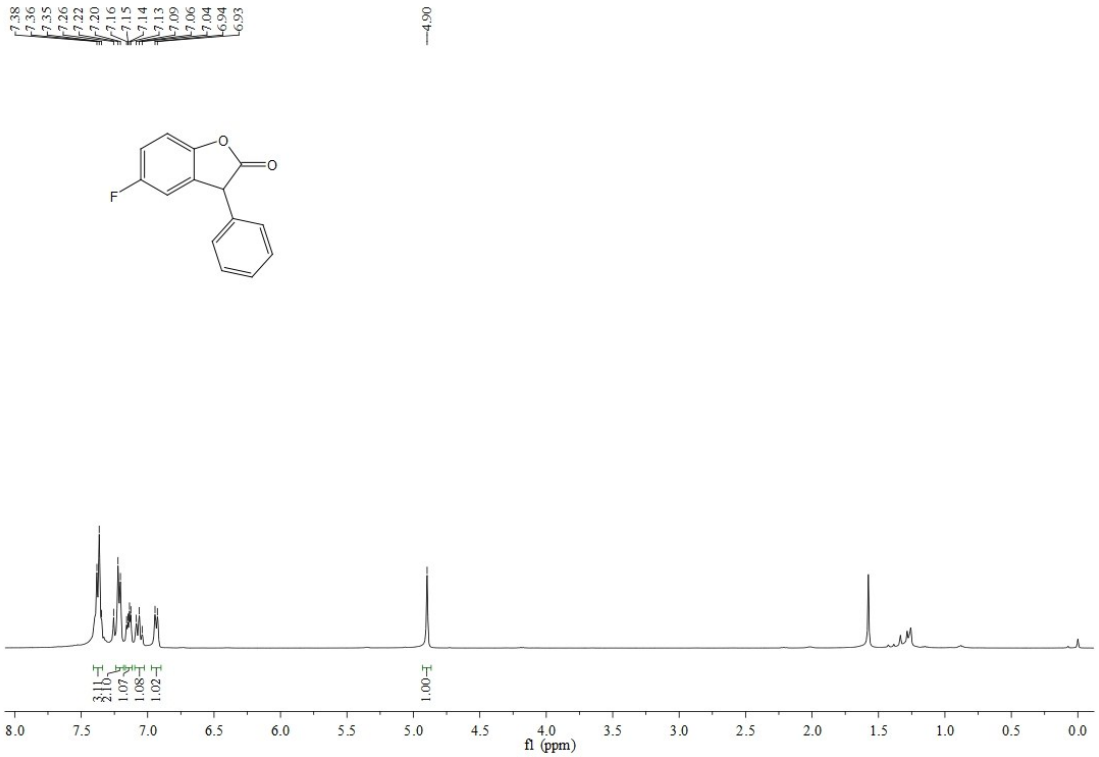


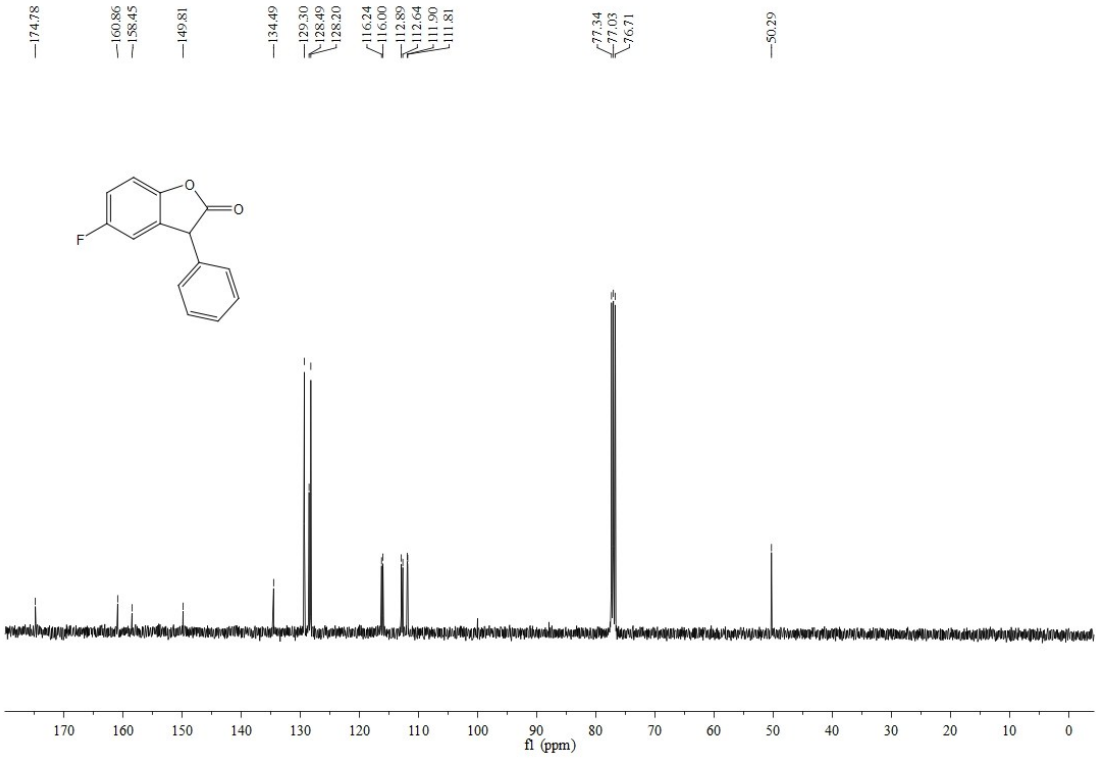
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3i



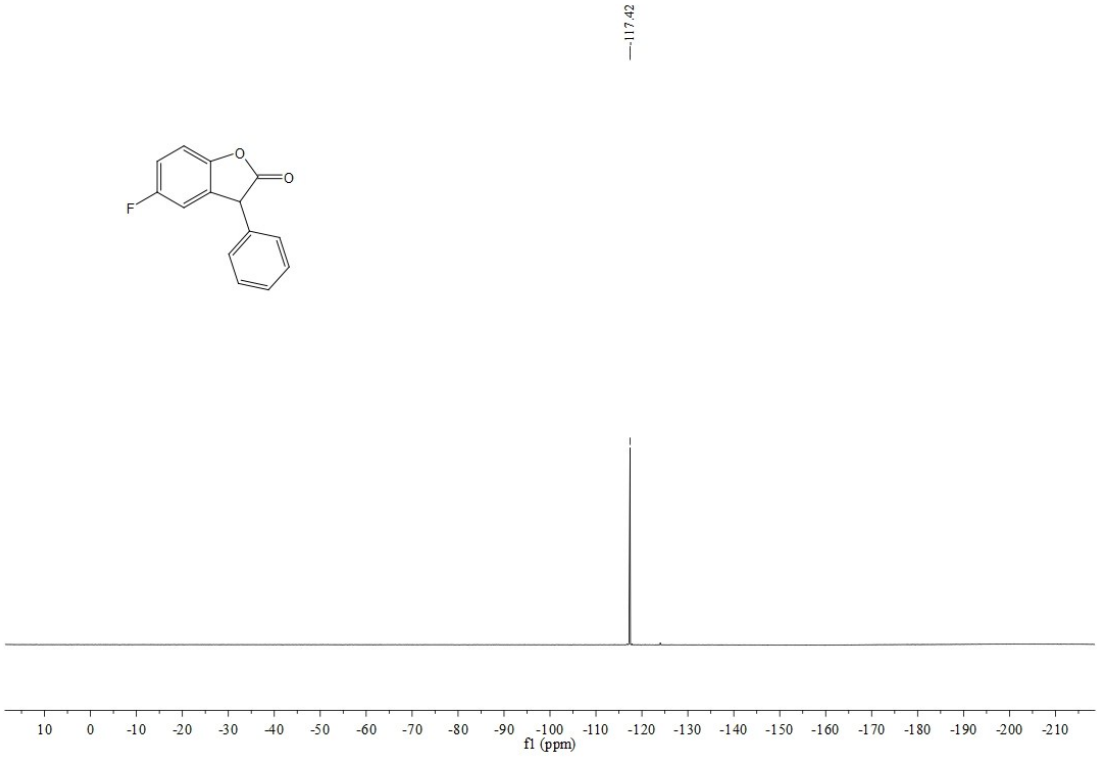
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3j



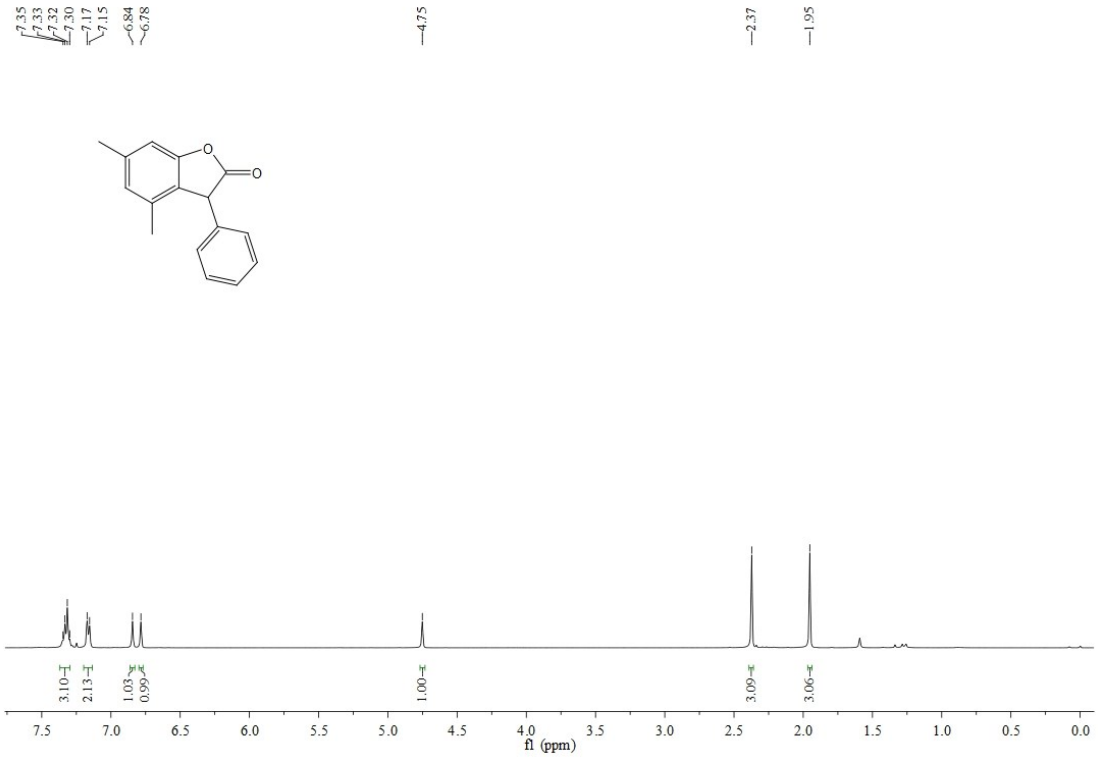
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3j



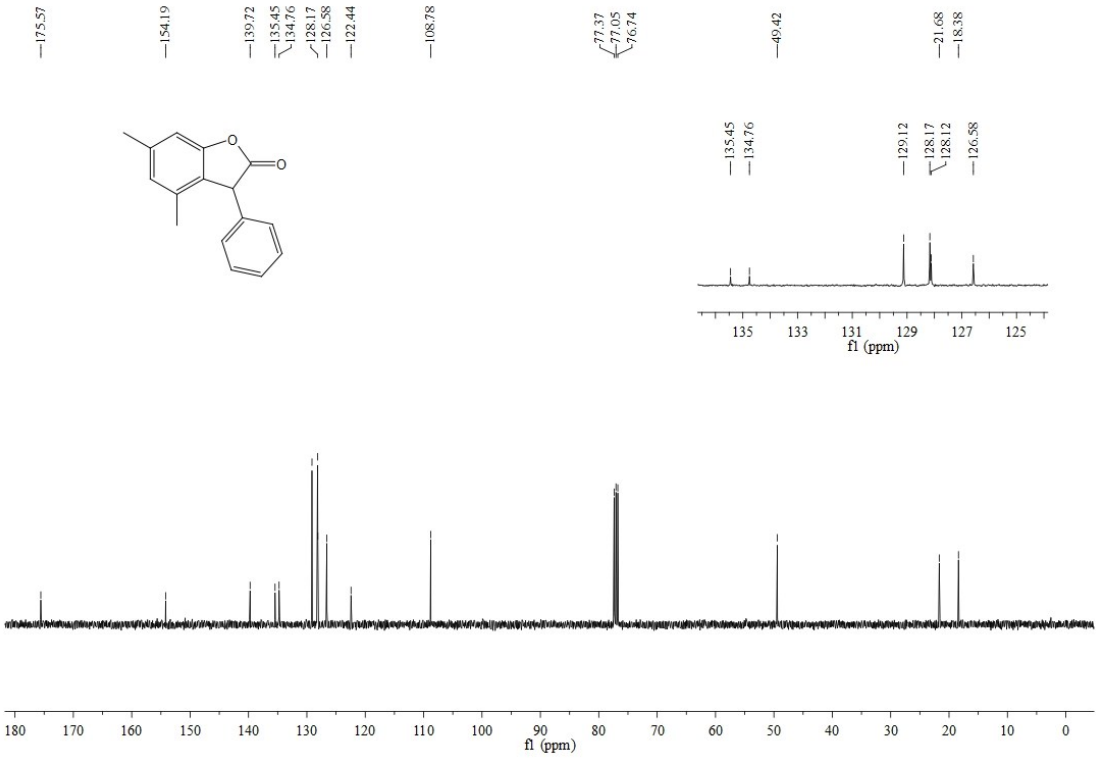
^{19}F NMR (376 MHz, $CDCl_3$) spectrum for 3j



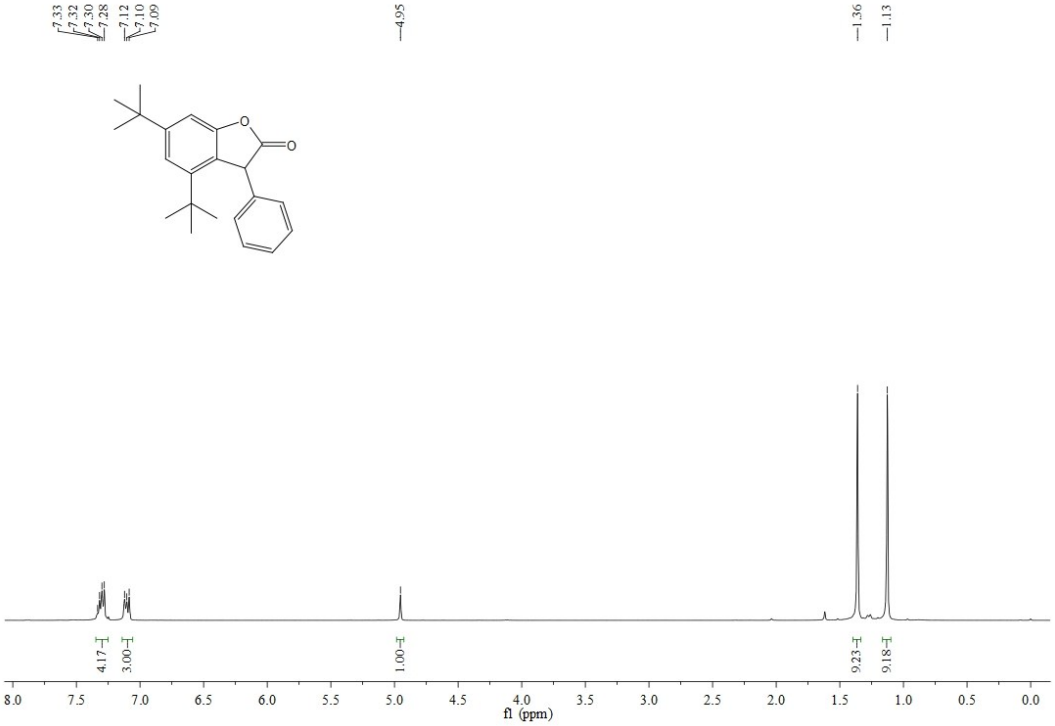
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3k



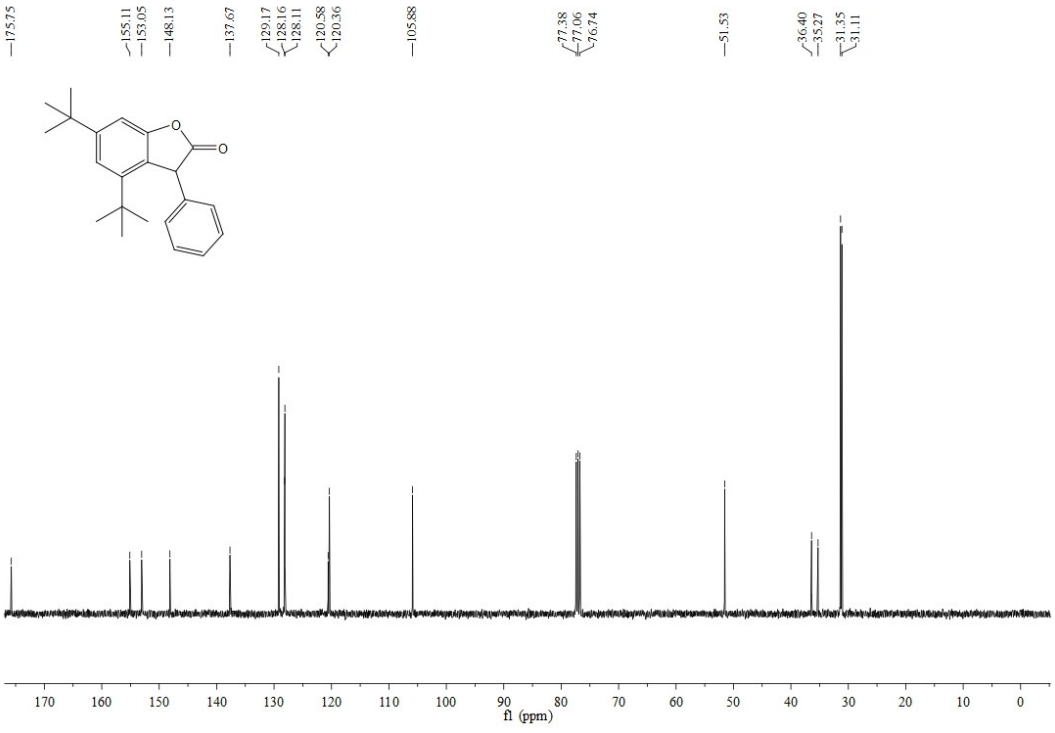
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3k



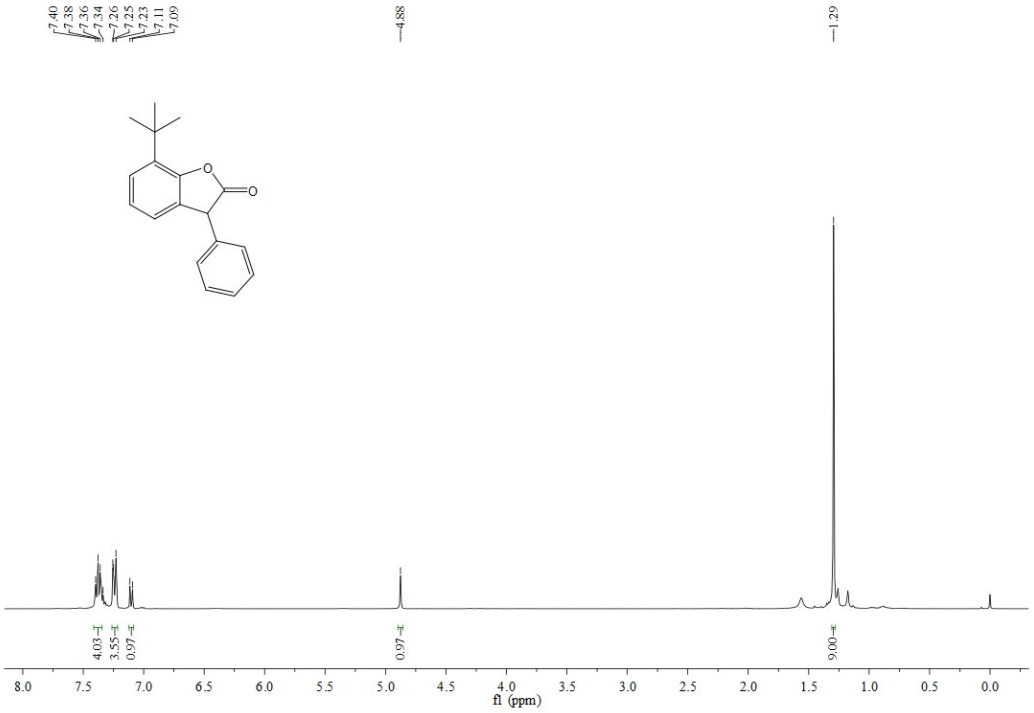
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3l



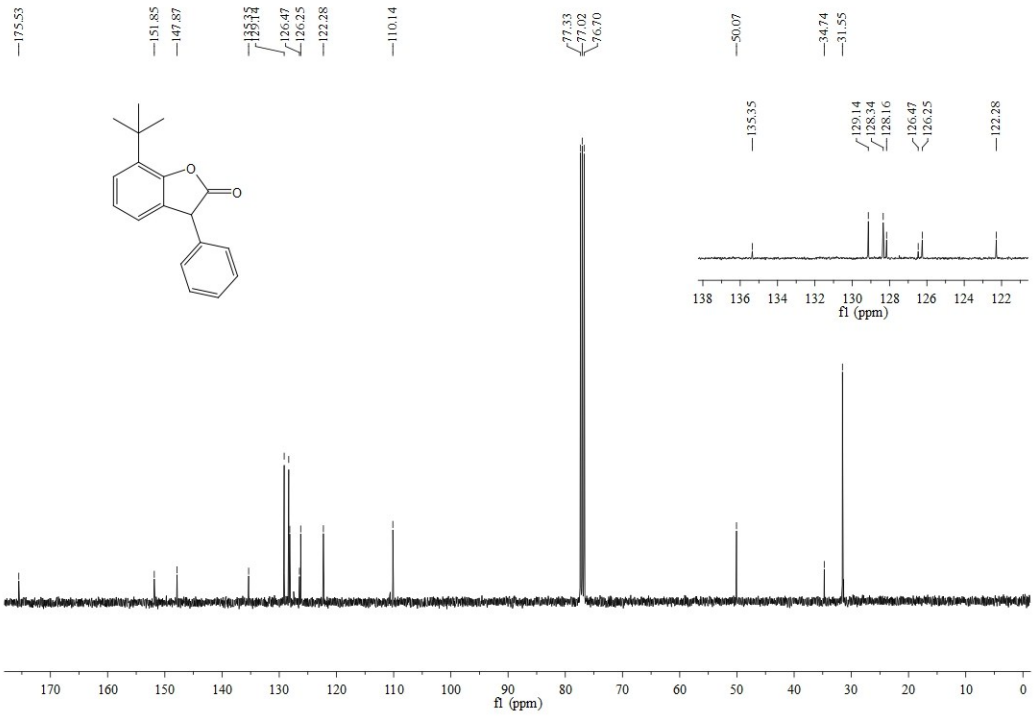
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3l



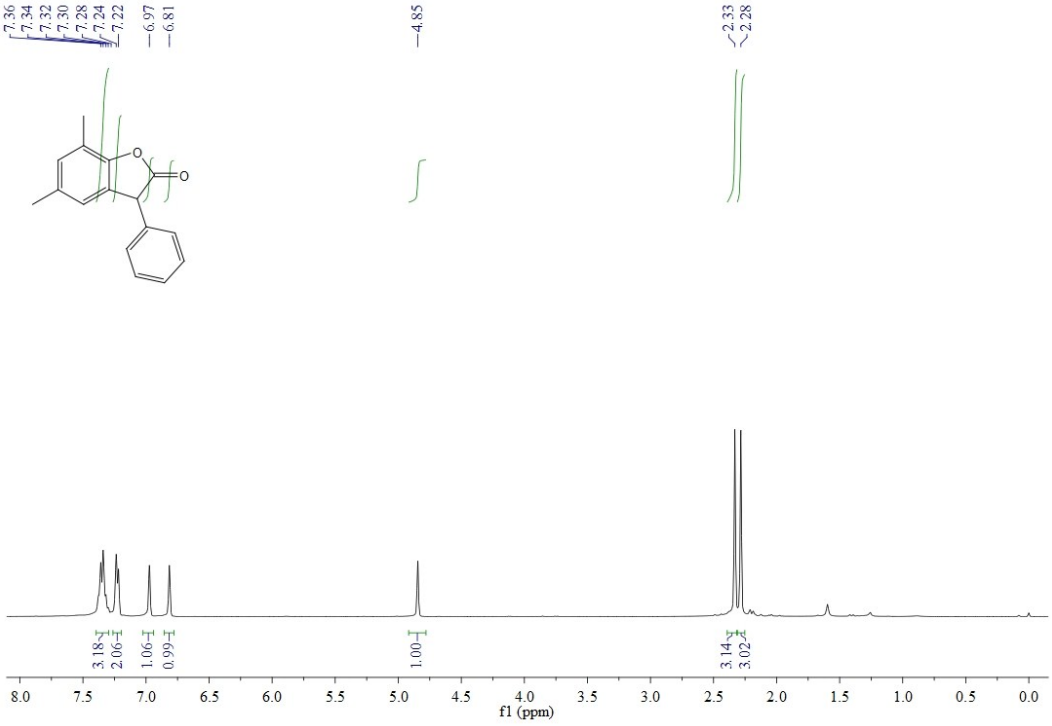
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3m



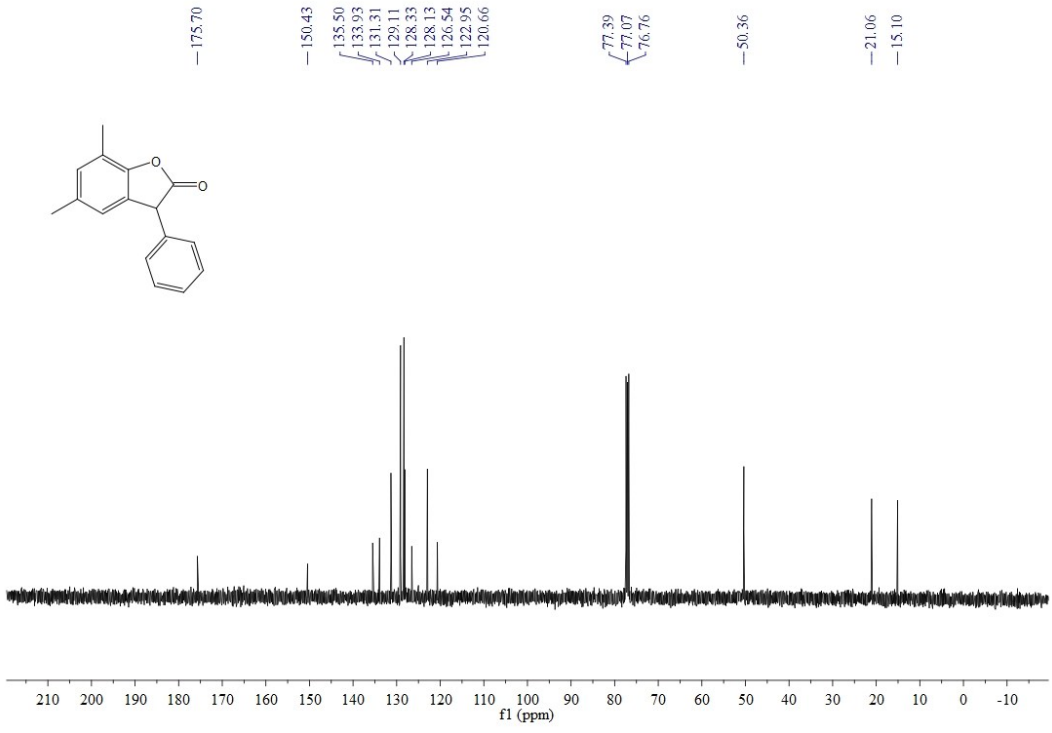
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3m



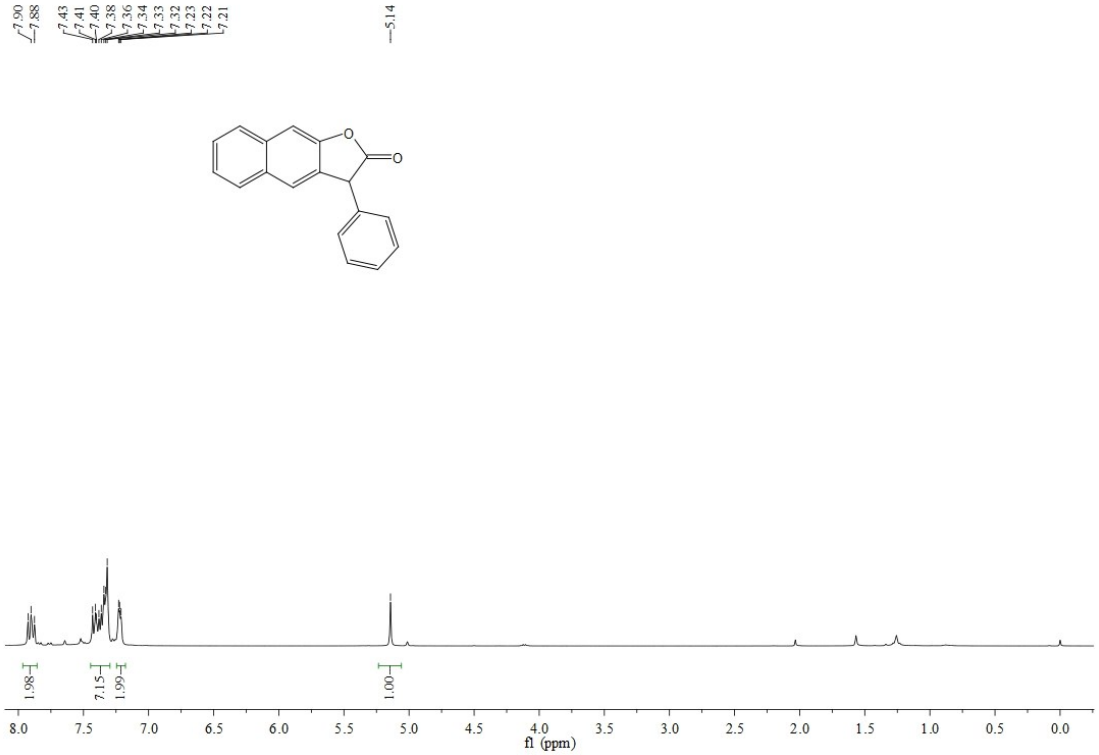
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3n



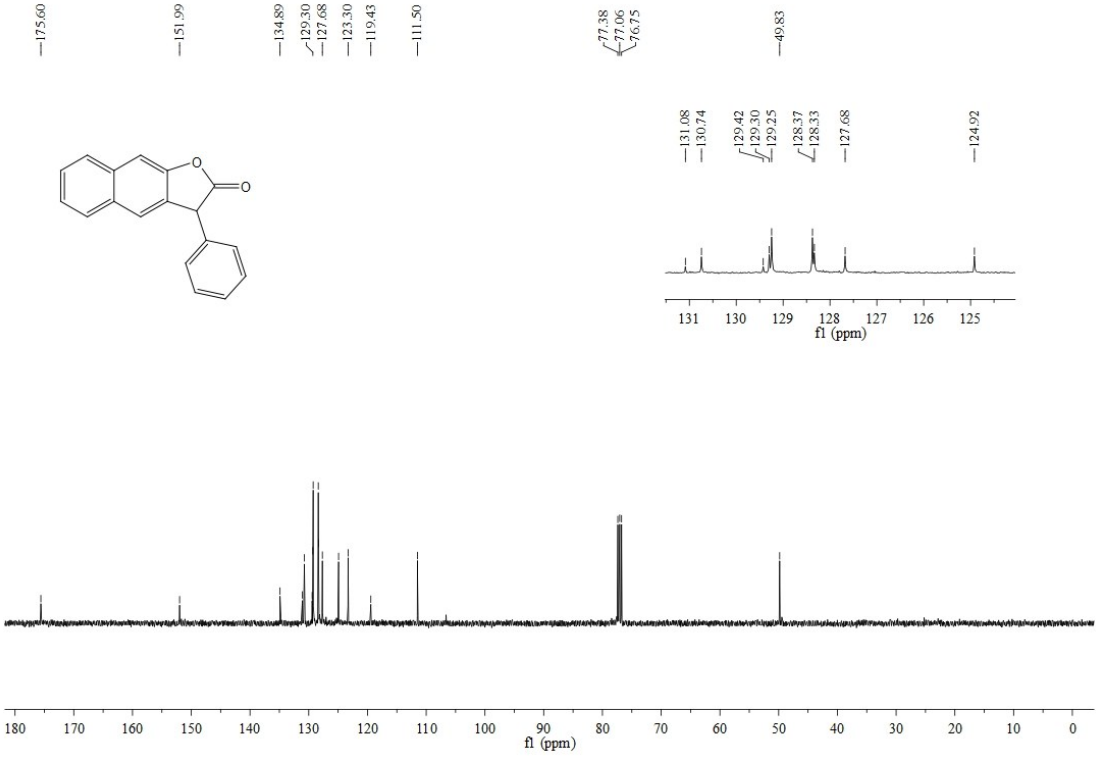
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3n



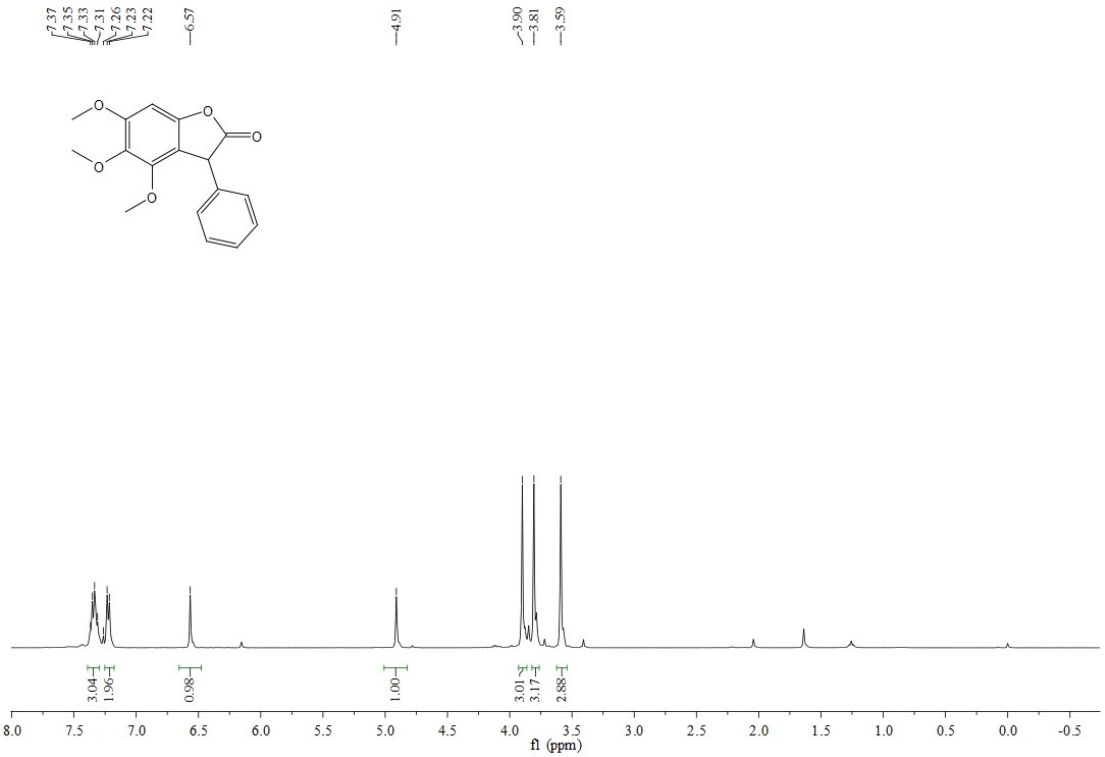
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3o



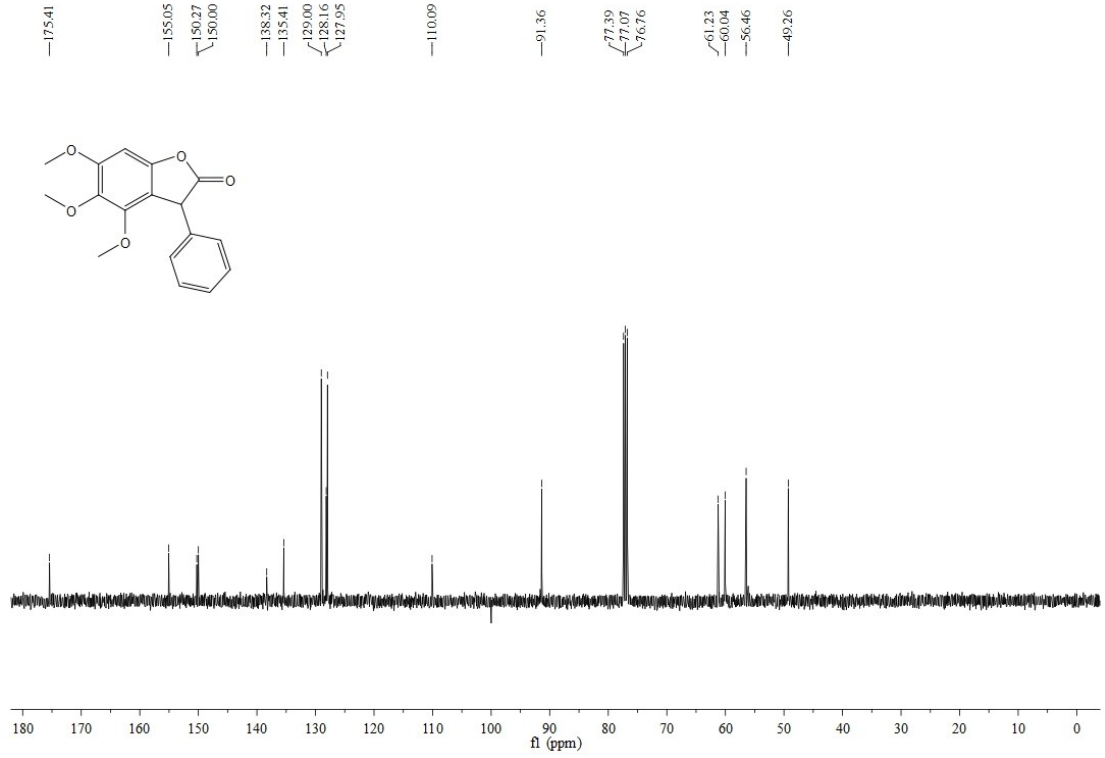
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3o



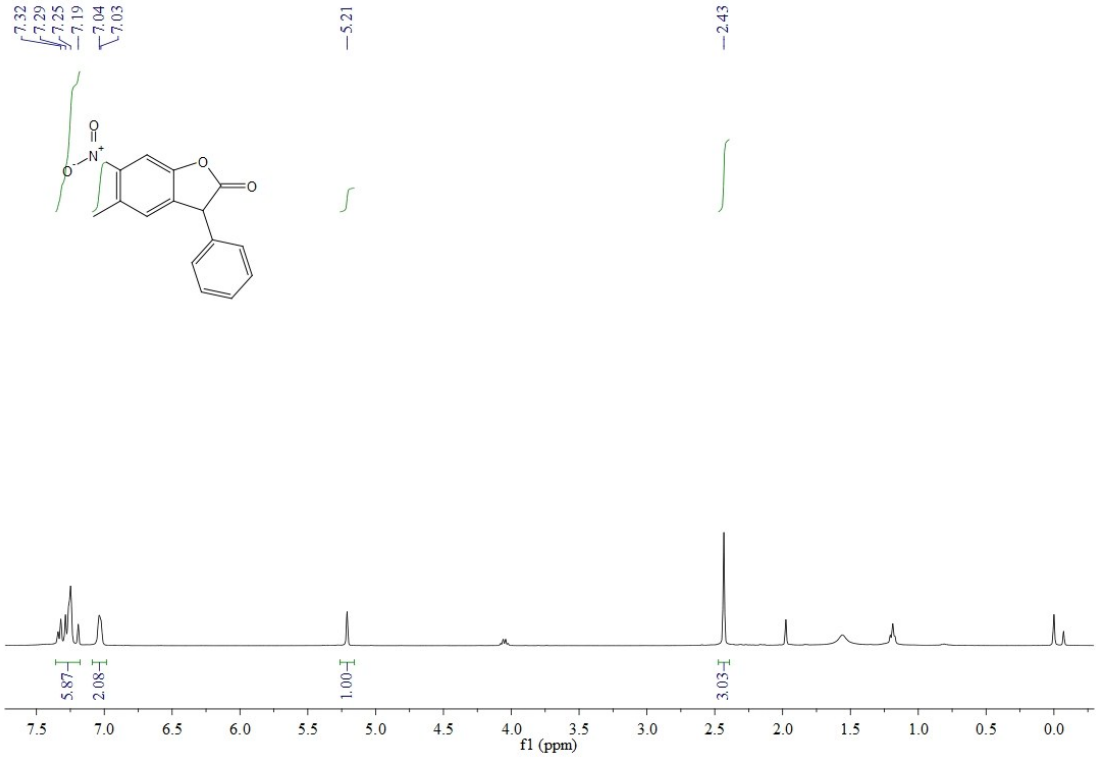
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3p



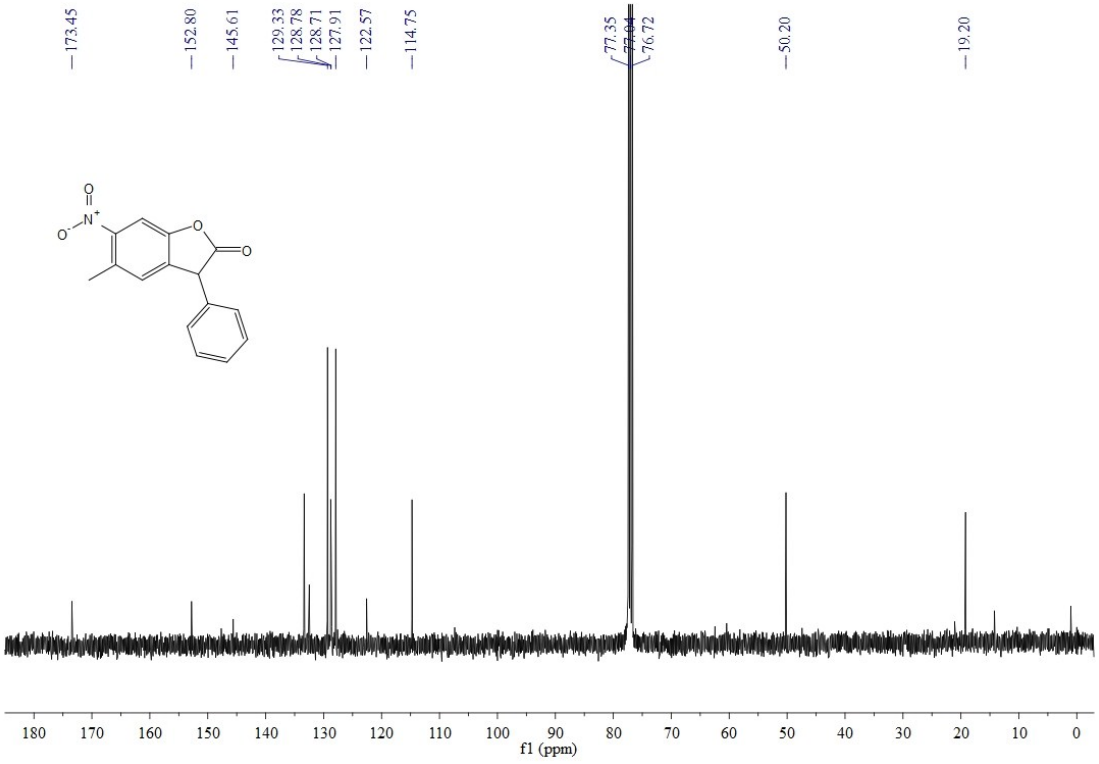
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3p



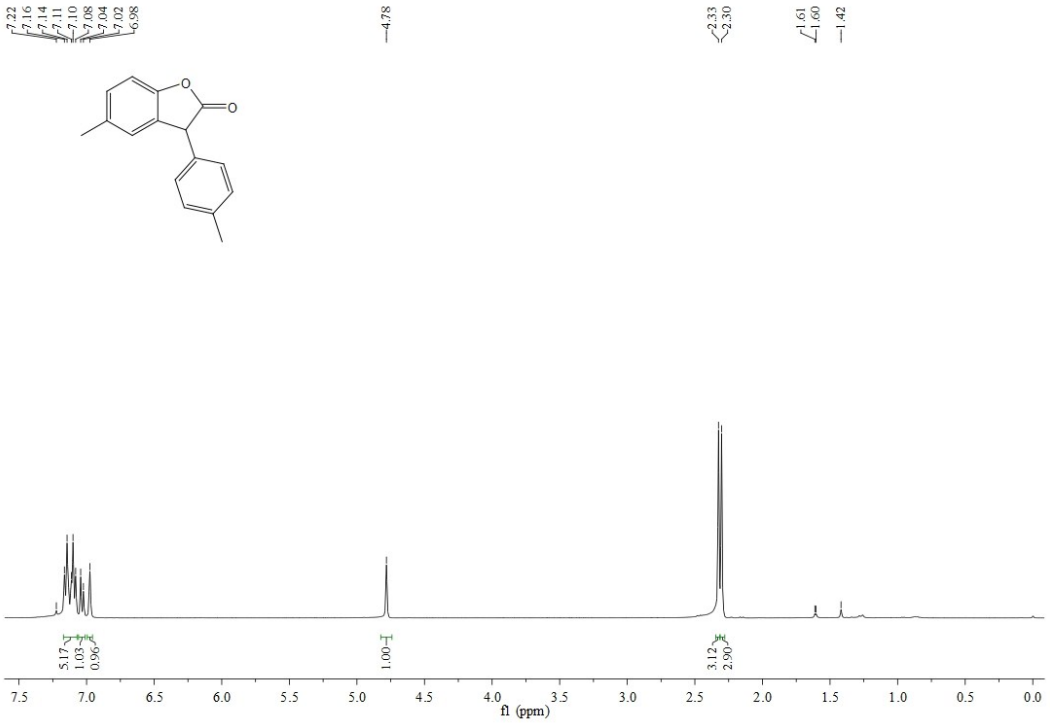
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 3q



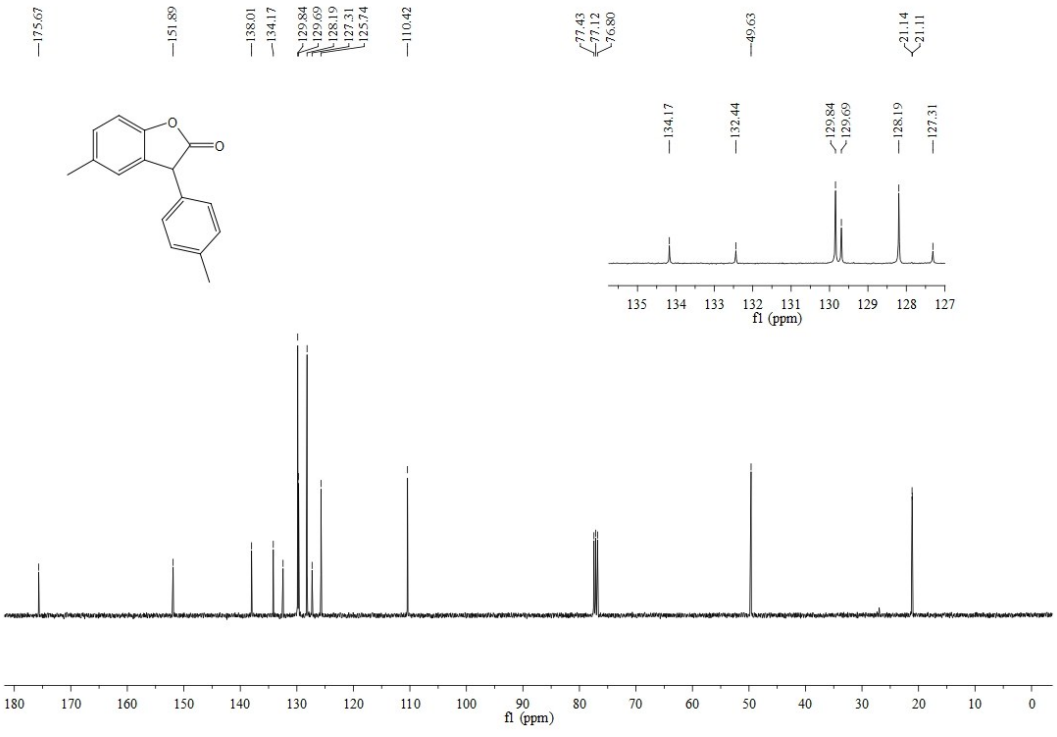
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 3q



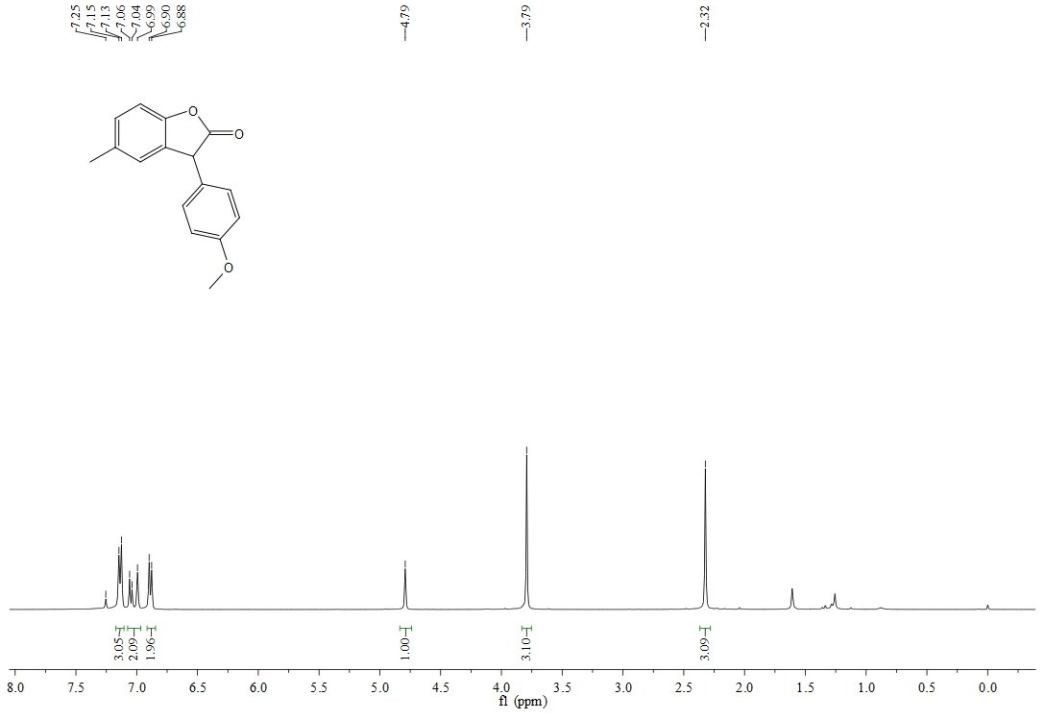
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 4a



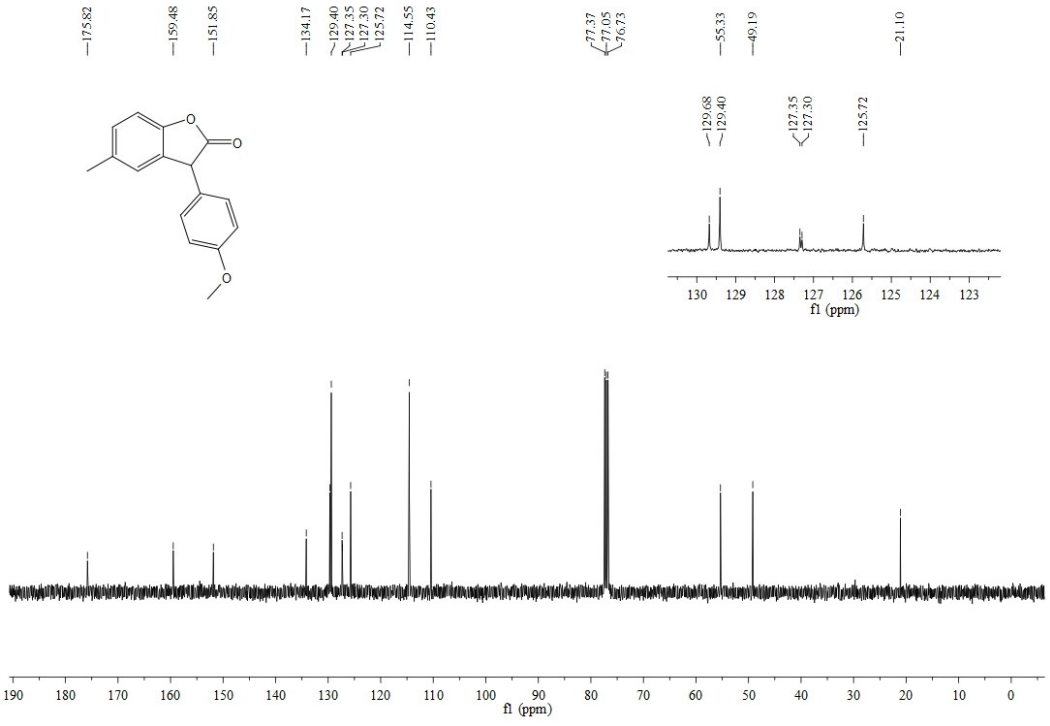
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 4a



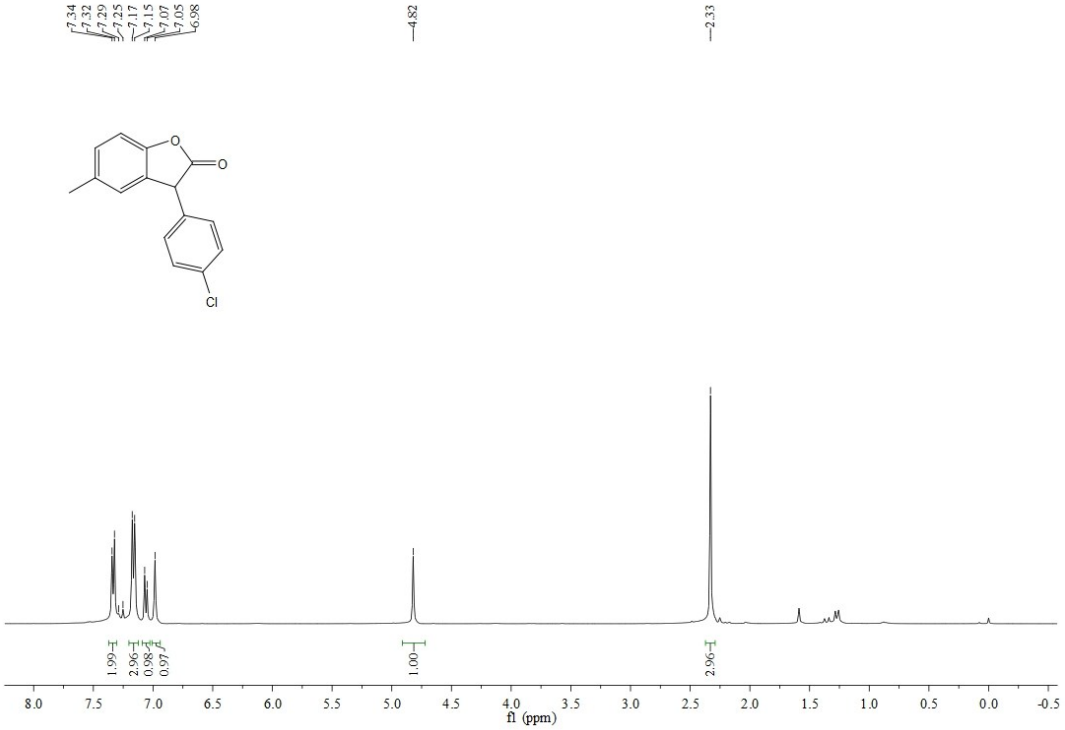
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 4b



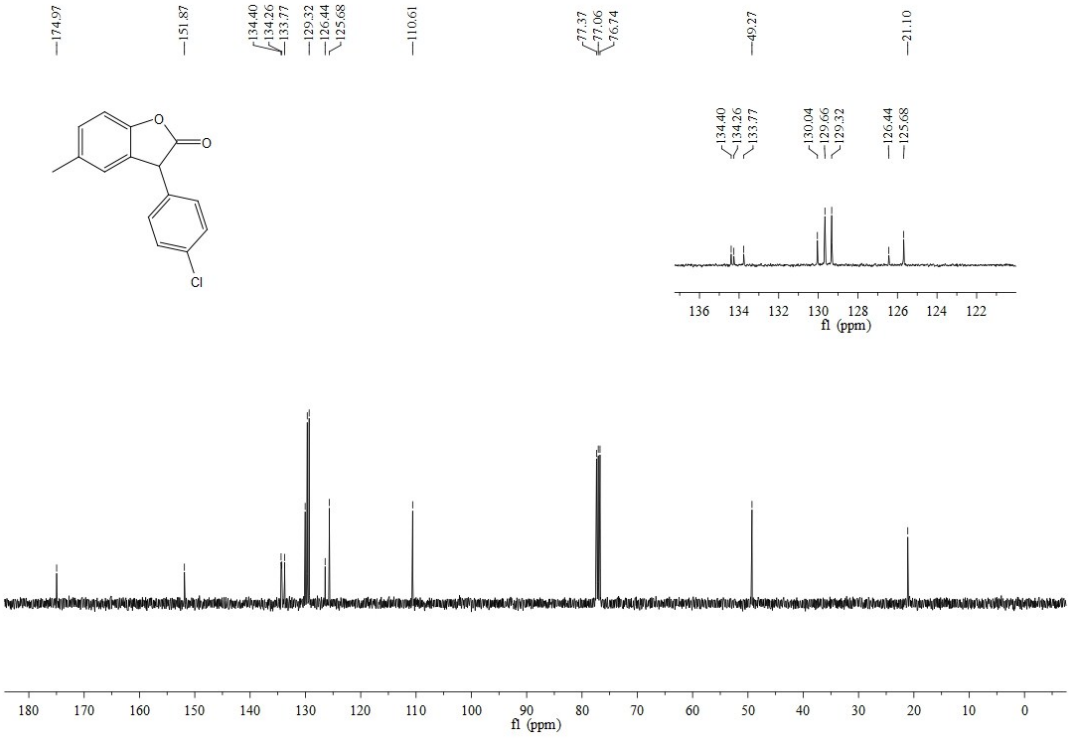
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 4b



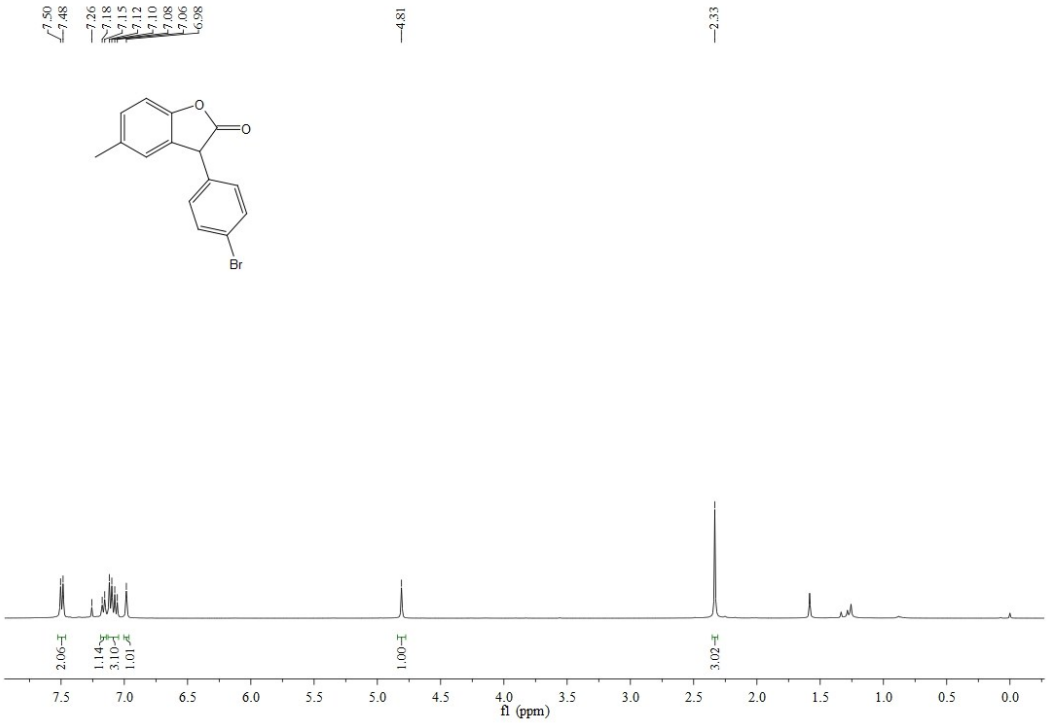
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 4c



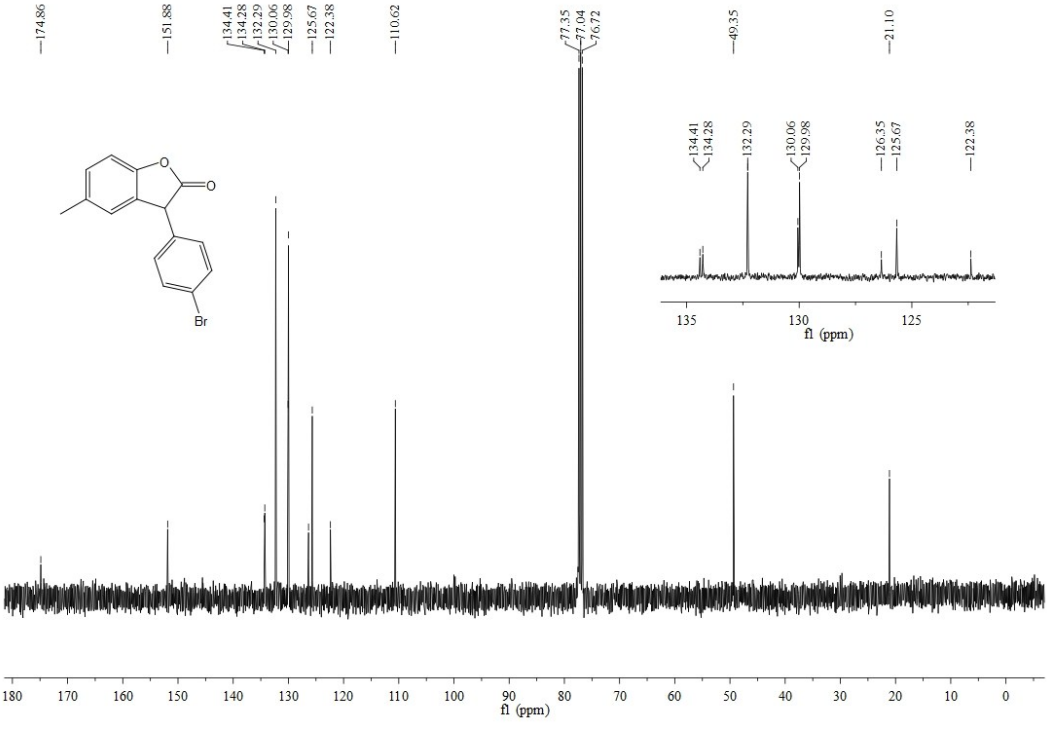
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 4c



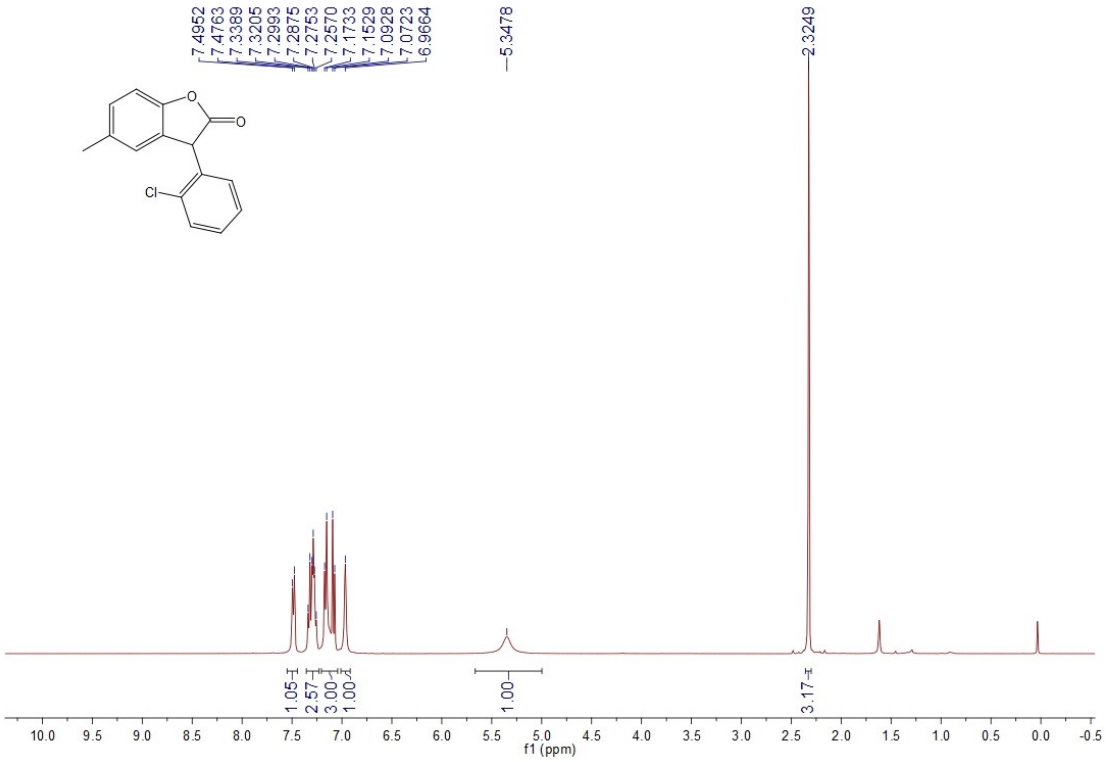
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 4d



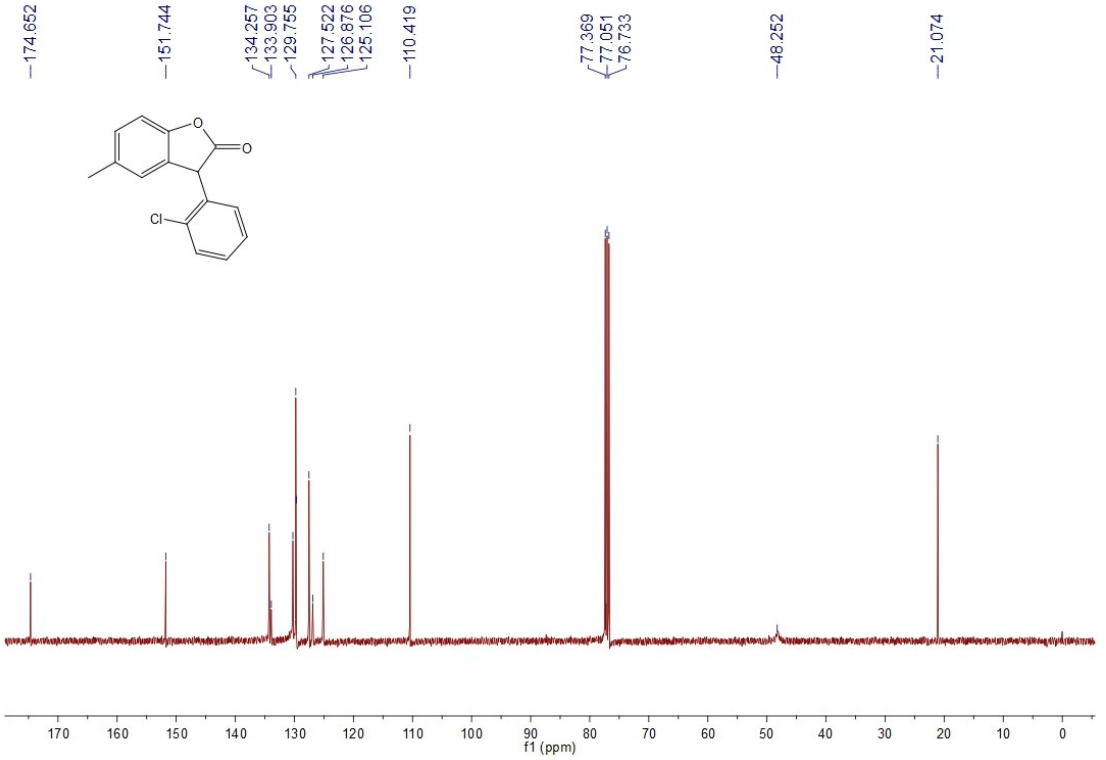
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 4d



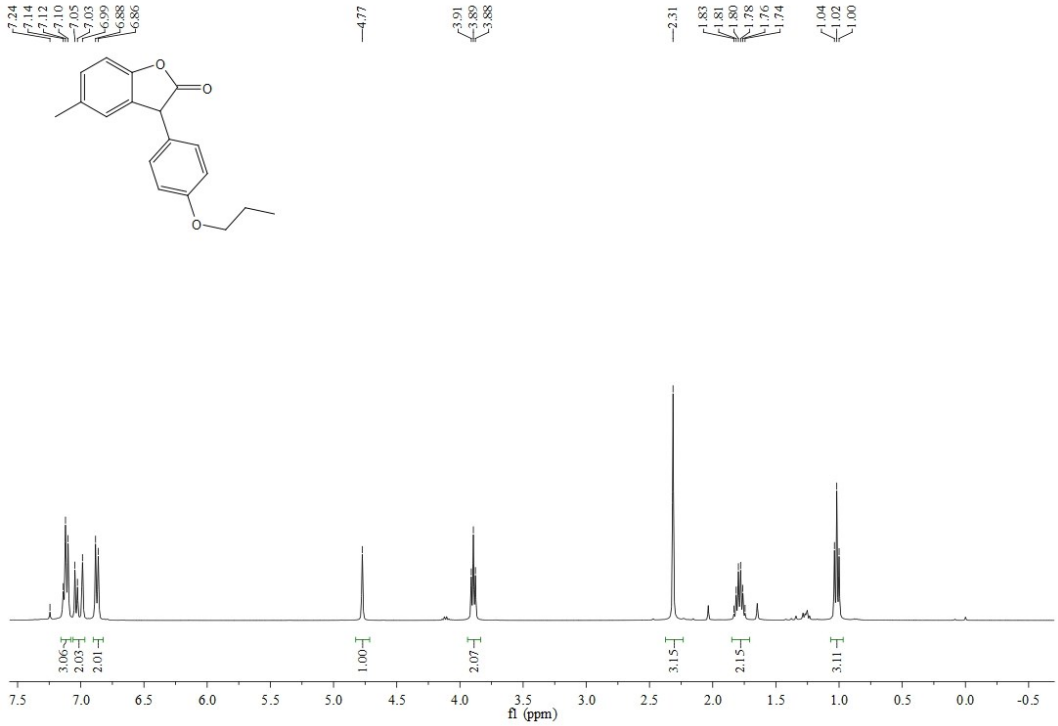
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 4e



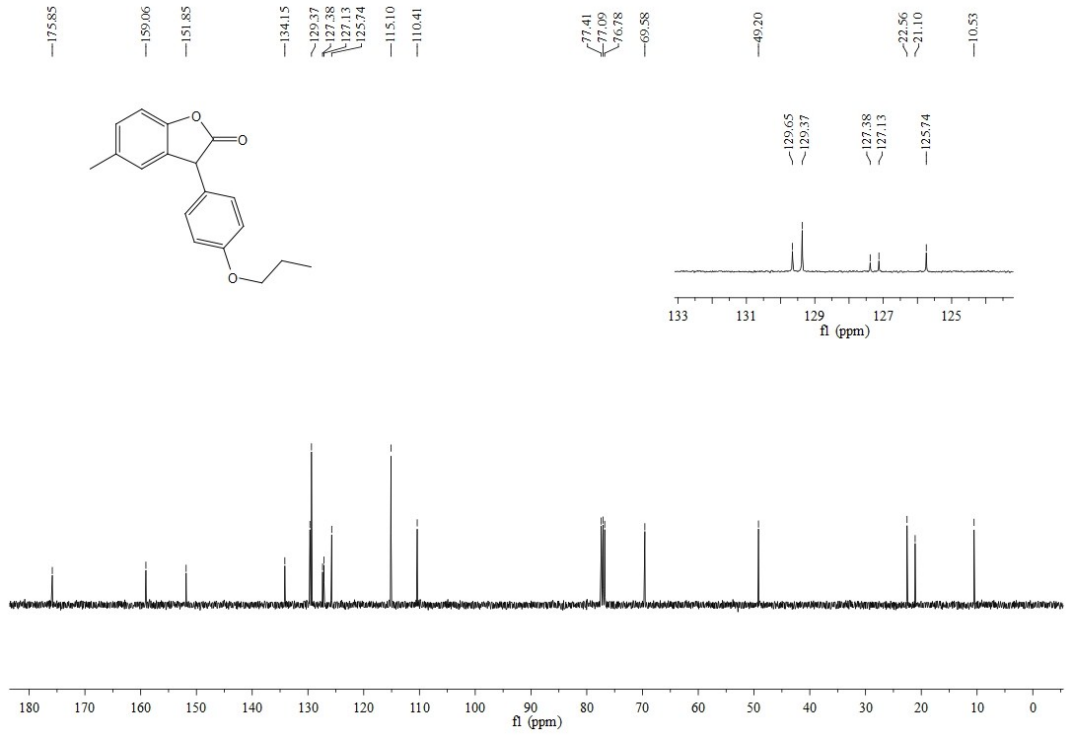
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 4e



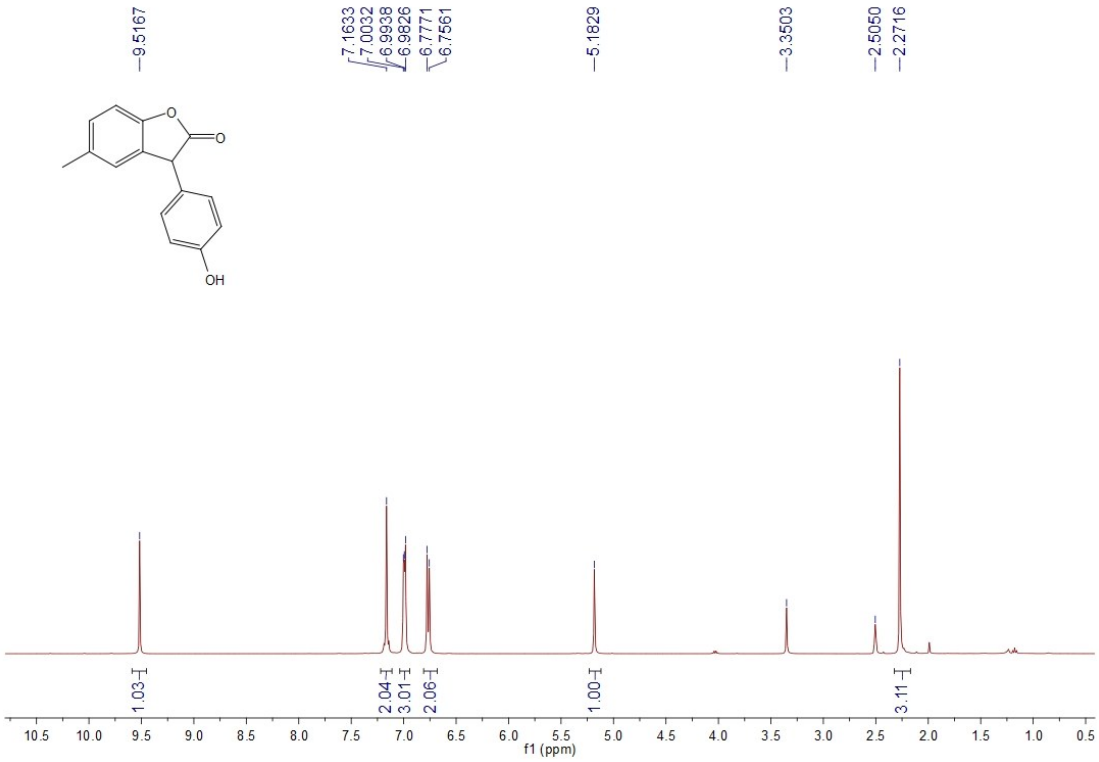
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 4f



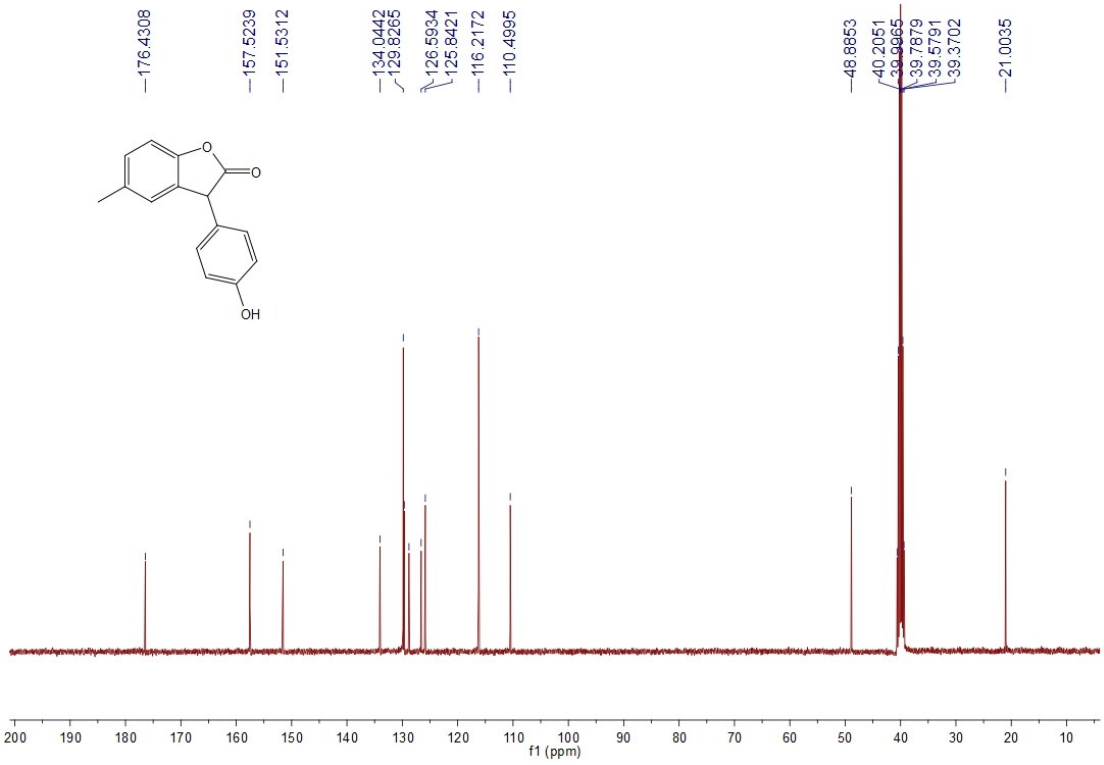
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 4f



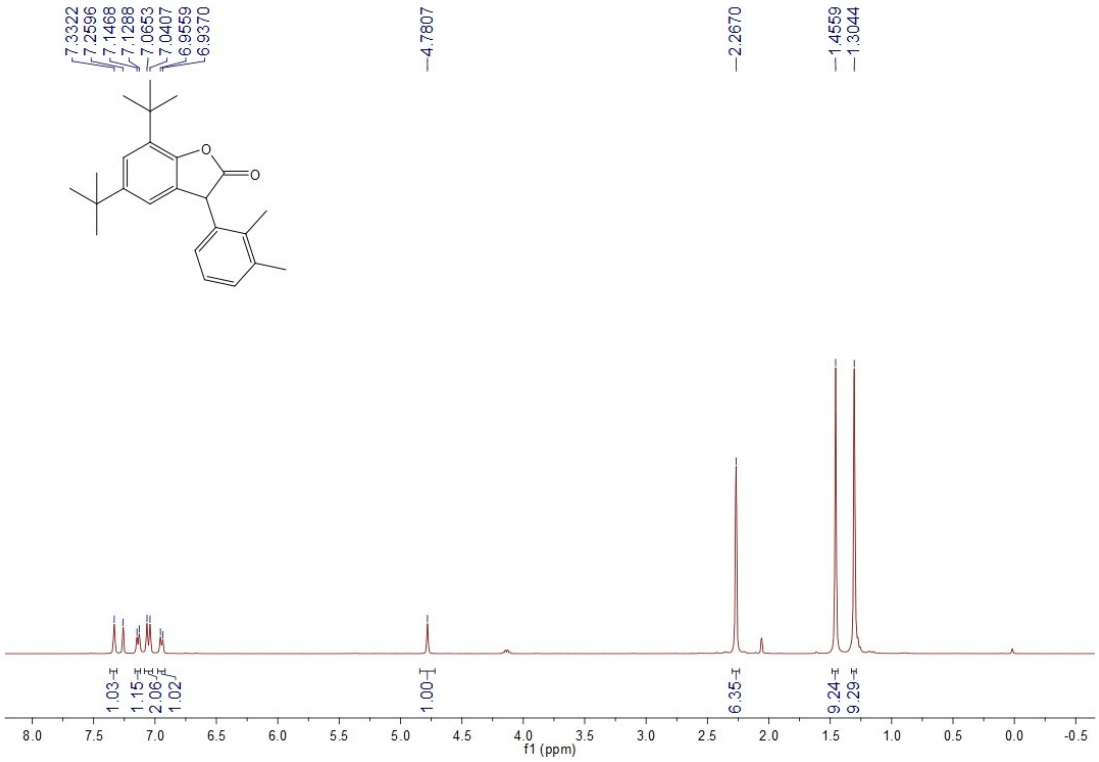
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 4g



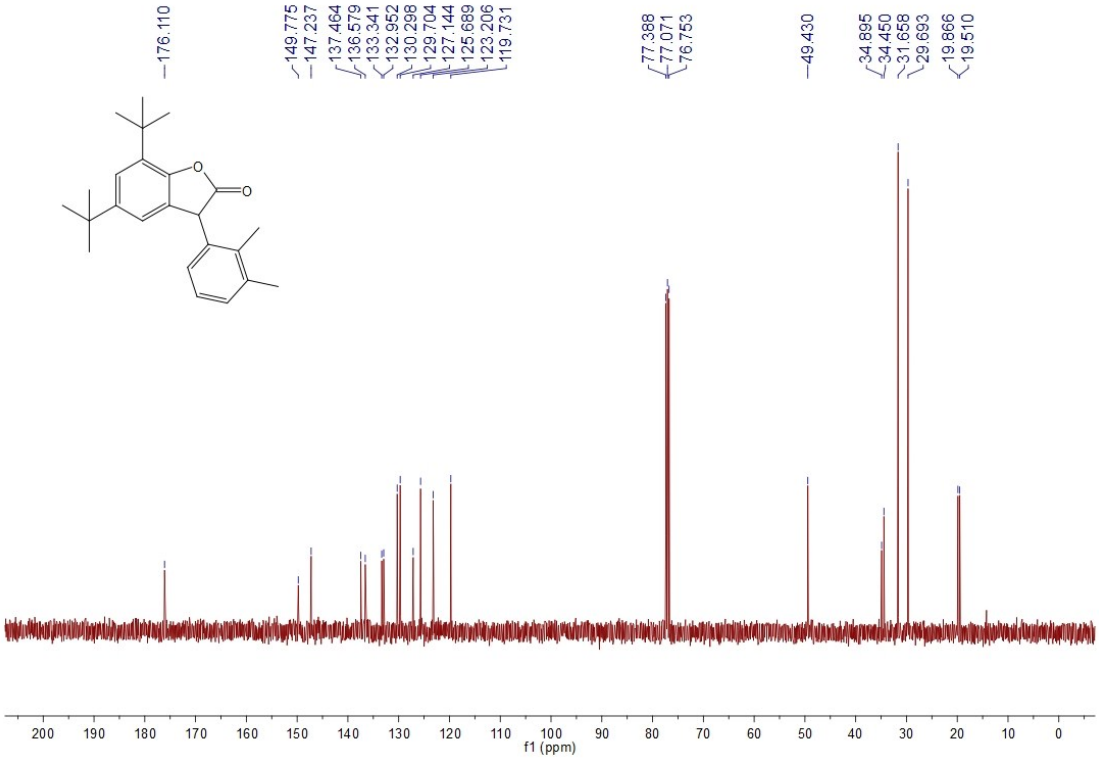
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 4g



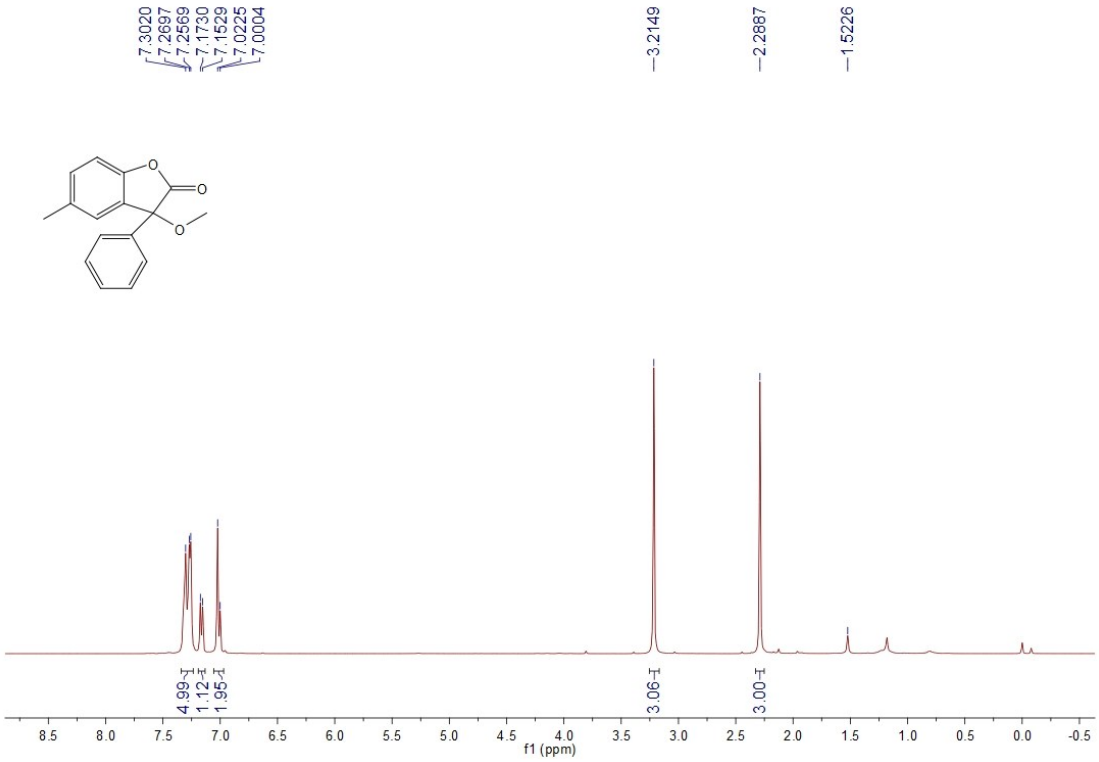
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for HP-136



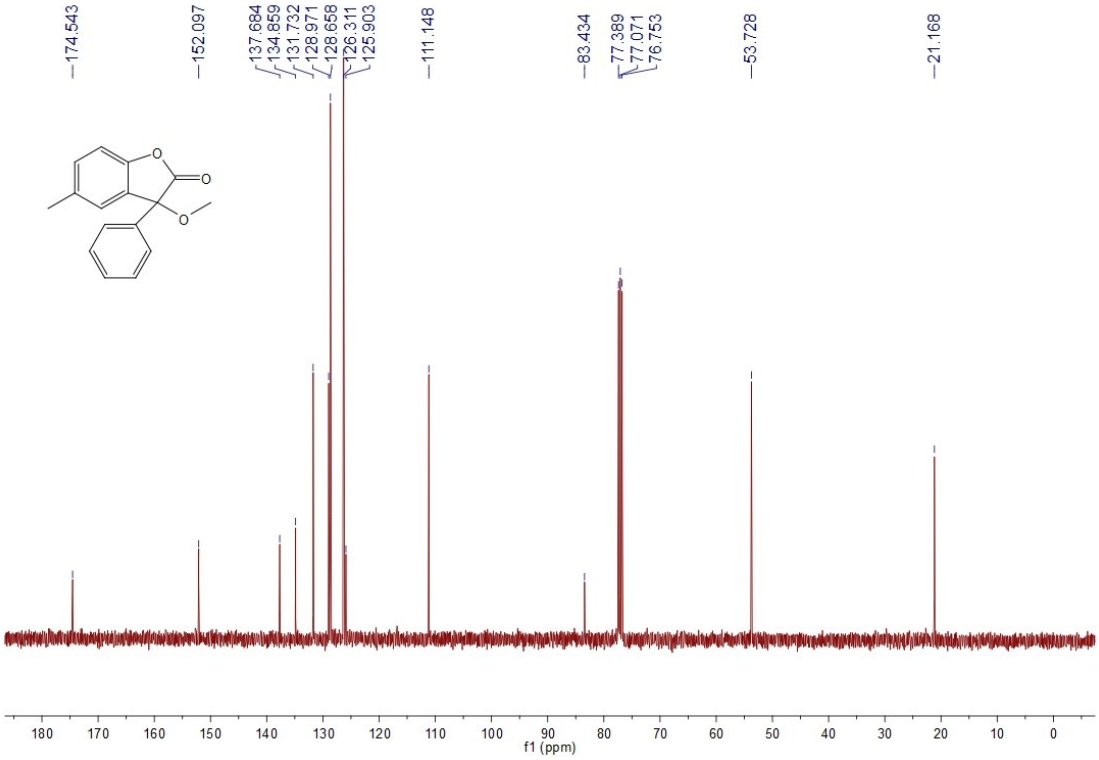
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for HP-136



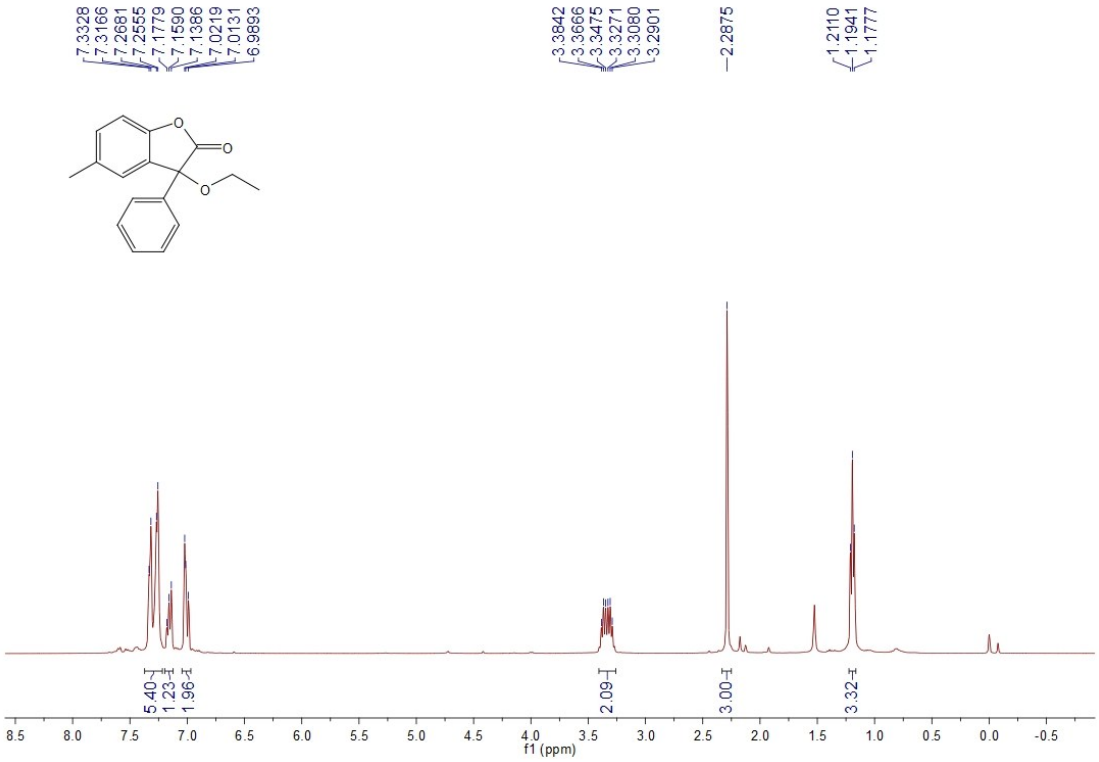
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 6a



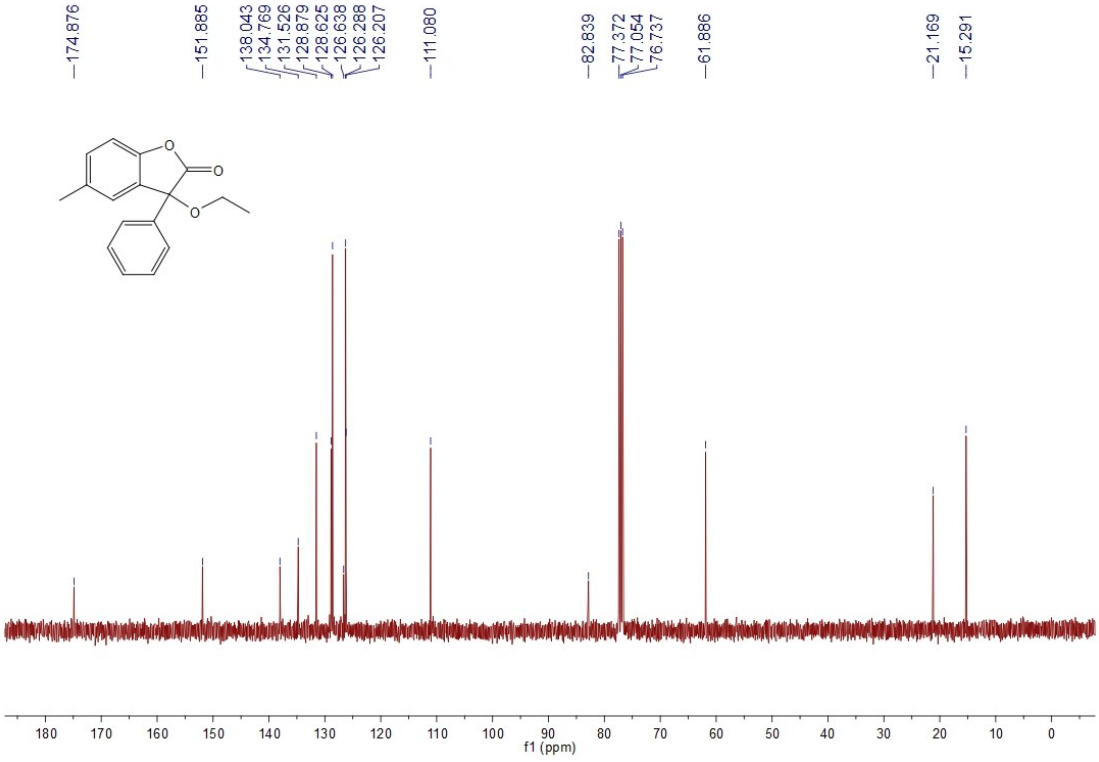
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 6a



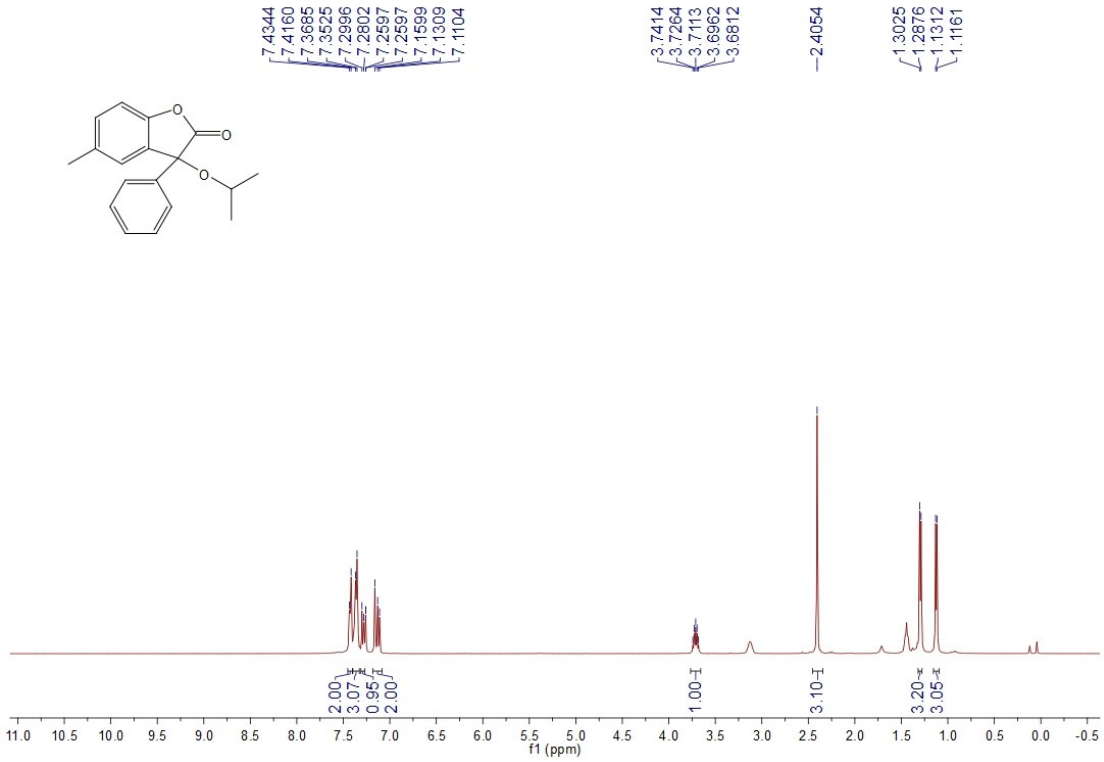
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 6b



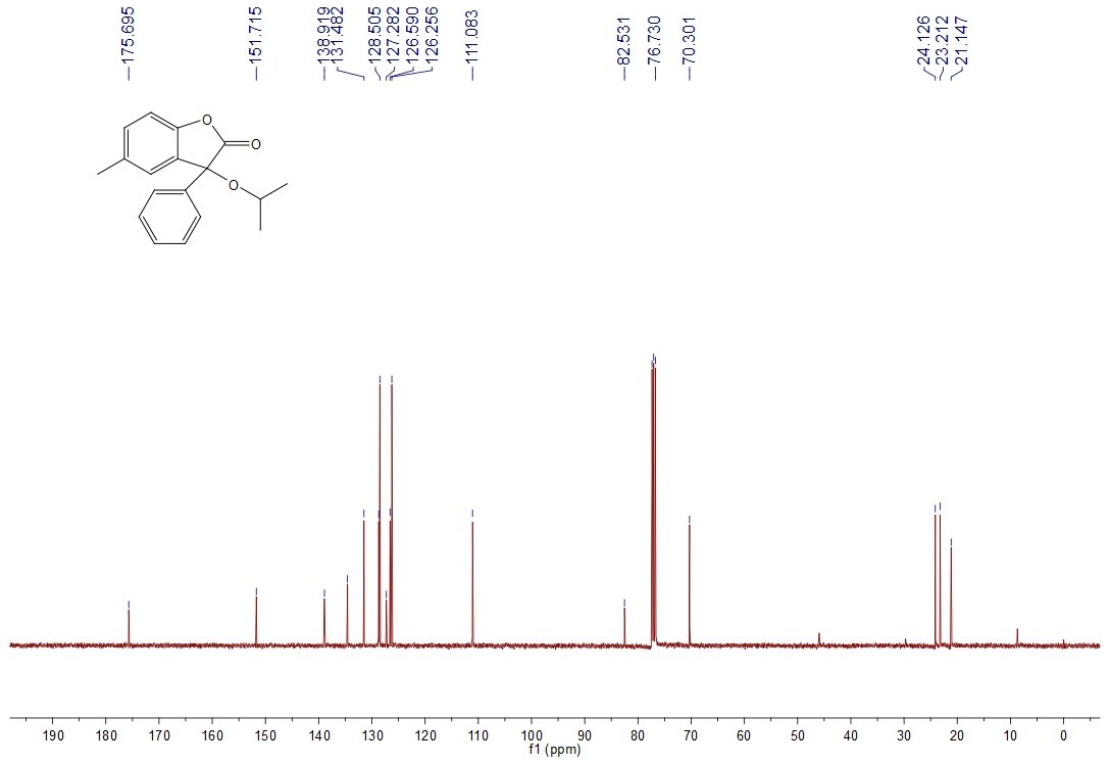
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 6b



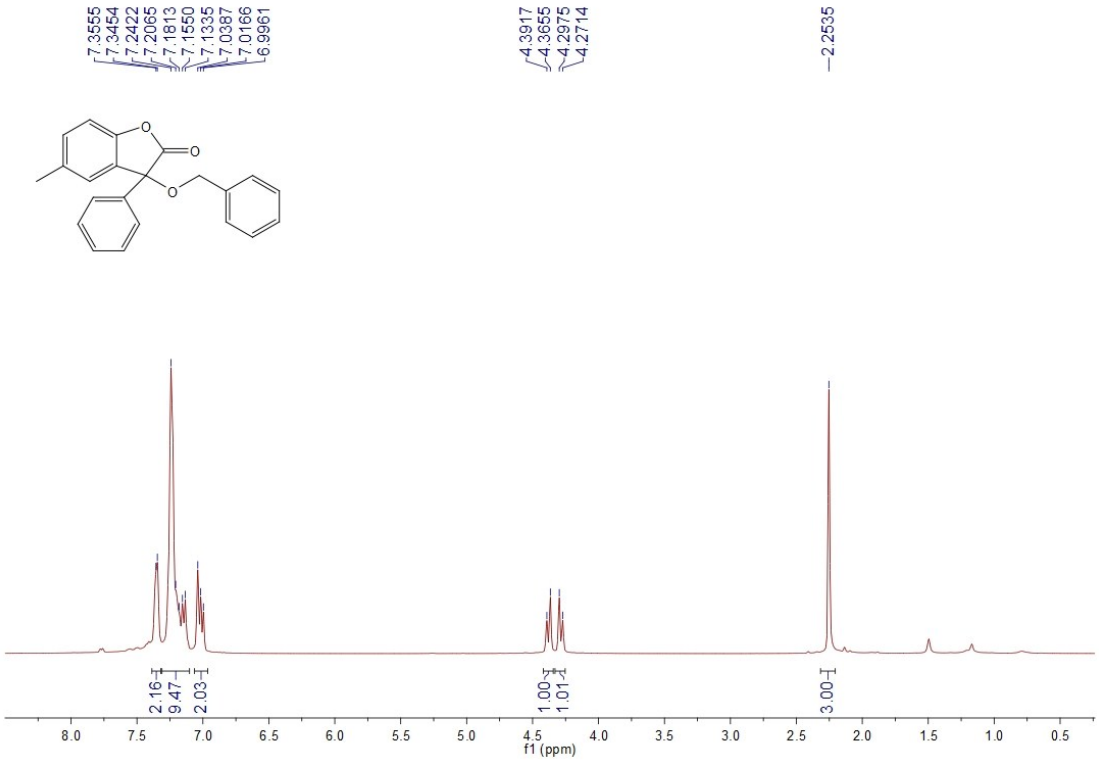
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 6c



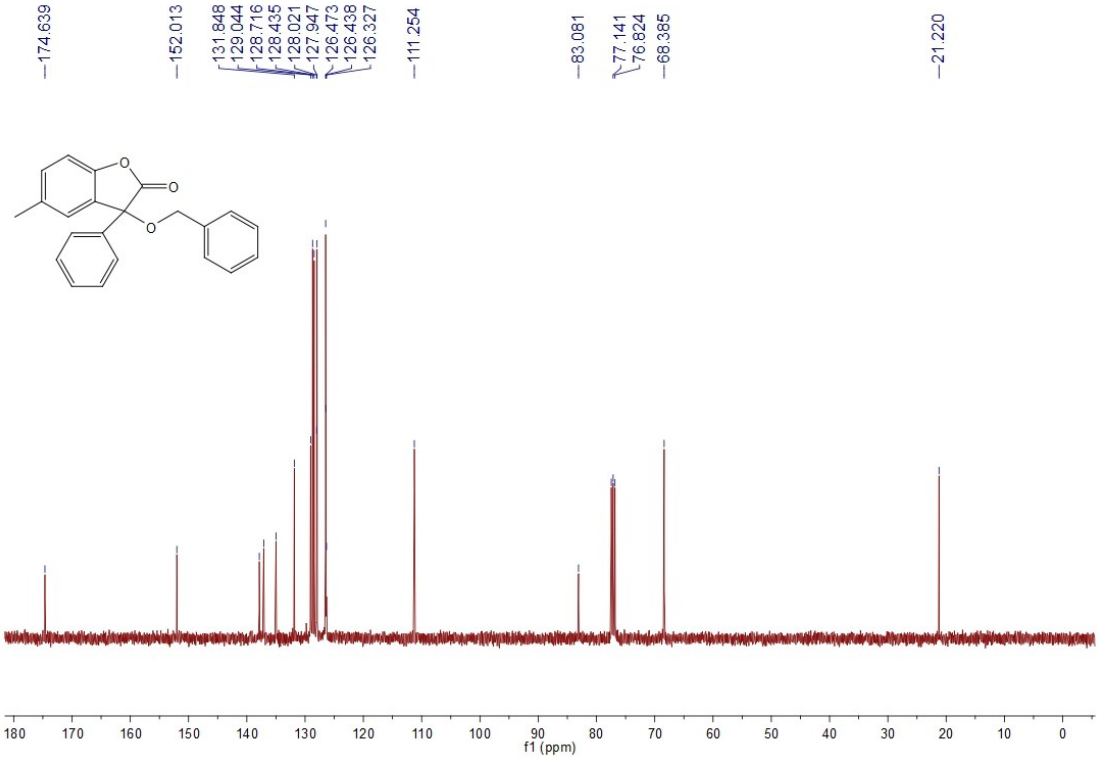
^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 6c



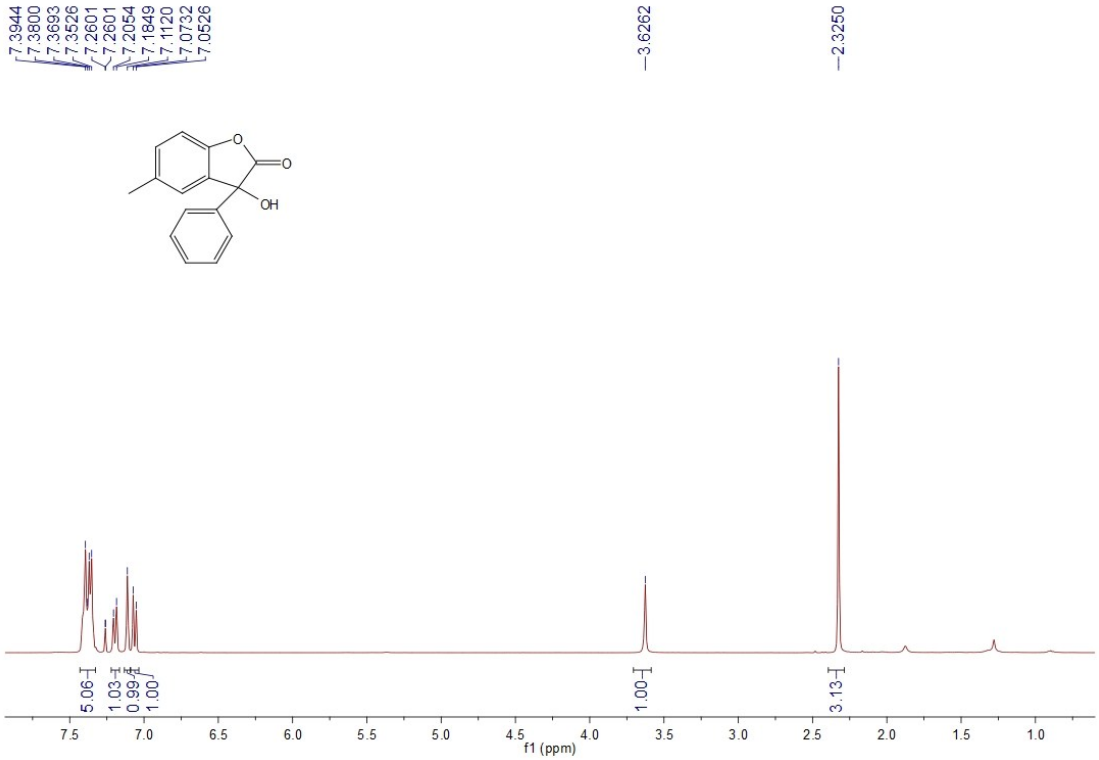
^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 6d



^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 6d



^{1}H NMR (400 MHz, $CDCl_3$) spectrum for 6e



^{13}C NMR (100 MHz, $CDCl_3$) spectrum for 6e