Electronic Supplementary Material (ESI) for Polymer Chemistry.

Supporting Information for

Chiral Phosphoric Acids Catalyzed Asymmetric Kinetic Resolution Polymerization of 6-Aryl-ε-Caprolactones

Chengdong Lv,[a,b] Guangqiang Xu,*[a] Rulin Yang,[a,b] Li Zhou[a] and Qinggang Wang*[a,b]

a. Key Laboratory of Biobased Materials, Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences, Qingdao, 266101, China.

b. Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing, 100049, China.

Contents

1. Materials

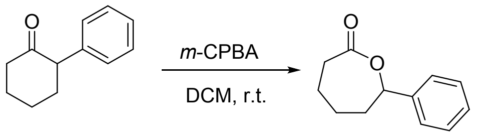
6-Aryl-ε-caprolactone monomers: 6-phenyl-caprolactone, 6-(*p*-chloroaryl)-caprolactone and 6-(*p*-^{t}butylaryl)-caprolactone were synthesized followed the reported literatures, purified by recrystallization two times from toluene, dried under vacuum for two days prior to use. Chiral phosphoric acids were purchased from Daicel Chiral Technologies without further purification, CPA-1: (*R*)-3,3'-Bis(2,4,6-triisopropylphenyl)-1,1'-binaphthyl-2,2'-diyl hydrogenphosphate; CPA-2: (*S*)-3,3'-Bis[3,5-bis(trifluoromethyl)phenyl]-1,1'-binapthyl-2,2'-diyl hydrogenphosphate; CPA-3: (*S*)-3,3'-Bis(2,4,6-triisopropylphenyl)-5,5',6,6',7,7',8,8'-octahydro-1,1-binaphthyl-2,2-diyl hydrogenphosphate. Benzyl alcohol (BnOH, > 99.9%) was received from Alfa Aesar, distilled by calcium hydride (CaH_2). The BnOH dissolved into a 1 M solution of toluene as the initiator. Triethylamine (Et_3N, > 99.9%, Sigma-Aldrich) in $CDCl_3$ was used as quenching solution. Amberlyst A21 (Aladdin) was used as received. All dry solvents were redistilled after collected from solvent purification system. Afterwards, they were stored over molecular sieves (4 Å) in a glovebox for no longer than 1 month. Chromatographic grade hexane, isopropanol and tetrahydrofuran were purchased from Honeywell LTD for the analysis of HPLC and GPC measurements. The detailed synthesis steps and spectral characterizations are showed below.

2. Instrumentation

^1H NMR, ^{13}C NMR measurements were performed at room temperature on Bruker Advance instrument at 400 MHz. $CDCl_3$ was used as an internal reference ($\delta = 7.26$). Molecular weights (M_ns) and molecular weight distributions (PDI) of the polymers were determined by gel permeation chromatography (GPC, Agilent 1260 LC, USA) using THF as the eluent (flow rate: 1 mL/min, at 40 °C) and the sample concentration was 1 mg/mL. The enantiomeric excess (*ee*) of the unreacted monomer was measured by Shimadzu Prominence LC-20A Series High Performance Liquid Chromatography (HPLC), and determined using a UV (190 nm) detector.

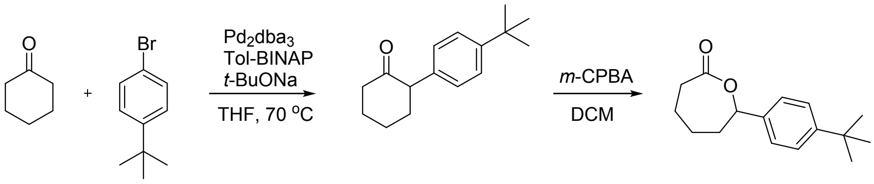
3. Preparation of the 6-aryl-ε-Caprolactones

3.1 Synthesis of the 6-phenyl-caprolactone (6-Ph-CL, 1a)



6-Phenyl-caprolactone was synthesized by the Baeyer-Villiger reaction. 2-Phenylcyclohexanone (522 mg, 3 mmol, 1 equiv.) was vigorously stirred with 3-chloroperoxybenzoic acid (*m*-CPBA, 1.03g, 6 mmol, 2 equiv.) in 10 mL DCM at room temperature. After 12 h, Na_2SO_3 (3 M, 10 mL) and saturated NaCl (10 mL) was added to the mixture. The reaction was extracted with DCM (15 mL) to obtain a crude product. The crude product was then purified by flash chromatography (PE:EA = 20:1) to give white solid (490 mg, 86% yield). ^{1}H NMR (400 MHz, Chloroform-*d*, 298 K) δ 7.49 – 7.28 (m, 5H), 5.42 – 5.13 (m, 1H), 2.89 – 2.63 (m, 2H), 2.20 – 1.91 (m, 4H), 1.82 – 1.67 (m, 2H). ^{13}C NMR (100 MHz, Chloroform-*d*, 298 K) δ 174.9, 140.8, 128.6, 128.1, 125.9, 82.1, 37.5, 35.0, 28.7, 22.9.

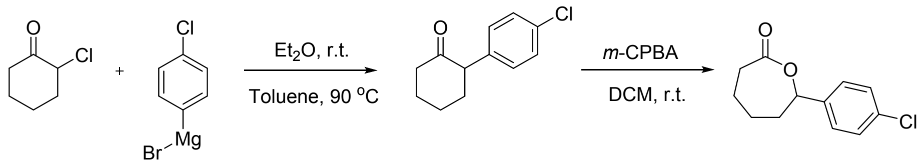
3.2 Synthesis of the 6-(*p*-^{t}butylaryl)-caprolactone (6-*p*-^{t}Bu-C_6H_4-CL, 1b)



2-(*p*-^{t}Butylaryl)-cyclohexanone was synthesized followed the literature.[2] An oven-dried round-bottomed flask containing reflux tube was charged with Pd_2dba_3 (350 mg, 0.38 mmol, 0.0075 equiv.), (*S*)-Tol-BINAP ligand (620 mg, 0.92 mmol, 0.018 equiv.), and *t*-BuONa (3.18 g, 33 mmol, 0.65 equiv.). The flask was evacuated and back filled with argon. THF (40 mL) was added followed by 1-bromo-4-*tert*-butylbenzene (5.4 g, 25 mmol, 0.5 equiv.), cyclohexanone (5 g, 51 mmol, 1 equiv.), and additional THF (20 mL). The resulting red mixture was heated under argon at 70 °C until the starting 1-bromo-4-*tert*-butylbenzene had been consumed as judged by TLC. The reaction was cooled to room temperature, and diethyl ether (100 mL) and H_2O (100 mL) were added. The aqueous layer was separated and extracted with diethyl ether (25 mL). The combined organic layers were washed with brine (200 mL), dried over Na_2SO_4, filtered and concentrated. The crude product was then purified by flash chromatography (PE:EA = 100:1) on silica gel. The general procedure gave colorless oil (4.5 g, 77% yield).

6-(*p*-^{t}Butylaryl)-caprolactone was synthesized by the Baeyer-Villiger reaction. 2-(*p*-^{t}Butylaryl)-cyclohexanone (460 mg, 2 mmol, 1 equiv.) was vigorously stirred with *m*-CPBA (688 mg, 4 mmol, 2 equiv.) in 15 mL DCM at room temperature, After 14 h, Na_2SO_3 (3 M, 15 mL) and saturated NaCl (15 mL) was added to the mixture. The reaction was extracted with DCM (15 mL) to obtain a crude product. The crude product was then purified by flash chromatography (PE:EA = 20:1) to give white solid (344 mg, 71% yield). ^{1}H NMR (400 MHz, Chloroform-*d*, 298 K) δ 7.40 – 7.35 (m, 2H), 7.33 – 7.30 (m, 2H), 5.27 (d, *J* = 8.6 Hz, 1H), 2.84 – 2.70 (m, 2H), 2.12 – 1.94 (m, 4H), 1.79 – 1.66 (m, 2H), 1.31 (s, 9H). ^{13}C NMR (100 MHz, Chloroform-*d*, 298 K) δ 175.0, 151.1, 137.8, 125.7, 125.5, 82.0, 37.3, 35.0, 34.6, 31.3, 28.6, 22.9.

3.3 Synthesis of the 6-(*p*-chloroaryl)-caprolactone (6-*p*-Cl-C_6H_4-CL, 1c)



2-(*p*-Chloroaryl)-cyclohexanone was synthesized followed the reported literature.[1] 2-Chlorocyclohexanone (5.3 g, 40 mmol, 1 equiv.) was added via injector into a new prepared 80 mL arylmagnesium bromide solution (1 M in THF, 50 mL, 50 mmol, 1.25 equiv.) in 80 mL ether at a rate under nitrogen. The ether was completely distilled out after 2 hours and 70 mL anhydrous toluene was added, the mixture was refluxed at 90 °C overnight. Then the reaction mixture was cooled to room temperature, hydrolyzed with water and extracted with 200 mL EtOAc. The organic layers were combined, washed with brine (100 mL), dried over Na_2SO_4, filtered and concentrated. The crude product was then purified by flash chromatography (PE:EA = 10:1). The general procedure gave white solid (2.2 g, 26% yield).

6-(*p*-Chloroaryl)-caprolactone was synthesized by the Baeyer-Villiger reaction. 2-(*p*-Chloroaryl)-cyclohexanone (416 mg, 2 mmol, 1 equiv.) was vigorously stirred with *m*-CPBA (688 mg, 4 mmol, 2 equiv.) in 15 mL DCM at room temperature. After 12 h, Na_2SO_3 (3 M, 15 mL) and saturated

NaCl (15 mL) was added to the mixture. The reaction was extracted with DCM (15 mL) to obtain a crude product. The crude product was then purified by flash chromatography (PE:EA = 20:1) to give white solid (270 mg, 60% yield). ^{1}H NMR (400 MHz, Chloroform-*d*, 298 K) δ 7.33 (s, 4H), 5.27 (d, *J* = 8.7 Hz, 1H), 2.85 – 2.65 (m, 2H), 2.16 – 1.90 (m, 4H), 1.83 – 1.63 (m, 2H). ^{13}C NMR (100 MHz, Chloroform-*d*, 298 K) δ 174.7, 139.5, 134.0, 128.9, 127.4, 81.4, 37.7, 35.1, 28.7, 22.9.

4. Typical procedure for polymerization of 6-aryl-ε-caprolactone

In a typical polymerization reaction, a dry 5 mL schlenk tube was evacuated and back filled with argon three times, was then introduced into an Argon-filled glovebox. 6-Aryl-ε-caprolactone (6-*p*-Cl-C_6H_4-CL as example) (56 mg, 250 μmol, 50 equiv.), CPA-3 catalyst (3.8 mg, 5 μmol, 1 equiv.), and initiator of BnOH solution (5 μL, 5 μmol, 1 equiv.) were dissolved in toluene (1 mL) in the schlenk tube. Polymerization was vigorously stirred for the certain time at 90 °C. Then the reactions were quenched by a mount of addition of Et_3N solvent (1 M in $CDCl_3$) at a certain time. Monomer conversion was monitored by ^{1}H NMR spectrum and calculated by comparing the integration of the methine signals of unreacted monomer to the methine region of the polymer before precipitation.

Withdrawn solvent of reaction was removed by vacuum and polymeric residue was analysed by GPC technology to afford M_ns and PDI values, meanwhile *ee* value of unreacted monomer was detected by chiral HPLC using the part monomer. The solvent was removed via vacuum pump, and the unreacted monomer was collected with TLC after coloration, filtered through a 0.2 μm syringe filter, unreacted monomer was dissolved into mixture solvent (*n*-hexane : *i*-PrOH = 90:10) and the *ee* value of the monomer was measured by chiral HPLC, utilizing a Chiracel OD-3 column (*n*-hexane : *i*-PrOH = 95:5; 1.0 mL/min). The selectivity factor, *s*, was determined from the Kagan's equation $s = \ln[(1 - c)(1 - ee)]/\ln[(1 - c)(1 + ee)]$, where *c* is the monomer conversion and *ee* is the enantiomeric excess of the unreacted monomer.

5. AKRP of 6-*p*-Cl-C_6H_4-CL using CPA-3 as the organocatalyst

Table S1. Asymmetric kinetic resolution polymerization study of 6-(*p*-chloroaryl)-caprolactone using CPA-3.

Entry[a]	Time (h)	Conv.[b] (%)	$M_{n,GPC}$[c] (g/mol)	PDI[c]	*ee*[d] (%)	*s*-factor[e]
1	4	17	1800	1.14	10	3.2
2	7	20	2400	1.17	14	4.0
3	9	26	2900	1.19	19	4.0
4	12	36	3300	1.20	29	4.1
5	17	44	4200	1.21	38	4.1
6	21	50	4800	1.19	38	3.1
7	32	58	5500	1.20	42	2.7
8	38	66	5500	1.25	49	2.6
9	48	70	6000	1.25	57	2.7
10	60	77	6400	1.28	61	2.4
11	72	81	6600	1.28	65	2.3
12	108	91	6700	1.33	69	1.9

[a] Reactions were carried in toluene at 90 °C; $[\text{monomer}]_0/[\text{Cat.}]_0/[\text{BnOH}]_0 = 50/1/1$; $[\text{monomer}]_0 = 0.17 \text{ mol L}^{-1}$. [b] Determined by ^{1}H NMR in $CDCl_3$. [c] Determined by GPC in THF against polystyrene standards. [d] Enantiomeric excess of the unreacted monomer was measured by chiral HPLC. [e] Selectivity factor (*s*) was determined from the equation $s = k_{fast}/k_{slow} = \ln[(1\text{-conv.})(1\text{-}ee)]/\ln[(1\text{-conv.})(1 + ee)]$.

6. Alcoholysis reaction and polymerization reaction of 6-*p*-Cl-C_6H_4-CL using CPA-3 as the organocatalyst

In a typical alcoholysis reaction, a dry schlenk tube was evacuated and back filled with argon three times, was then introduced into an Argon-filled glovebox. 6-*p*-Cl-C_6H_4-CL (11 mg, 50 μmol, 1 equiv.), CPA-3 catalyst (1.8 mg, 2.5 μmol, 0.05 equiv.), and initiator of BnOH solution (25 μL, 25 μmol, 0.5 equiv.) were dissolved in toluene (0.5 mL) in the schlenk tube at 0 or 50 °C. Alcoholysis reaction was vigorously stirred for the certain time. Then a small amount of reactions were quenched by addition of Et_3N solvent (1 M in

$CDCl_3$) at a certain time. Monomer conversion was monitored by ^1H NMR spectrum, meanwhile *ee* value of unreacted monomer was detected by chiral HPLC. Subsequently 6-*p*-Cl-C_6H_4-CL (44 mg, 200 μmol, 4 equiv.) in 2 mL toluene was added into the alcoholysis reaction at 0 or 50 °C for the certain time, the conversion and *ee* value of unreacted monomer were detected by ^1H NMR spectrum and chiral HPLC simultaneously. Detailed operations followed the steps mentioned above.

7. Figures

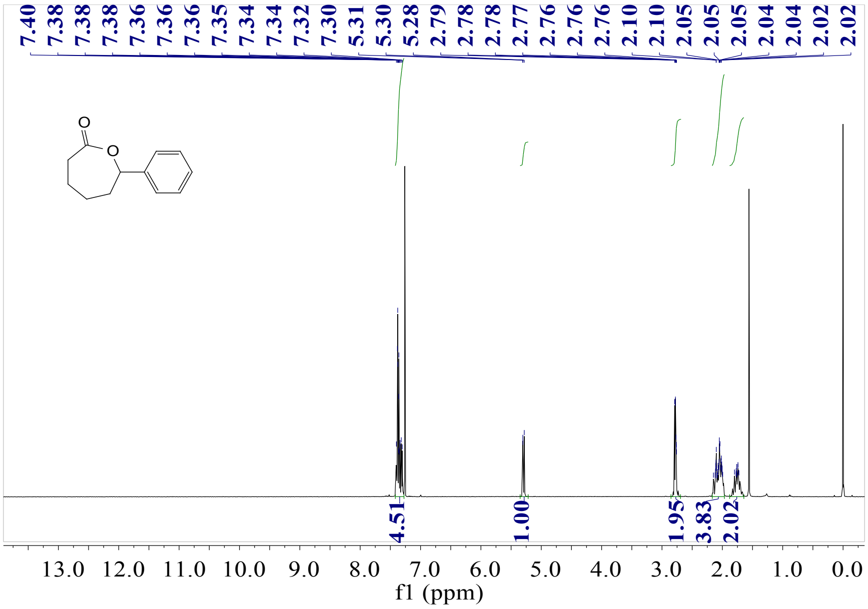


Figure S1a. ^1H NMR spectrum of 6-Ph-CL (400 MHz, Chloroform-*d*, 298 K).

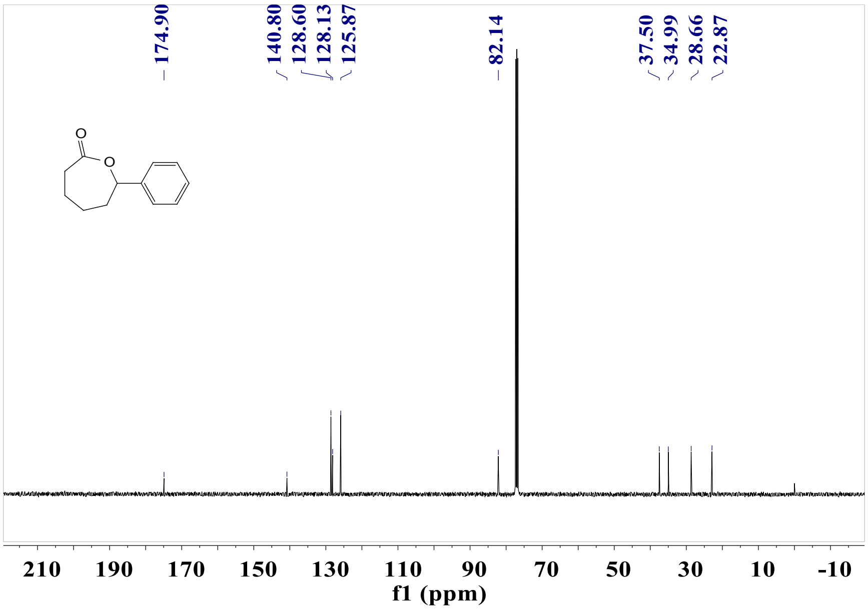


Figure S1b. ^{13}C NMR spectrum of 6-Ph-CL (100 MHz, Chloroform-*d*, 298 K).

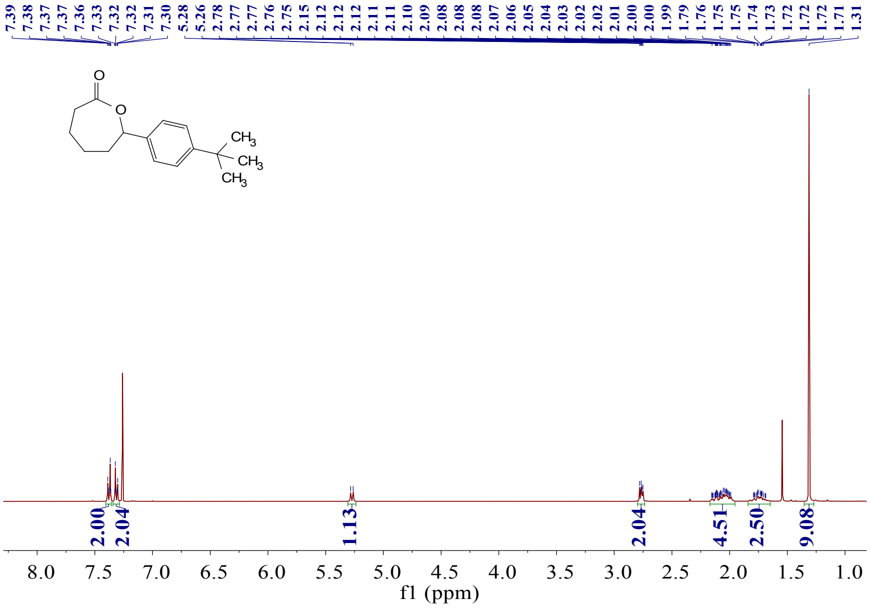


Figure S2a. ^{1}H NMR spectrum of 6-*p*-^{t}Bu-C_6H_4-CL (400 MHz, Chloroform-*d*, 298 K).

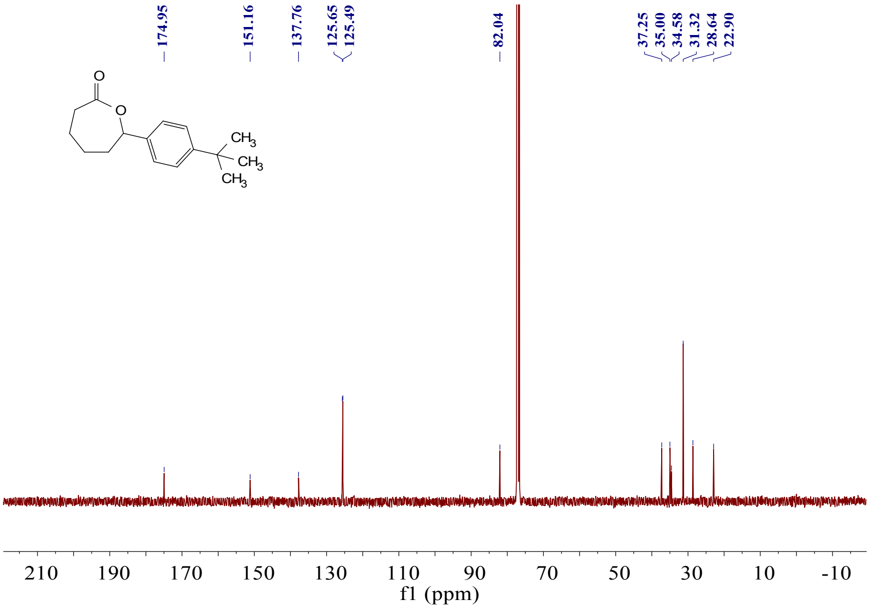


Figure S2b. ^{13}C NMR spectrum of 6-*p*-^{t}Bu-C_6H_4-CL (100 MHz, Chloroform-*d*, 298 K).

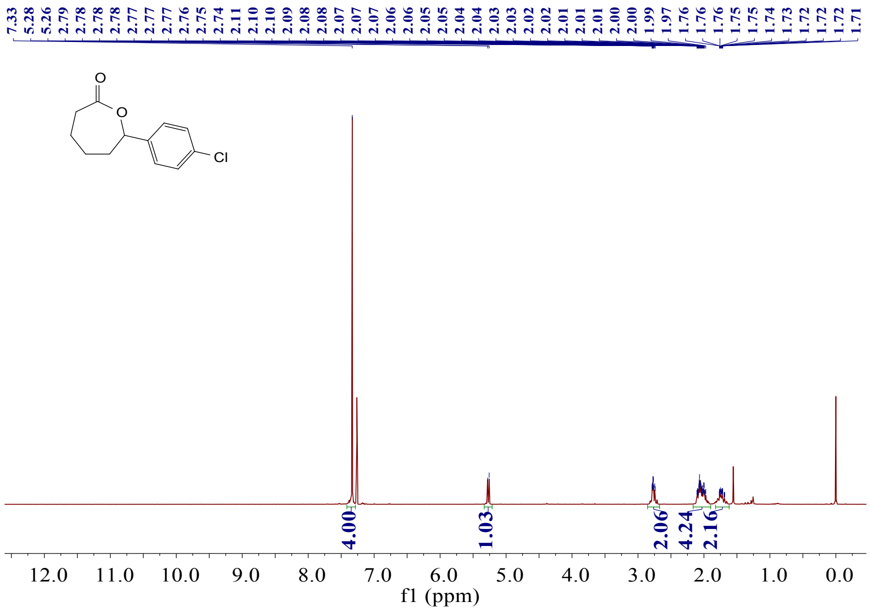


Figure S3a. ^{1}H NMR spectrum of 6-*p*-Cl-C_6H_4-CL (400 MHz, Chloroform-*d*, 298 K).

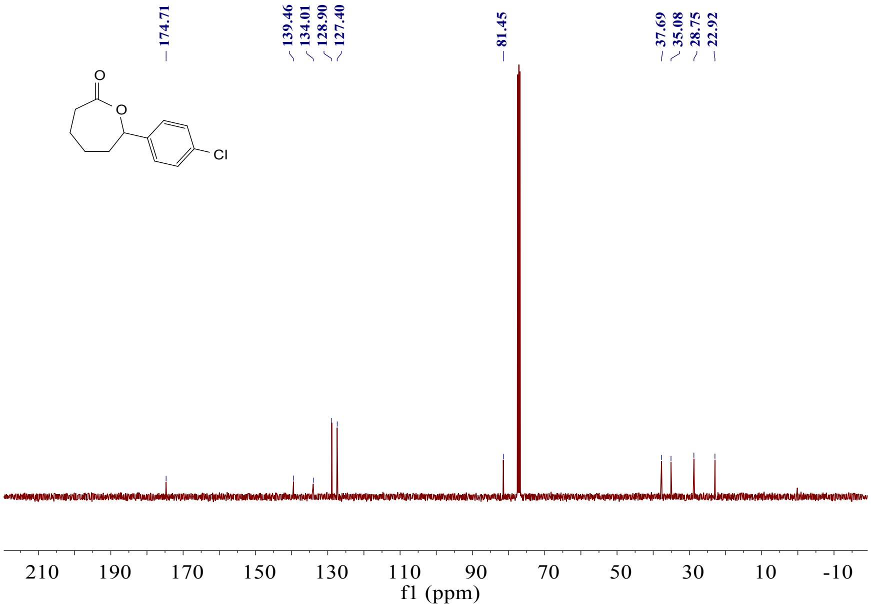
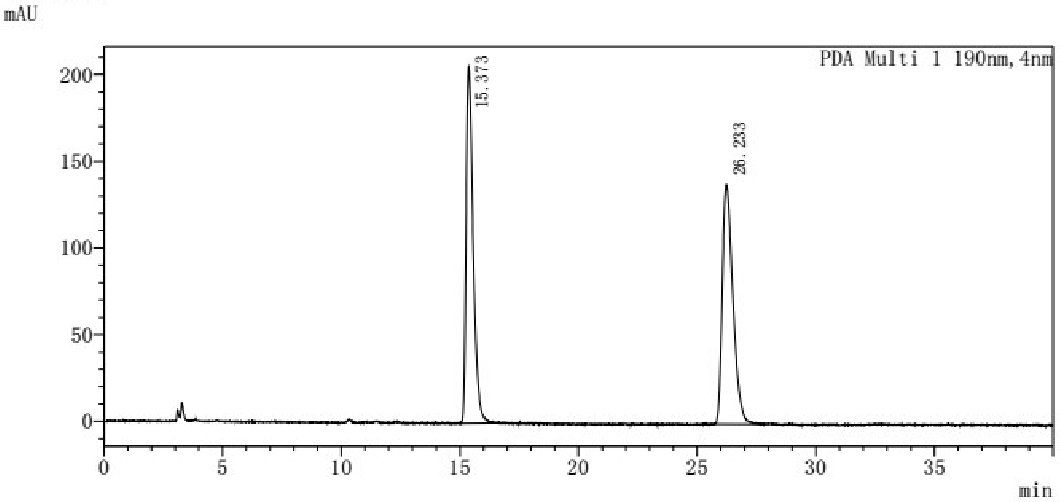


Figure S3b. ^{13}C NMR spectrum of 6-*p*-Cl-C_6H_4-CL (100 MHz, Chloroform-*d*, 298 K).

〈色谱图〉



〈峰表〉

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	15.373	4308440	205667	50.036
2	26.233	4302278	138035	49.964
总计		8610718	343702	100.000

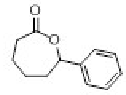
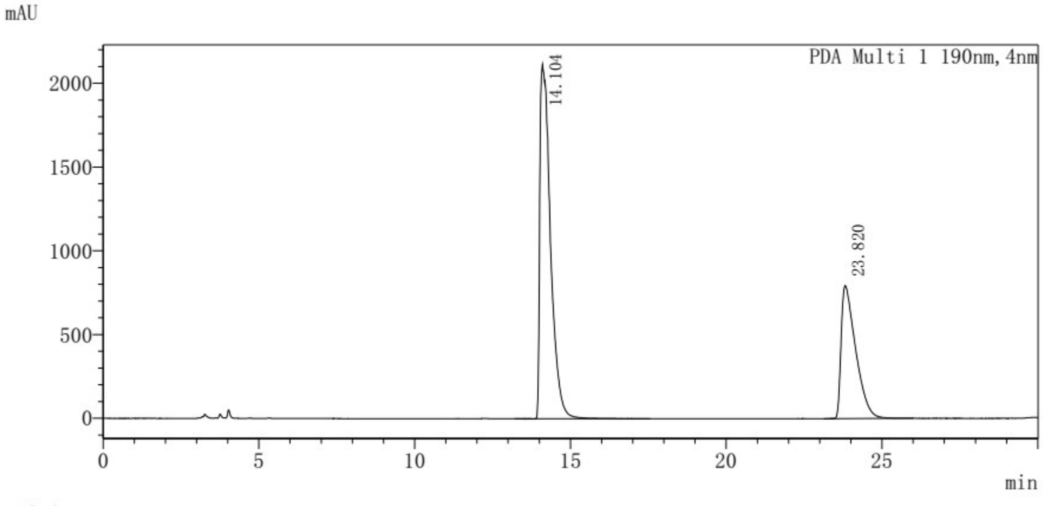


Figure S4. HPLC chromatograms of the *rac*-6-Ph-CL. Column, Chiralpak OD-3; flow rate, 1 mL/min; eluent, hexane/isopropanol = 95/5; detector, UV (190 nm)

〈色谱图〉



〈峰表〉

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	14.104	50262985	2114768	66.120
2	23.820	25754386	794183	33.880
总计		76017371	2908952	100.000

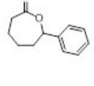
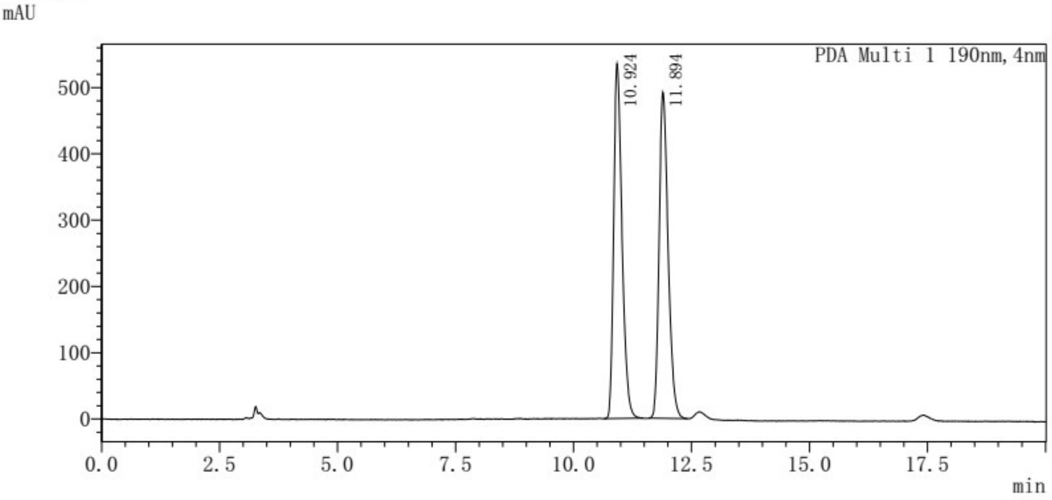


Figure S5. HPLC chromatograms of the unreacted 6-Ph-CL in the reaction of Table 1, Entry 5

〈色谱图〉



〈峰表〉

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	10.924	6559233	534411	50.117
2	11.894	6528558	491561	49.883
总计		13087791	1025971	100.000

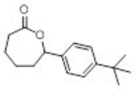
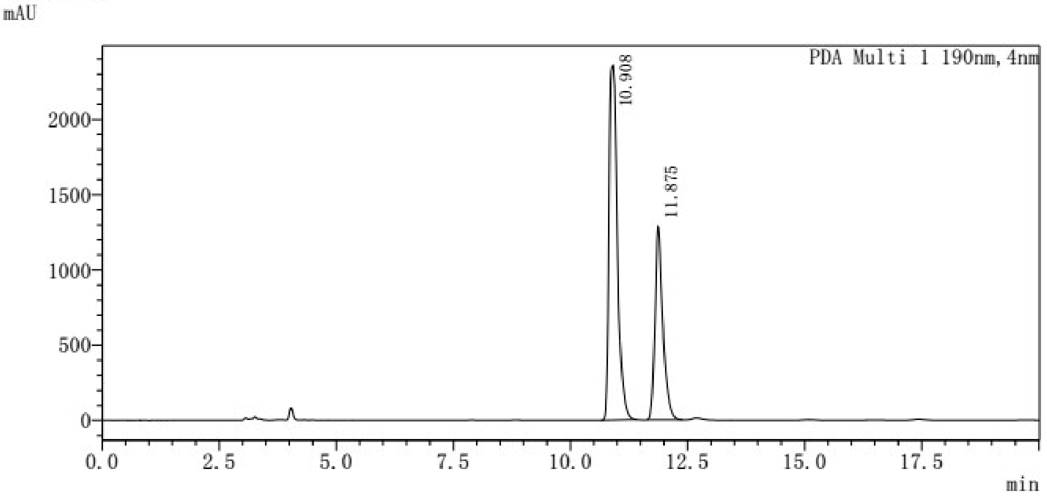


Figure S6. HPLC chromatograms of the *rac*-6-*p*-^{t}Bu-C$_6$H$_4$-CL. Column, Chiralpak OD-3; flow rate, 1 mL/min; eluent, hexane/isopropanol = 95/5; detector, UV (190 nm)

〈色谱图〉



〈峰表〉

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	10.908	29167334	2355908	65.782
2	11.875	15171822	1282441	34.218
总计		44339157	3638349	100.000

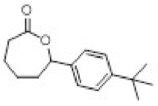
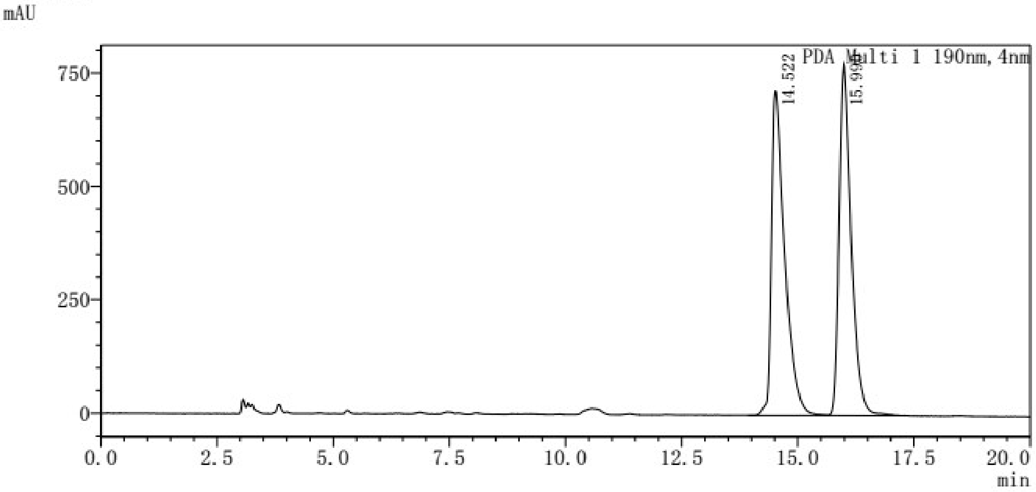


Figure S7. HPLC chromatograms of the unreacted 6-*p*-^{t}Bu-C$_6$H$_4$-CL in the reaction of Table 1, Entry 9

〈色谱图〉



〈峰表〉

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	14.522	14212857	714675	50.201
2	15.990	14099112	773436	49.799
总计		28311969	1488111	100.000

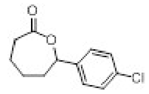
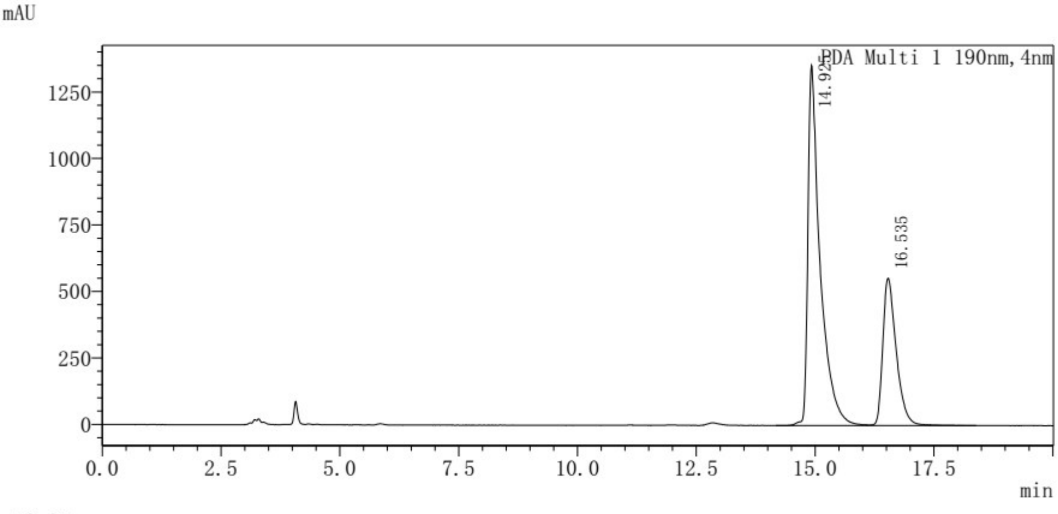


Figure S8. HPLC chromatograms of the *rac*-6-*p*-Cl-C_6H_4-CL. Column, Chiralpak OD-3; flow rate, 1 mL/min; eluent, hexane/isopropanol = 95/5; detector, UV (190 nm)

〈色谱图〉



〈峰表〉

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	14.925	24156398	1353575	68.896
2	16.535	10905776	554181	31.104
总计		35062175	1907756	100.000

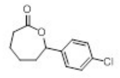
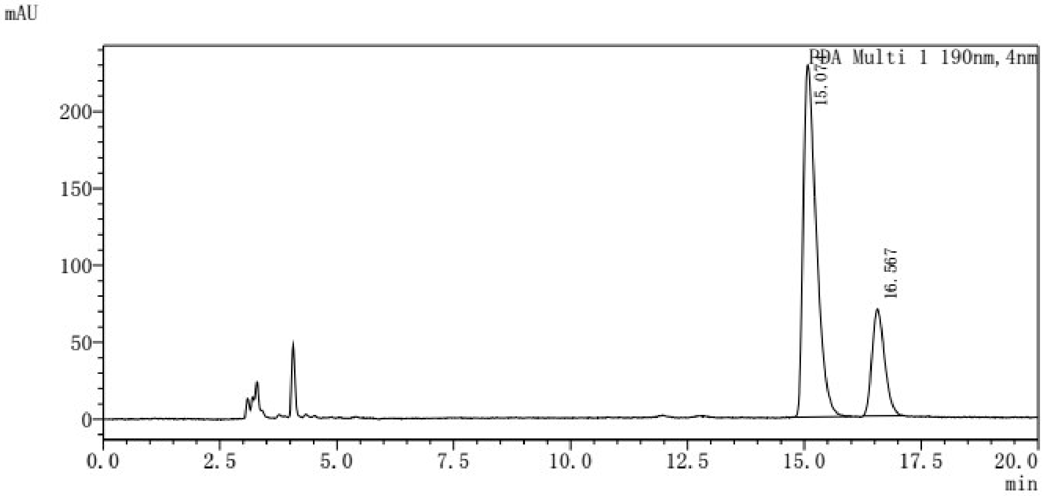


Figure S9. HPLC chromatograms of the unreacted 6-*p*-Cl-C_6H_4-CL in the reaction of Table 1, Entry 10

<色谱图>



<峰表>

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	15.074	4443609	228429	77.432
2	16.567	1295141	69371	22.568
总计		5738751	297800	100.000

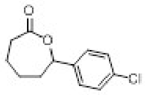
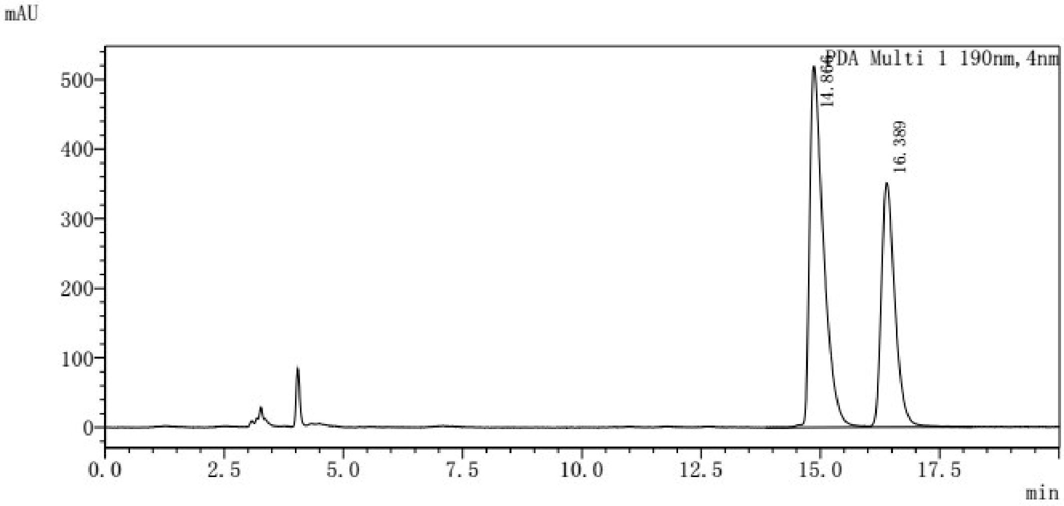


Figure S10. HPLC chromatograms of the unreacted 6-*p*-Cl-C_6H_4-CL of step 1 in Table 2, Entry 1

<色谱图>



<峰表>

PDA Ch1 190nm

峰号	保留时间	面积	高度	面积%
1	14.866	10513046	518637	60.195
2	16.389	6951891	350904	39.805
总计		17464937	869541	100.000

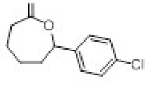


Figure S11. HPLC chromatograms of the unreacted 6-*p*-Cl-C_6H_4-CL of step 2 in Table 2, Entry 3

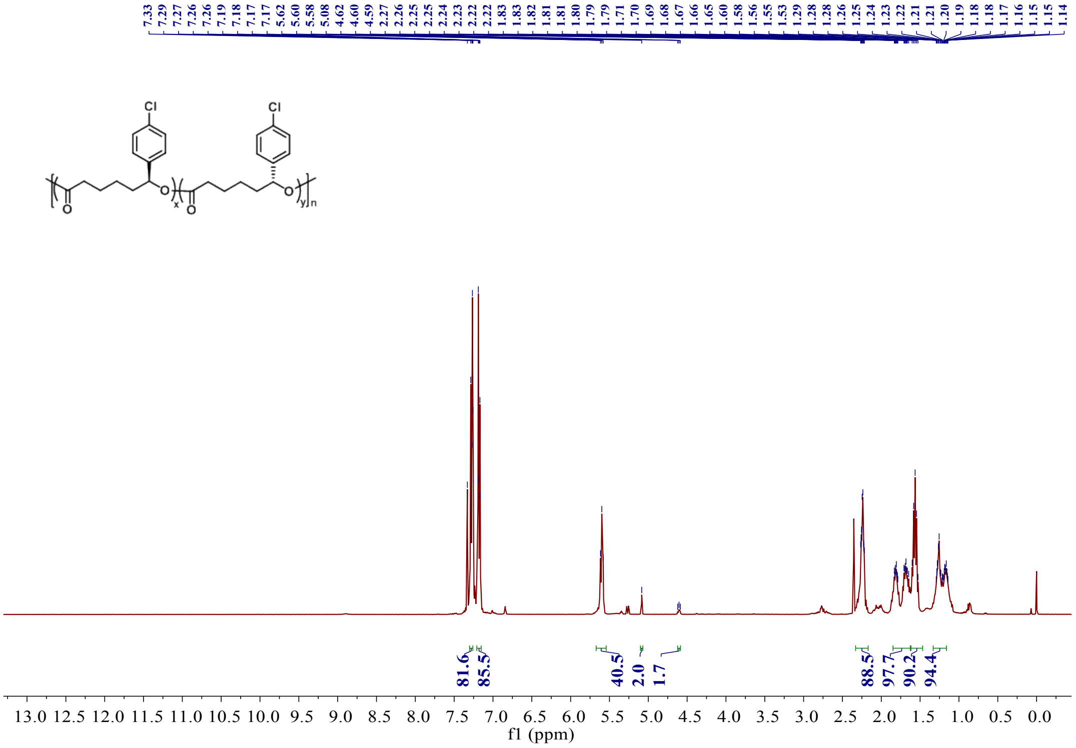


Figure S12a. ^{1}H NMR spectrum of poly(6-*p*-Cl-C_6H_4-CL) (400 MHz, Chloroform-*d*, 298 K) (Table 1, Entry 10).

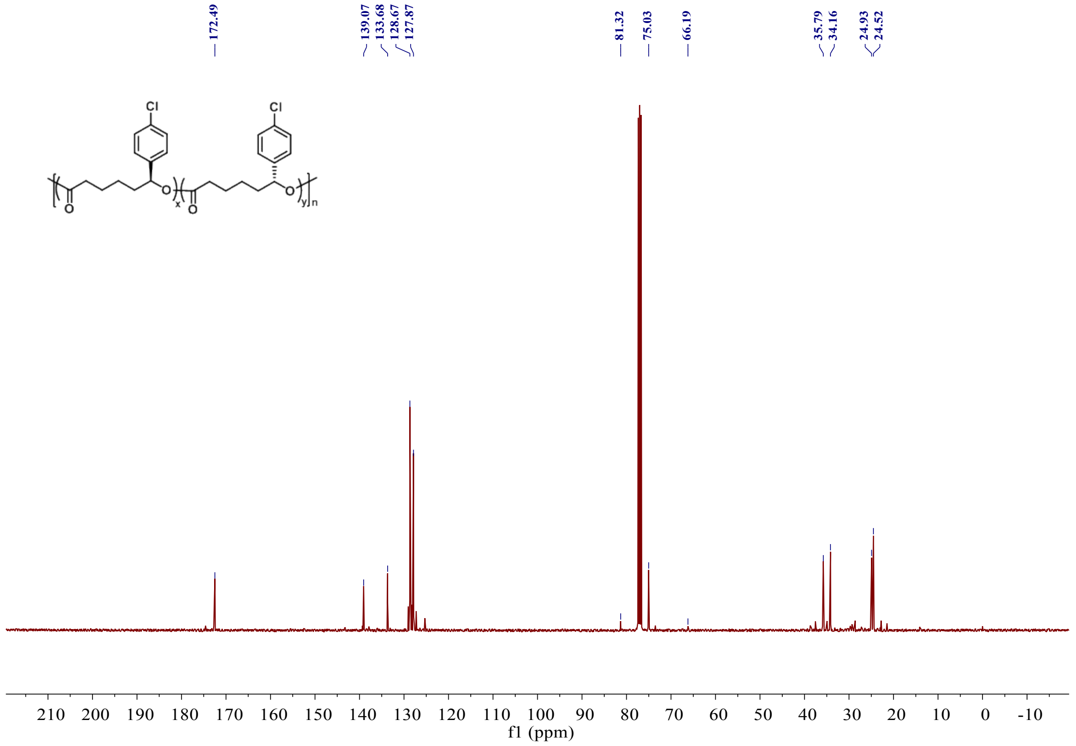


Figure S12b. ^{13}C NMR spectrum of poly(6-*p*-Cl-C_6H_4-CL) (100 MHz, Chloroform-*d*, 298 K) (Table 1, Entry 10).

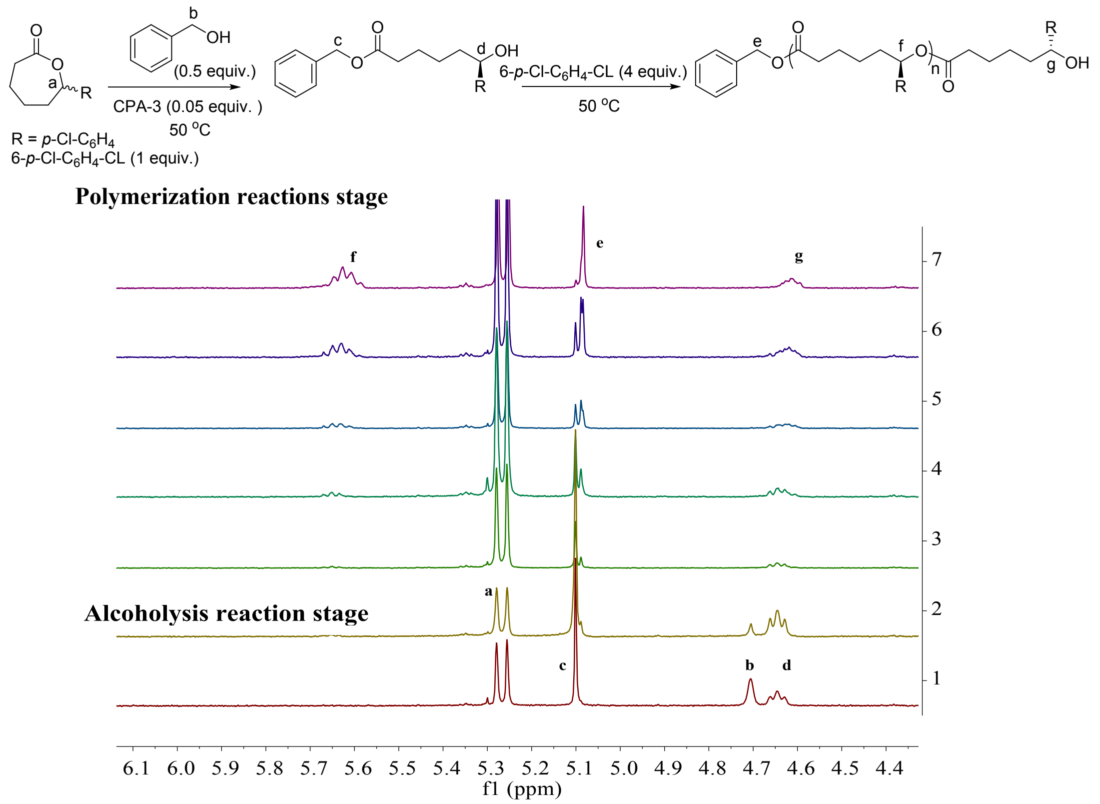
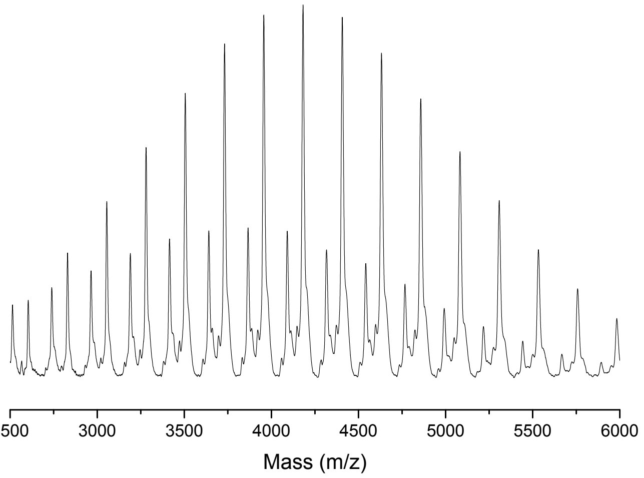


Figure S13. ^{1}H NMR spectrum of alcoholysis reaction and polymerization reaction of 6-*p*-Cl-C_6H_4-CL using CPA-3 (Table 2, Entry 3)



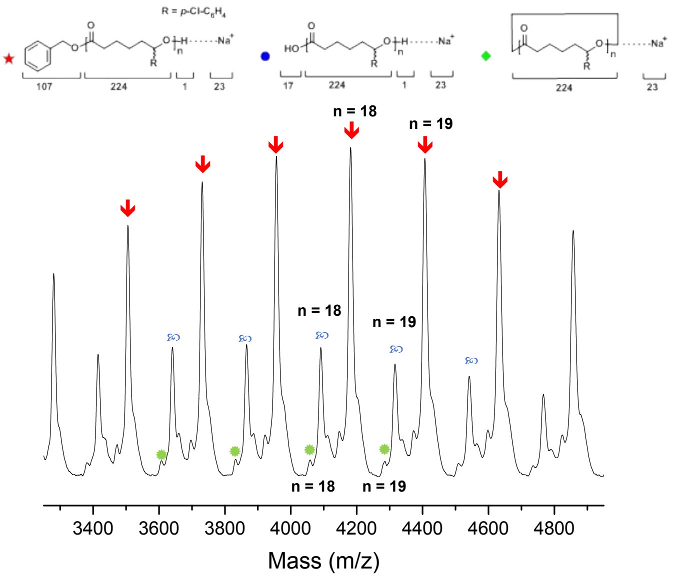


Figure S14. The MALDI-TOF mass spectrum of resulting polycaprolactones (The polymerization was performed in toluene (0.25M), $[M]_0/[Cat.]_0/[BnOH]_0 = 50:1:1$, Conv. = 76%).

The MALDI-TOF mass spectrum data confirmed the end-group identity, as the main series of peaks corresponded to 108 + 23 + 224 × n, which showed that the linear growth of monomer units with benzyl alcohol as initiator. Another relatively minor distribution indicated that partial polymers were end-capped with hydroxyl group, this may be due to the polymerization initiated by trace water in the reaction system. In addition, evidence of slight cyclization product was also detected by MALDI-TOF mass analysis. There are also some small peaks that cannot be attributed, which indicated some side reaction occurred.

8. References

1. M. Palucki and S. L. Buchwald, *J. Am. Chem. Soc.*, 1997, **119**, 11108-11109.

2. J.-H. Xie, S. Liu, X.-H. Huo, X. Cheng, H.-F. Duan, B.-M. Fan, L.-X. Wang and Q-L. Zhou, *J. Org. Chem.,* 2005, **70**, 2967-2973.