Electronic Supplementary Material (ESI) for Polymer Chemistry.

Supporting Information

Preparation of Semifluorinated Poly(meth)acrylates by Improved Photo-Controlled Radical Polymerization without the Use of Fluorinated RAFT Agent: Facilitating Surface Fabrication with Fluorinated Materials

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1. General information

1.1 Materials

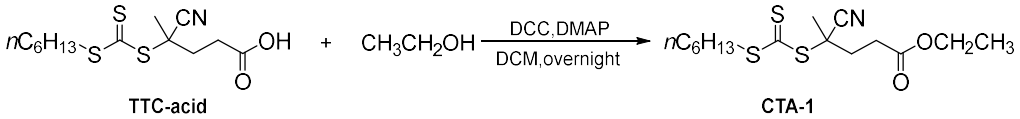
Semi-fluorinated monomers including trifluoroethyl methacrylate (TFEMA), nonafluorohexyl methacrylate (NFHMA), hexafluorobutyl methacrylate (HFBMA), dodecafluoroheptyl methacrylate (DDFHMA), hexafluorobutyl acrylate (HFBA) and nonafluorohexyl acrylate (NFHA) were purchased from Sigma-Aldrich or Adamas. All monomers were filtered through a plug of basic alumina before use. Dimethyl sulfoxide (DMSO) was freshly distilled from CaH_2. Other reagents and solvents were purchased from Sigma-Aldrich, Adamas or TCI, and were used as received without further purification.

1.2 Analytical Methods

Nuclear magnetic resonance (NMR) was recorded on an Advance III 400 MHz Bruker spectrometer at 298 K. ^{1}H NMR signals were measured in deuterochloroform ($CDCl_3$) or Acetone-d_6, and are reported in δ units, parts per million (ppm). ^{13}C NMR signals are reported in ppm units. Gel permeation chromatography (GPC) measurements were performed in THF at 35°C (elution rate = 0.35 mL/min) on an TOSOH equipped with a Bryce refractive index detector. Three columns were used, including one 6 μm superMultipore HZ-H gel column and two 4 μm superMultipore HZ-M columns. The calibration was performed with PS standards. Matrix-Assisted Laser Desorption Ionization time of flight (MALDI-ToF) mass spectrometry was conducted with a AB SCIEX 5800 MALDI-ToF/ToF mass spectrometer.

All reactions were conducted upon exposure to LED light irradiation. The light source is placed 1 cm in front of the vial. The dosage of light for white LEDs is estimated to be ~33 mW/cm^2, and for blue LEDs is estimated to be ~2 mW/cm^2.

2. Synthesis and characterization of CTA



Scheme S1. Synthetic route for CTA-1.

An oven-dried 250 mL round-bottom flask equipped with a magnetic stir bar was charged with TTC-acid [1] (5 mmol, 1.595 g), *N,N'*-dicyclohexylcarbodiimide (DCC, 1.34 g, 6.5 mmol), 4-(dimethylamino)pyridine (DMAP, 15.27 mg, 0.0125 mmol) and 10 mL anhydrous CH_2Cl_2 (DCM). The flask was cooled to 0°C, ethanol (876 μL, 15 mmol) was added into the flask in three portions. Then, the mixture was stirred at room temperature overnight. After the reaction was completed, the reaction solution was filtered, concentrated, and purified by column chromatography (50% ethyl acetate in petroleum ether) to afford target CTA-1 as a yellow liquid (1.04 g, 60 % yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 4.19 (q, J = 8.0 Hz, 2 H), 3.35 (t, J = 8.0 Hz, 2 H), 2.36 - 2.66 (m, 4 H), 1.90 (s, 3 H),1.72 (m, 2 H), 1.28 -1.46 (m, 9 H), 0.91(t, J = 4.0 Hz, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ: 216.95, 171.47, 119.02, 61.06, 46.37, 37.04, 33.88, 31.23, 29.83, 28.59, 27.64, 24.86, 22.46, 14.17, 13.99 ppm.

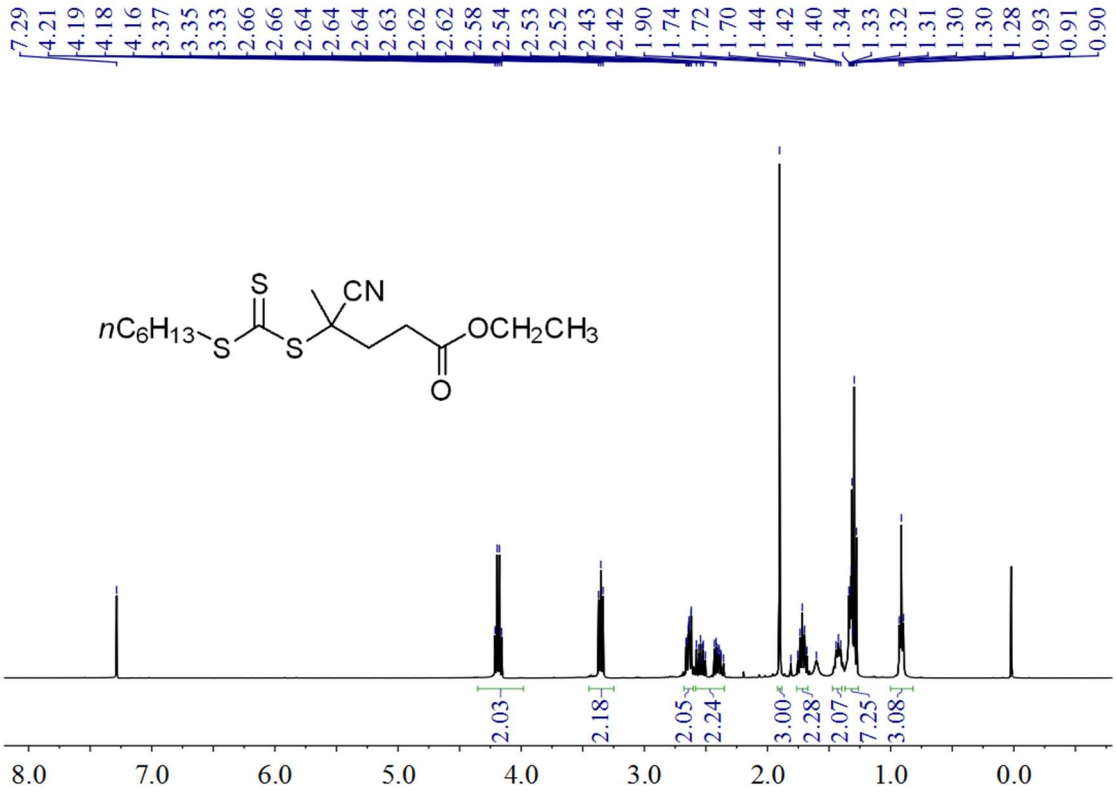


Figure S1. ^{1}H NMR Spectra of CTA-1.

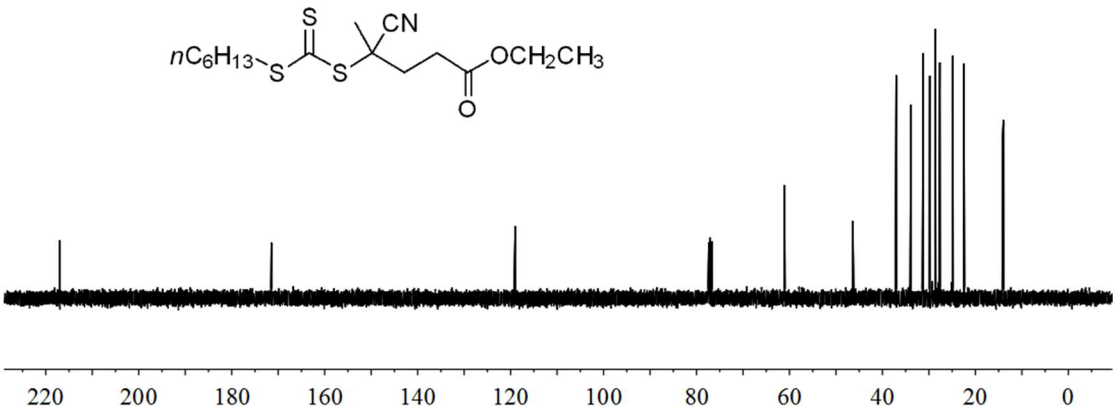
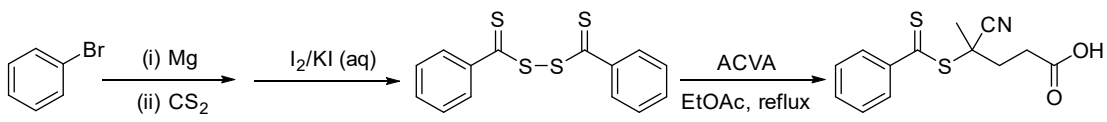
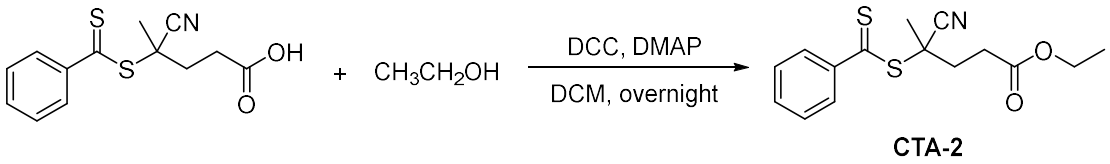


Figure S2. ^{13}C NMR Spectra of CTA-1.





Scheme S2. Synthetic route for CTA-2.

This compound was prepared according to a modified procedure from literature. [2] In an oven-dried three-neck flask, magnesium (0.2 g, 8.2 mmol, 1.2 eq.) was suspended in 30 mL of dry diethyl ether. A solution of bromobenzene (1.07 g, 6.85 mmol, 1.0 eq.) in 3 mL diethyl ether was added dropwise into the flask. After addition, the mixture was refluxed for 2 h and cooled to -5 °C. During 10 min, carbon disulfide (1.6 g, 21.3 mmol, 2.6 eq.) in 5 mL dry THF was added dropwise. The solution was stirred at room temperature for 20 min and refluxed for 20 min. Afterwards, cold 10% HCl (aqueous solution) was added dropwise. After phase separation, the organic phase was extracted three times with 10 % NaOH (aqueous solution). The combined aqueous phases were washed with 50 mL diethyl ether. To the residual aqueous phase, 10 % I_2/KI aqueous solution was added dropwise over 30 min with strong stirring. The reaction mixture was allowed to stand overnight. The purple precipitate was filtered off and washed with water until the filtrate became colorless. Di(thiobenzoyl)disulfide were obtained as a purple solid (0.53 g, 1.72 mmol, 50 % yield).

Di(thiobenzoyl)disulfide (0.53 g, 1.72 mmol, 1.3 eq.) and 4,4'-azobis(4-cyanopentanoic acid) (ACVA, 0.37 g, 1.32 mmol, 1.0 eq.) were dissolved in 30 mL ethyl acetate. The solution was degassed via 3 freeze-pump-thaw cycles and heated to reflux for 20 h. Subsequently, the solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica-gel with *n*-hexane/EtOAc (volume ratio was changed from 50 % to 15 %). The pink fractions were combined and the solvent was evaporated. 4-Cyano-4-(phenylcarbonothioylthio)pentanoic acid was obtained as a pink liquid (0.59 g, 2.1 mmol, 60 % yield).

4-Cyano-4-(phenylcarbonothioylthio)pentanoic acid (0.5 g, 2.1 mmol) was added into an oven-dried 250 mL round-bottom flask equipped with a magnetic stir bar, and

charged with DCC (0.56 g, 2.73 mmol), DMAP (6.4 mg, 0.0525 mmol) and 5 mL anhydrous DCM. The flask was cooled to 0 °C, and ethanol (368 μL, 6.3 mmol) was added in three portions. Then, the mixture was stirred at room temperature overnight. After the reaction was completed, the reaction solution was filtered and purified by column chromatography (10 % EtOAc in petroleum ether) to afford target CTA-2 as a purple liquid (0.42 g, 65% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.28 -7.94 (m, 5 H), 4.20 (q, *J* = 8.0 Hz, 2 H), 2.42 -2.75 (m, 4 H), 1.96 (s, 3 H), 0.91 (t, *J* = 8.0 Hz, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ: 222.30, 171.52, 144.57, 133.01, 128.57, 126.68, 118.70, 61.08, 45.78, 33.48, 29.87, 24.14, 14.18 ppm.

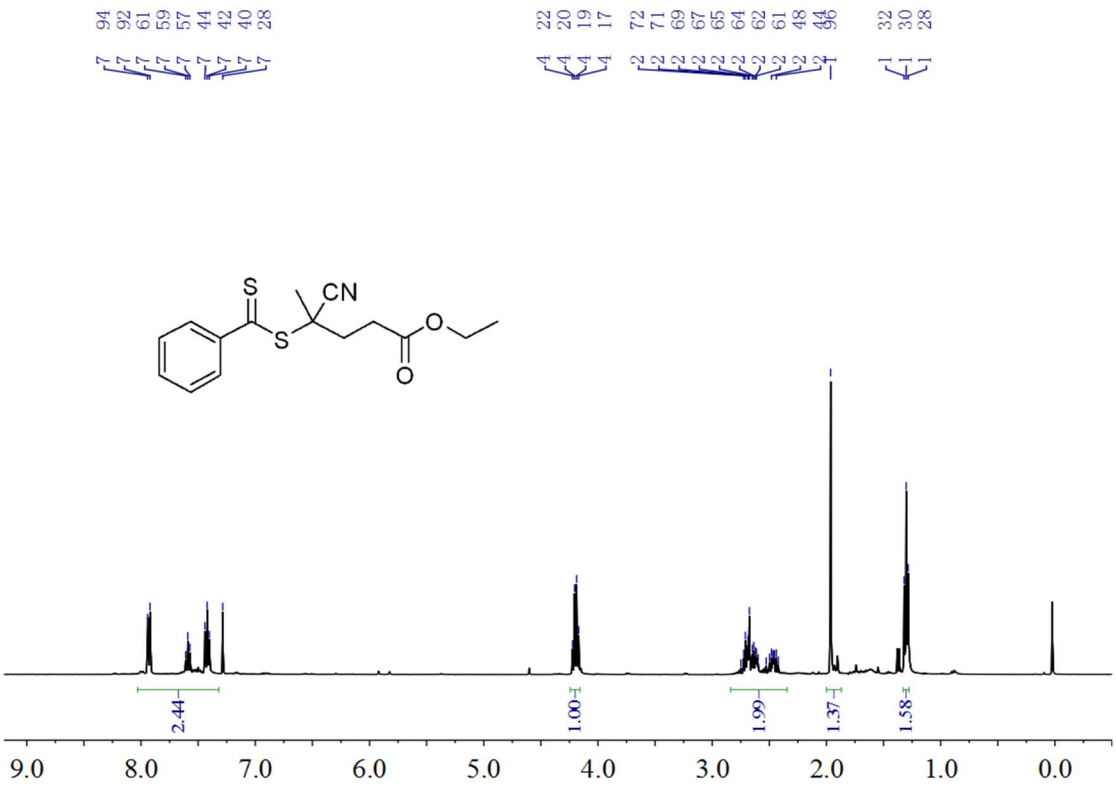


Figure S3. ^{1}H NMR Spectra of CTA-2.

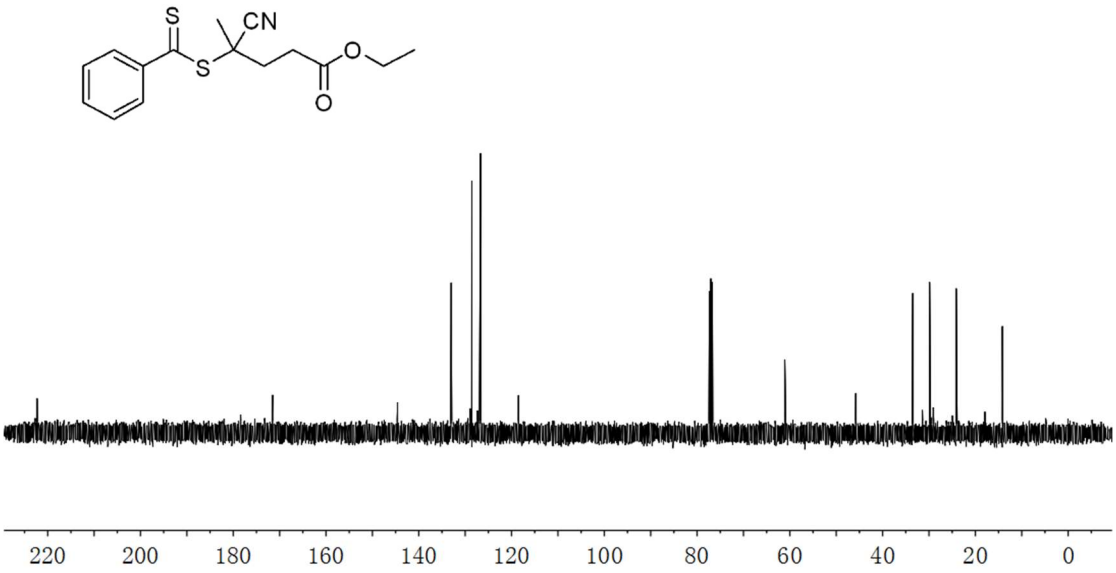
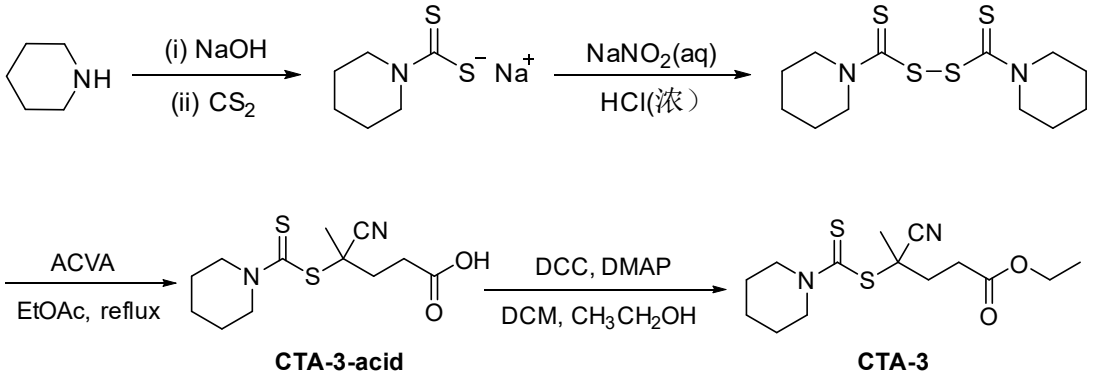


Figure S4. ^{13}C NMR Spectra of CTA-2.



Scheme S3. Synthetic route for CTA-3.

The compound was prepared according to a modified procedure from literature. [3] In a round-bottom flask, carbon disulfide (0.05 mol, 3.0 mL) was added in small portions to an equimolar solution mixture of sodium hydroxide (2.0 g, 0.05 mol) and piperidine (0.05 mol). The mixture was cooled at 0 °C. After 20 min, a precipitate was formed. After filtration, the obtained solid was re-crystallized with a mixture of acetone/petroleum ether. The final product was collected, washed with chloroform and

dried under vacuum. Sodium dimethylcarbamodithioate (8.24 g, 0.045 mol, 90 % yield) were obtained as a white solid.

In a round-bottom flask, the mixture of sodium dimethylcarbamodithioate (0.76 g, 5.4 mmol), sodium nitrite (0.38 g, 5.4 mmol, dissolved in 2 mL methanol) and 10 mL water was stirred at 0-5 °C for 10 min. Then, 2 mL concentrated HCl was added dropwise into the mixture, and the reaction mixture was stirred at 0-5 °C for 30 min. 100 mL chloroform was added into the mixture. After phase separation, the water layer was extracted with chloroform for two times. Combined organic layer was washed with 30 mL distilled water for three times. The organic phase was further dried over sodium sulfate, concentrated under reduced pressure. Bis(piperidinothiocarbonyl)disulfide was obtained as white solid (0.432 g, 1.35 mmol ,50 % yield).

In a round-bottom flask, bis(piperidinothiocarbonyl)disulfide (0.432 g, 1.35 mmol, 1.0 eq.) and ACVA (0.378 g, 1.35 mmol, 1.0 eq.) was dissolved in 30 mL EtOAc. The solution was degassed via 3 freeze-pump-thaw cycles and heated to reflux for 20 h. After the reaction was completed, the reaction solution was filtered. The organic layer was concentrated and purified by column chromatography (10 % EtOAc in petroleum ether) to afford target CTA-3-acid as a pale yellow liquid (0.32 g, 41 % yield).

The obtained CTA-3-acid (1.12 mmol, 0.32 g) was added into an oven-dried 250 mL round-bottom flask equipped with a magnetic stir bar and charged with DCC (0.3 g, 1.456 mmol,), DMAP (3.4 mg, 0.028 mmol) and 5 mL anhydrous DCM. The mixture was cooled to 0°C, and ethanol (196 μL, 3.36 mmol) was added into the mixture in three portions. Then, the mixture was stirred at room temperature overnight. After the reaction was completed, the reaction solution was filtered, concentrated and purified by column chromatography (10 % EtOAc in petroleum ether) to afford target CTA-3 as a pale yellow liquid (0.235 g, 67 % yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 3.60-4.36 (m, 6 H), 2.38-2.71 (m, 4 H), 1.94 (s, 3 H), 1.65-1.8 (m, 6 H), 1.29 (t, J = 8.0 Hz, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ: 188.54, 171.80, 120.27, 60.91, 51.33, 46.17, 34.21, 30.04, 25.71, 25.43, 24.08, 14.17 ppm.

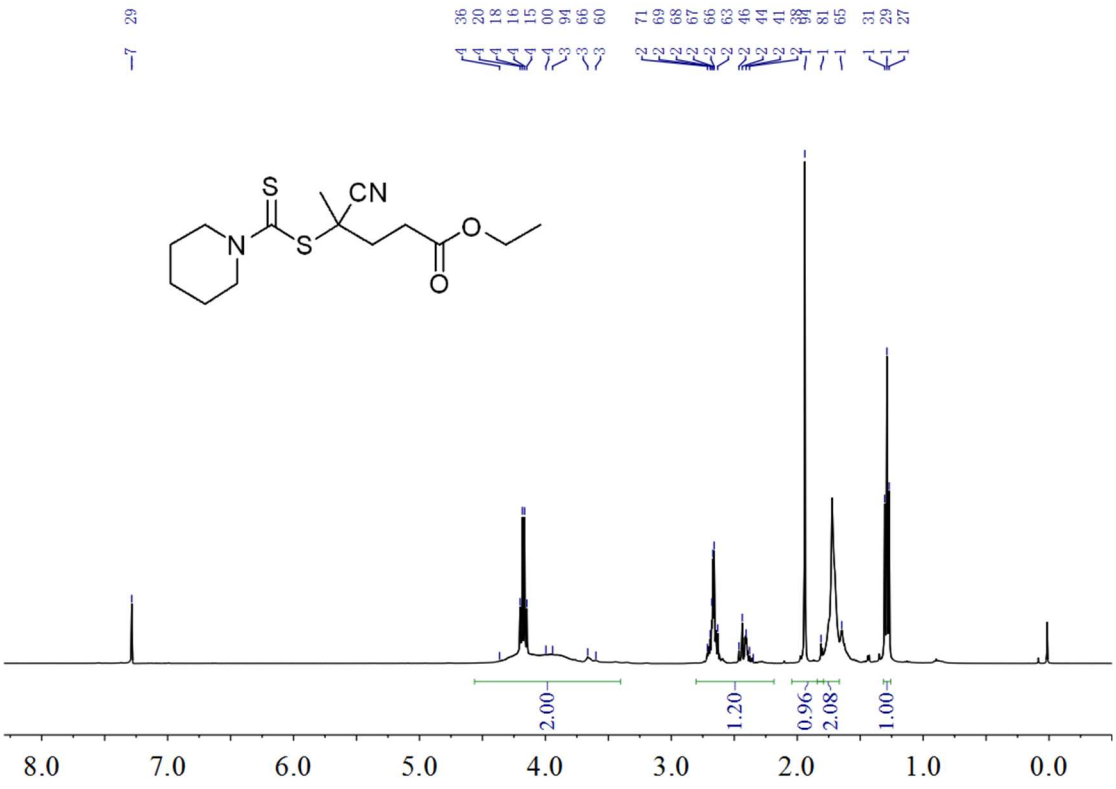


Figure S5. ^{1}H NMR Spectra of CTA-3.

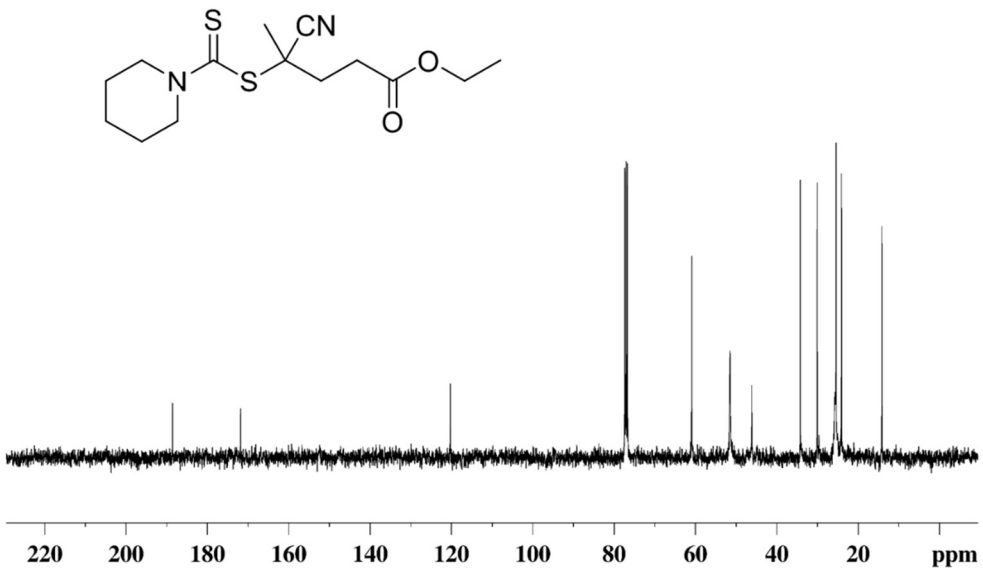
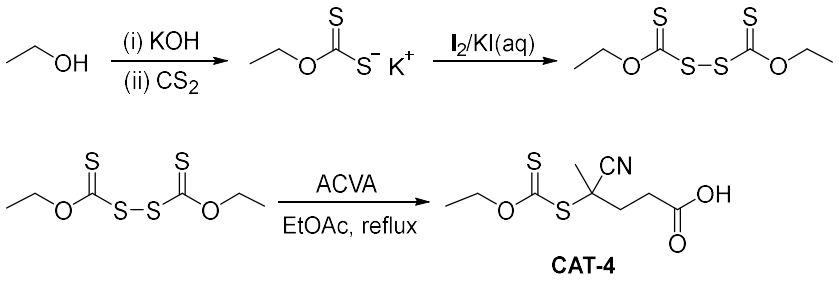


Figure S6. ^{13}C NMR Spectra of CTA-3.



Scheme S4. Synthetic route for CTA-4.

The compound was prepared according to a modified procedure from literature. [4] An oven-dried 250 mL round-bottom flask equipped with a magnetic stir bar was charged with 6 mL CS_2 (0.1 mol) and 50 mL ethanol. The flask was cooled to 0°C, and 20 mL of 5 M KOH aqueous solution was added dropwise into the flask with stirring. The solution was stirred at room temperature for 30 min to give a mixture containing potassium ethyl xanthate.

Aqueous solution of I_2/KI (10 %, 50 mL) was added dropwise to the xanthate solution via a dropping funnel over 30 min with strong stirring. The reaction mixture was allowed to stand overnight. 100 mL water was then added to the mixture, and the mixture was extracted with 50 mL ether for three times. The combined organic layer was washed with 100 mL water for three times. The resulting solution was dried over anhydrous $MgSO_4$ overnight. After removing the organic solvent via concentration, crude *O*,*O*-diethyl bisxanthate was obtained (6.5 g, 0.0268 mol, 80%).

In a round-bottom flask, *O*,*O*-diethyl bisxanthate (2 g, 8.25 mmol, 1.0 eq.) and ACVA (2.31 g, 8.25 mmol, 1.0 eq.) were dissolved in 80 mL EtOAc. The solution was degassed via 3 freeze-pump-thaw cycles and heated to reflux for 20 h. After the reaction was completed, the reaction solution was filtered, the organic phase was concentrated. The obtained residue was purified by column chromatography (5 % EtOAc in petroleum ether) to afford target CTA-4 as a yellow liquid (2.28 g, 56 % yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.10 (br, 1H), 4.75 (q, J = 8.0 Hz, 2 H), 2.28 -2.69 (m, 4 H), 1.78 (s, 3 H),1.54 (t, J = 8.0 Hz, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ: 206.72, 177.41, 119.56, 70.92, 44.69, 33.60, 29.69, 25.06, 13.43 ppm.

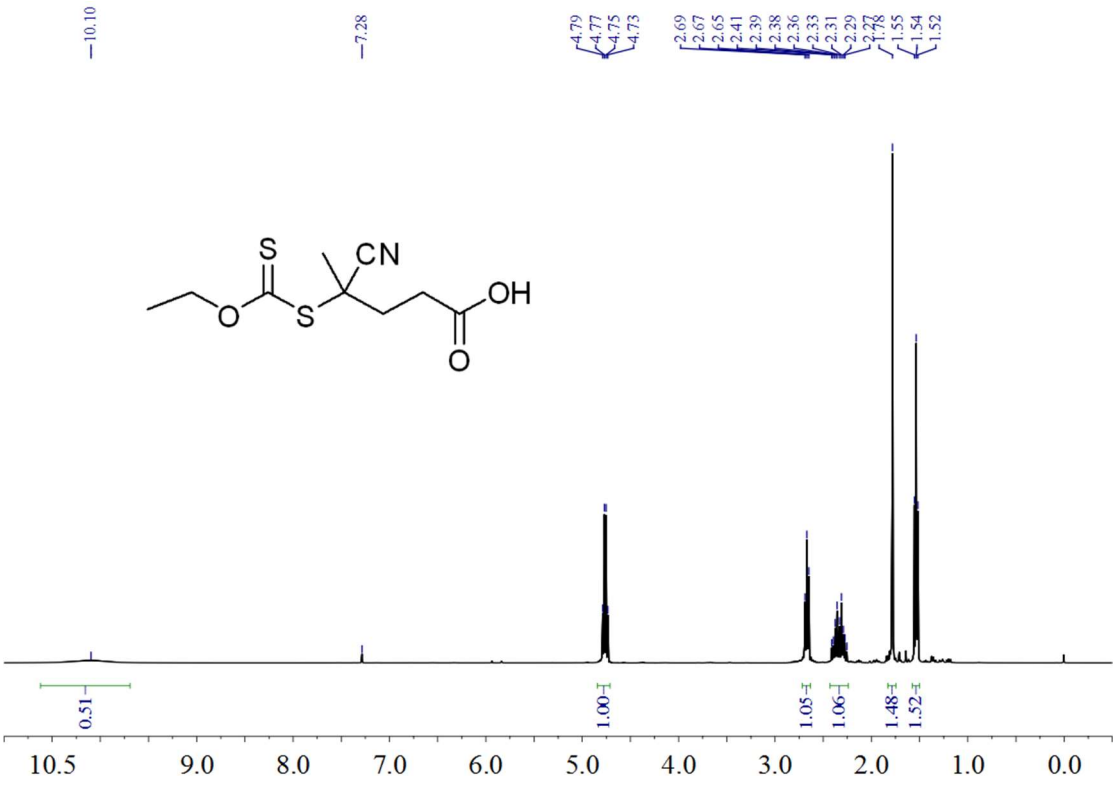


Figure S7. ^{1}H NMR Spectra of CTA-4.

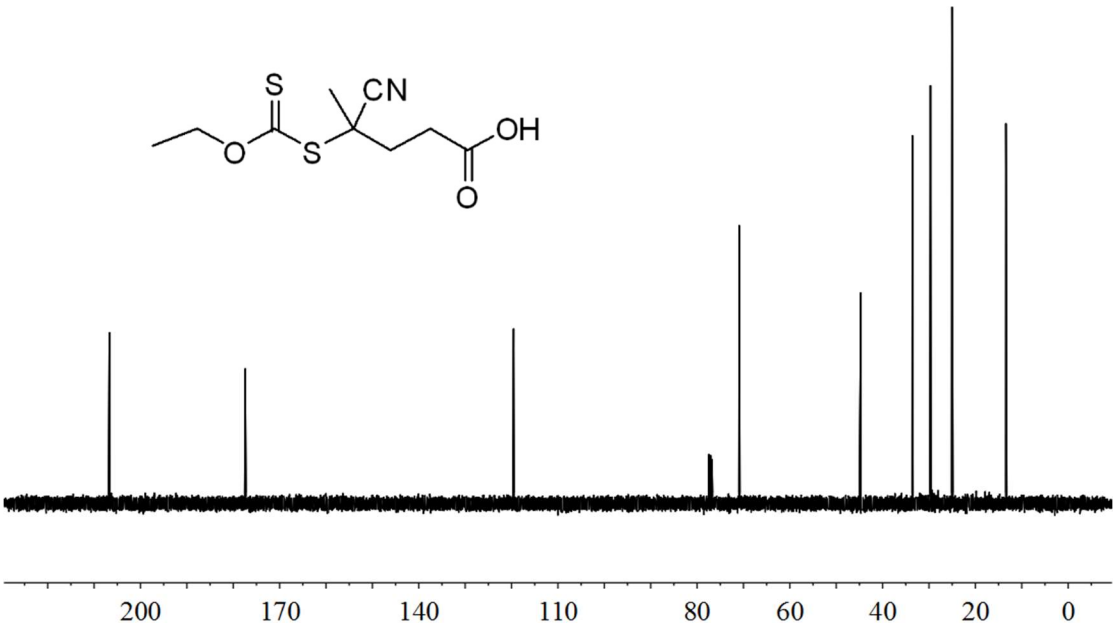
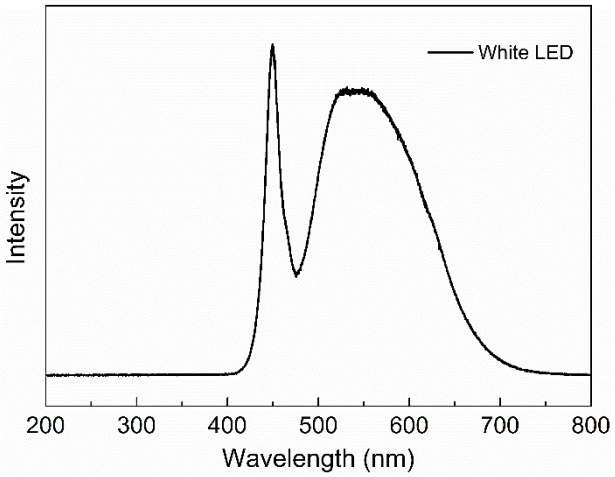


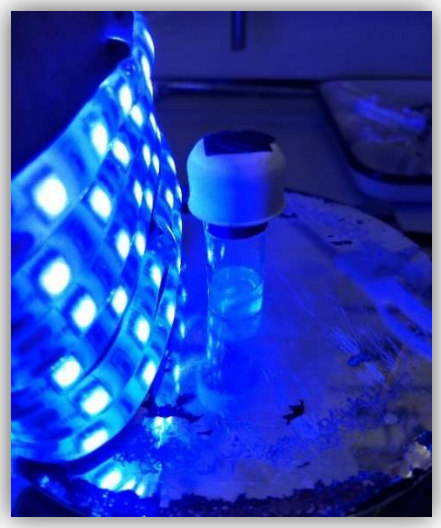
Figure S8. ^{13}C NMR Spectra of CTA-4.

A)

B)



C)



D)

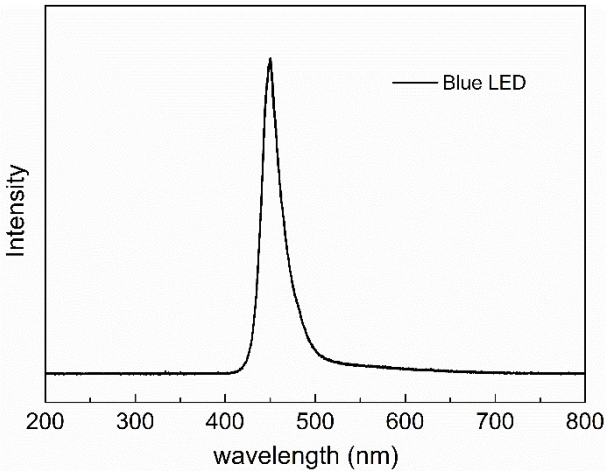


Figure S9. A) Setup for reactions under white LED light irradiation. B) Emission spectrum of white LED lights. C) Setup for reactions under purple LED light irradiation. B) Emission spectrum of blue LED lights.

3. Results for experiments in Figure 2

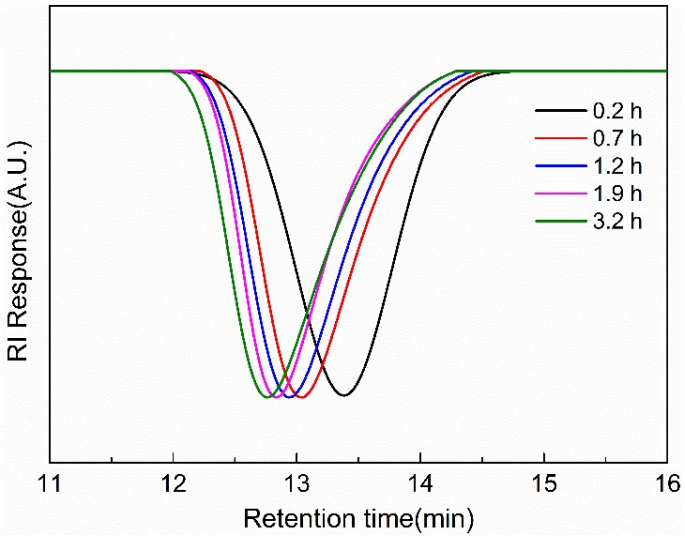


Figure S10. GPC traces for PNFHMA (green points from Figure 2).

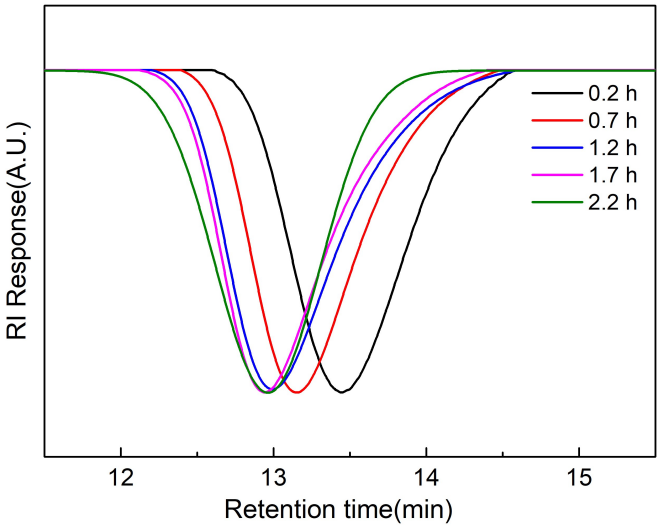


Figure S11. GPC traces for PNFHMA (blue points from Figure 2).

4. Results for experiments in Table 2

An oven-dried 4 mL vial equipped with a stir bar was charged with monomer (0.5 or 1.0 mmol), iniferter (the ratio to monomer is 1/20 to 1/100), photoredox catalyst CTA (if used) and DMSO (1 mL). After the vial was sealed with a rubber septum, the solution was deoxygenated with three freeze-pump-thaw cycles under N_2 atmosphere. Then, the mixture was stirred for corresponding reaction times in front of white LEDs or blue LEDs while cooling with compressed air to maintain room temperature. After reaction,

internal standard (ethyl benzoate, 0.5 or 1.0 mmol) was added via a syringe into the mixture with stirring. A small aliquot was taken and directly analyzed using ^{1}H NMR and GPC instruments to give monomer conversions, $M_{n,GPC}$ and molar mass distribution. When the purified semi-fluorinated polymers were needed (e.g., for MALDI-ToF, NMR or GPC analysis), the reaction solution was dropwisely added into the mixture solution of water and methanol with vigorous stirring to give the isolated target product.

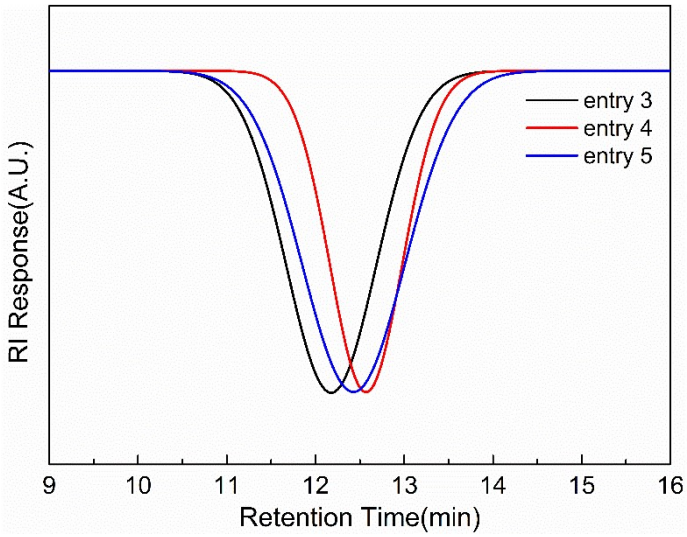


Figure S12. GPC traces for polymers in entries 3,4 and 5 of Table 2.

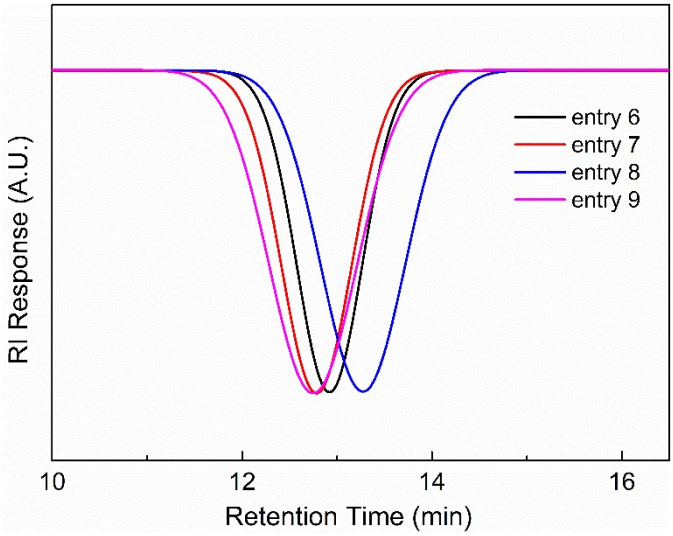


Figure S13. GPC traces for polymers in entries 6 to 9 of Table 2.

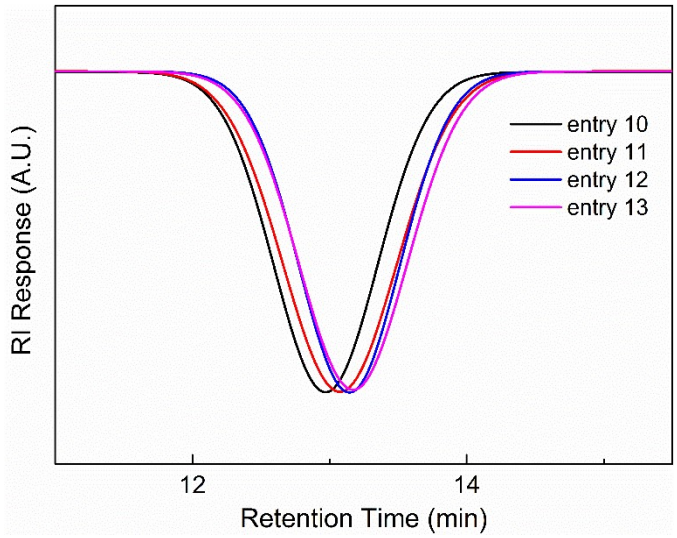


Figure S14. GPC traces for polymers in entries 10 to 13 of Table 2.

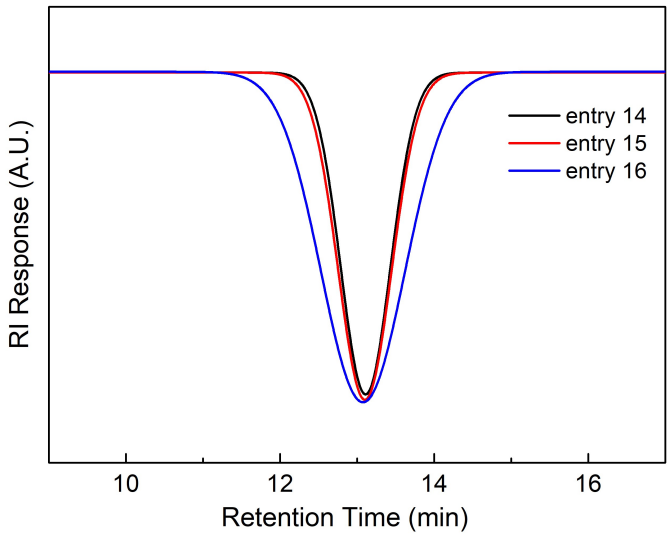


Figure S15. GPC traces for polymers in entries 14 to 16 of Table 2.

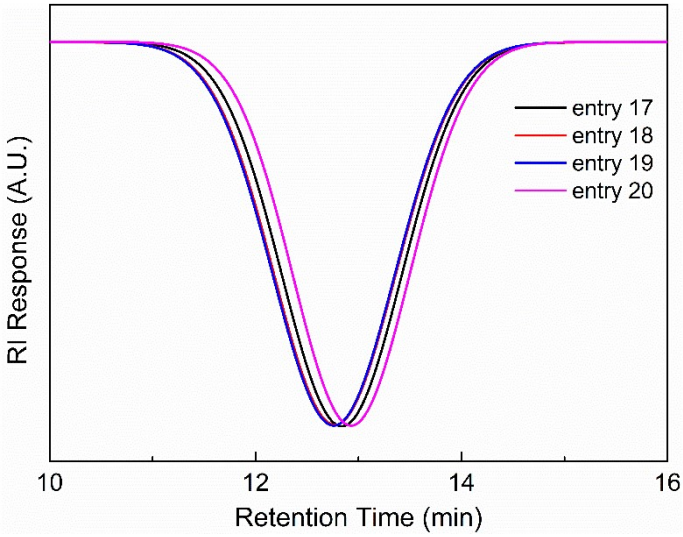
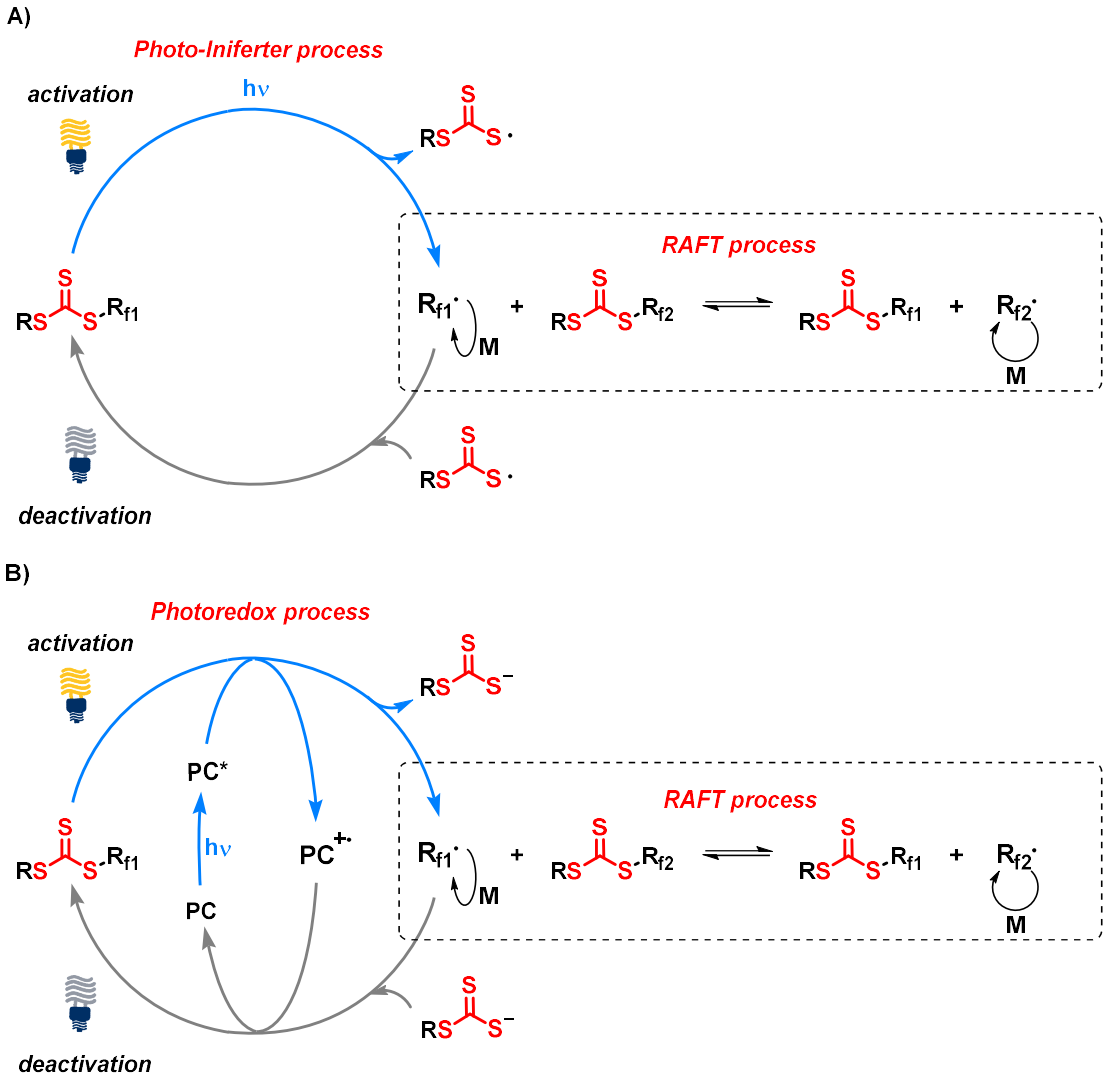
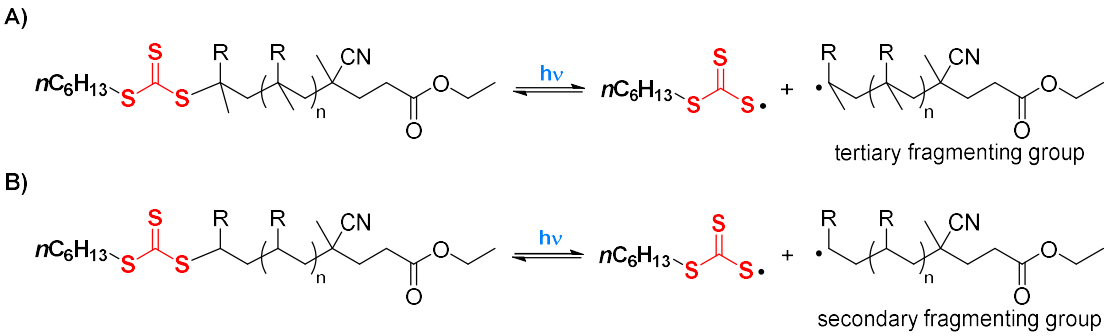


Figure S16. GPC traces for polymers in entries 17 to 20 of Table 2.



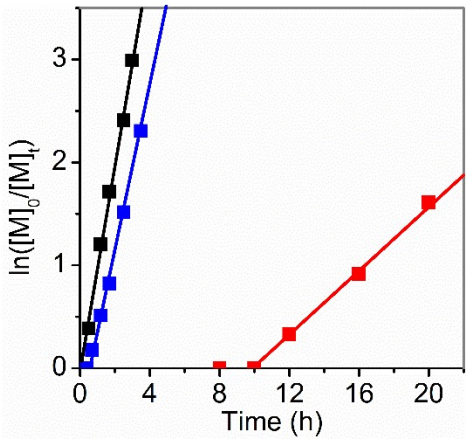
Scheme S5. Proposed mechanism for the photo-CRP from CTA-1 conducted A) without or B) with a catalyst.

5. Results for experiments in Table 3

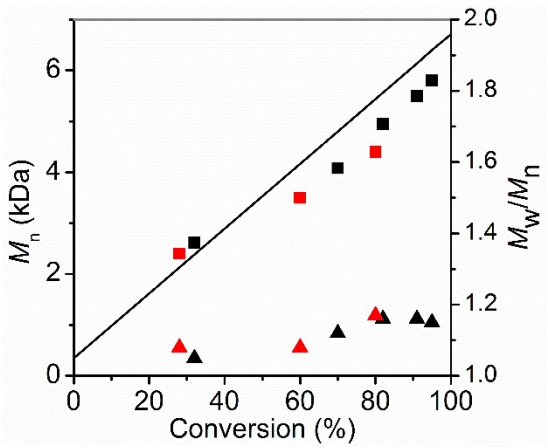


Scheme S6. The generation of tertiary and secondary fragmenting groups from macro-CTA-1 under light irradiation without a PC.

1A)



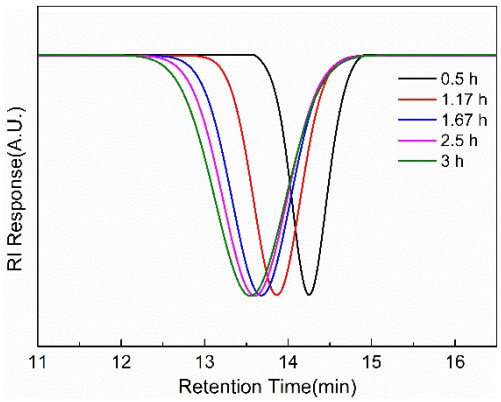
1B)



2A)

entry	t (h)	conv. (%)	$M_{n,GPC}$ (kDa)	Đ
1	0.5	32	2.6	1.05
2	1.17	70	4.1	1.12
3	1.67	82	4.9	1.16
4	2.5	91	5.5	1.16
3	3	95	5.8	1.15

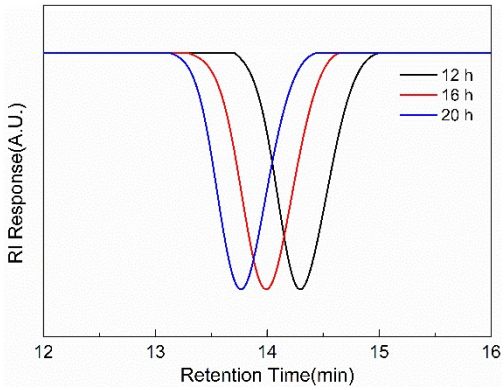
2B)



3A)

entry	t (h)	conv. (%)	$M_{n,GPC}$ (kDa)	Đ
1	8	0	-	-
2	10	0	-	-
3	12	28	2.5	1.09
4	16	60	3.4	1.10
3	20	80	4.2	1.16

3B)



Scheme S7. 1A) and 1B) Kinetic investigation for polymerization of NFHA in the presence (black points) and absence (red points) of catalyst. $[NFHA]_0/[CTA\text{-}1]/[PC]$ = 20/1/0.01 or 20/1/0. 1A) Kinetic investigation for polymerization of NFHMA in the absence (blue points) of catalyst. $[NFHMA]_0/[CTA\text{-}1]/[PC]$ = 20/1/0. 1A) Exposure time *vs* $\ln([M]_0/[M]_t)$. 1B) % conversion *vs* M_n (■) and % conversion *vs* *Đ* (▲). 2A) and 2B) Reaction results and GPC traces of black points from 1A). 3A) and 3B) Reaction results and GPC traces of red points from 1A).

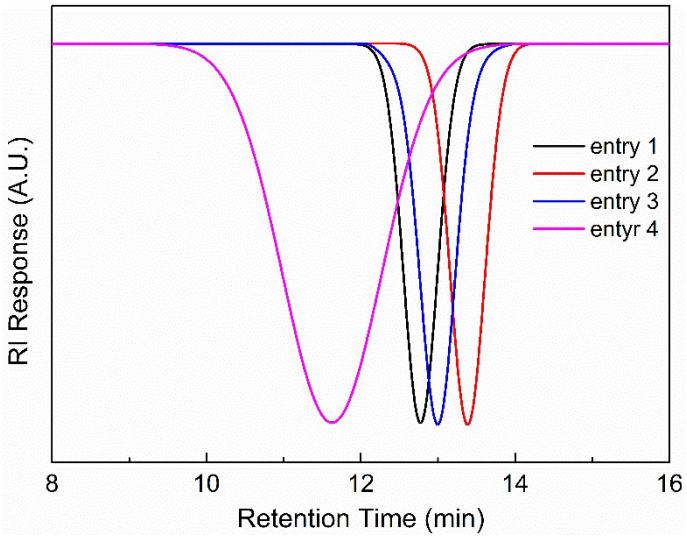


Figure S17. GPC traces for polymers in entries 1 to 4 of Table 3.

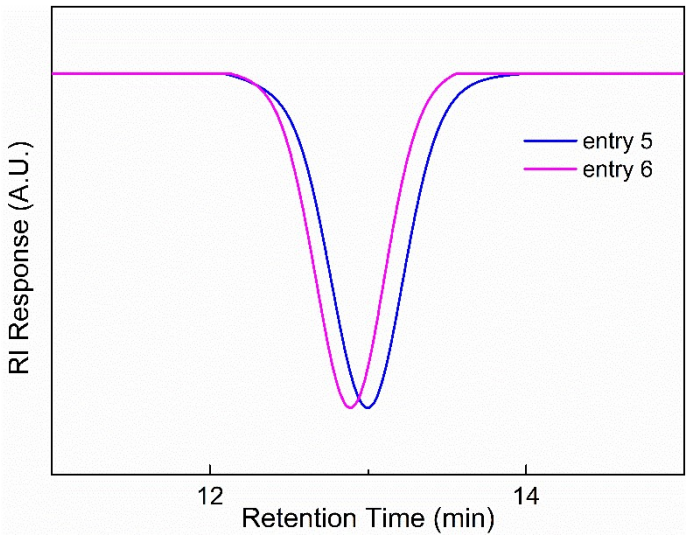


Figure S18. GPC traces for polymers in entries 5 and 6 of Table 3.

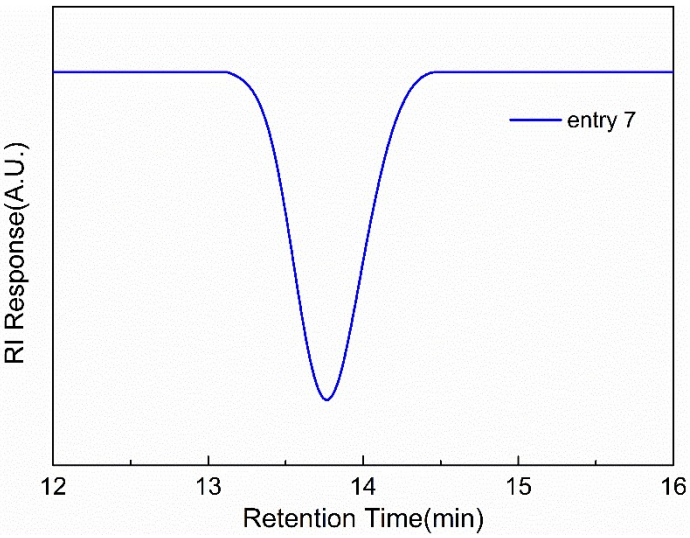


Figure S19. GPC traces for polymers in entries 7 of Table 3.

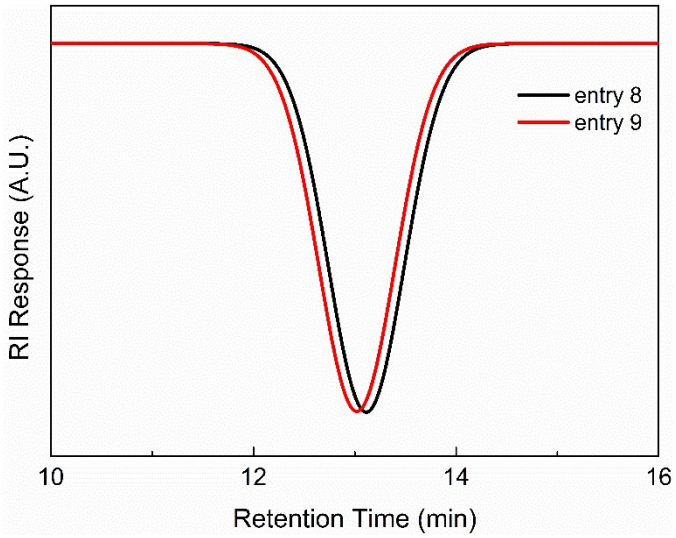


Figure S20. GPC traces for polymers in entries 7 of Table 3.

6. Results for experiments in Figure 7

An oven-dried 4 mL vial equipped with a stir bar was charged with DDFHBA (40 mg,0.1 mmol), CTA-1 (3.47 mg, 0.01 mmol) and DMSO (0.5 mL). The biPh-PTZ catalyst solution (25 μL, 0.002 mol/L, 1.23 mg/mL in DMSO) was added via a micro syringe into the vial. After the vial was sealed with a rubber septum, the solution was deoxygenated with three freeze-pump-thaw cycles under N_2 atmosphere. Then, the mixture was stirred for 3 h in front of a white LEDs bulb. After full conversion of monomer, deoxygenated MA (86 mg, 1 mmol) was added via a syringe under N_2 into the reaction mixture in dark. The mixture was stirred for 5 h under the visible light irradiation. A small aliquot was taken and directly analyzed using NMR and GPC instruments.

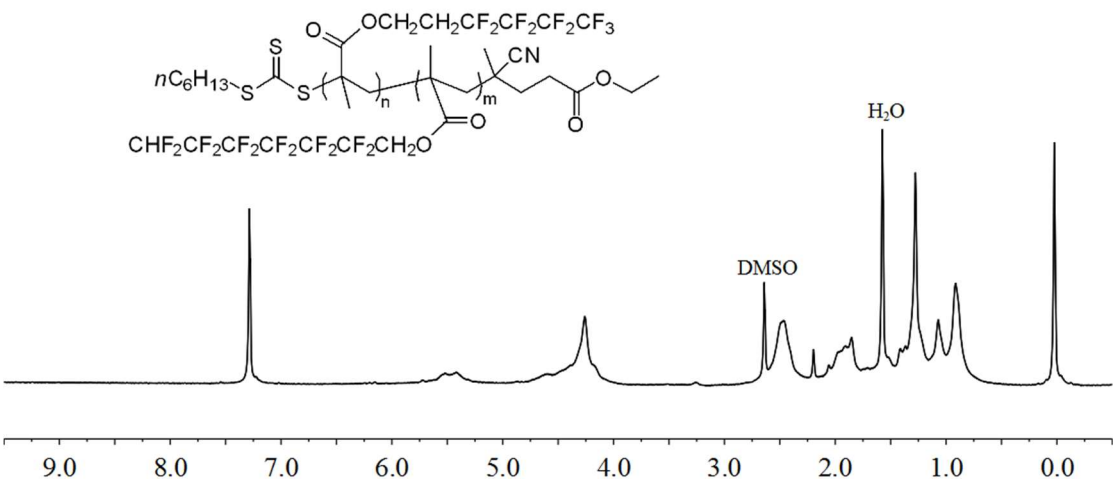


Figure S21. [1]H NMR Spectra of block polymer (PNFHMA-*b*-PDDFHMA)

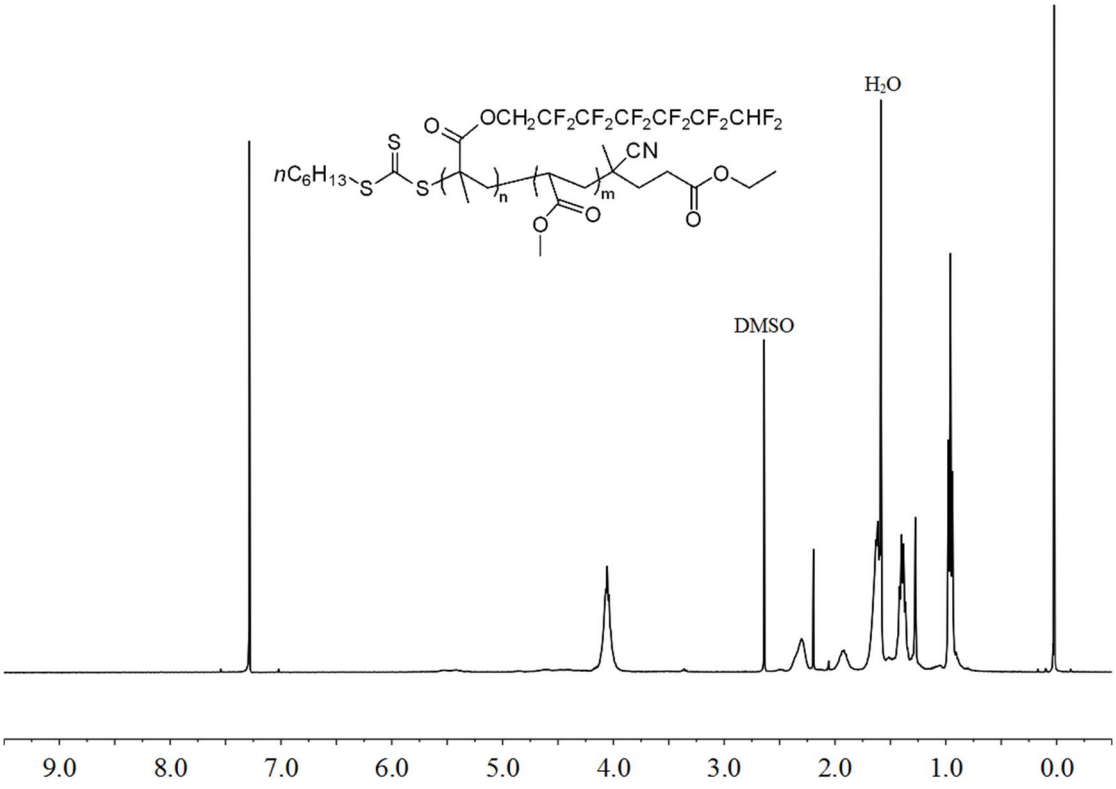


Figure S22. [1]H NMR Spectra of block polymer (PDDFHMA-*b*-PMA)

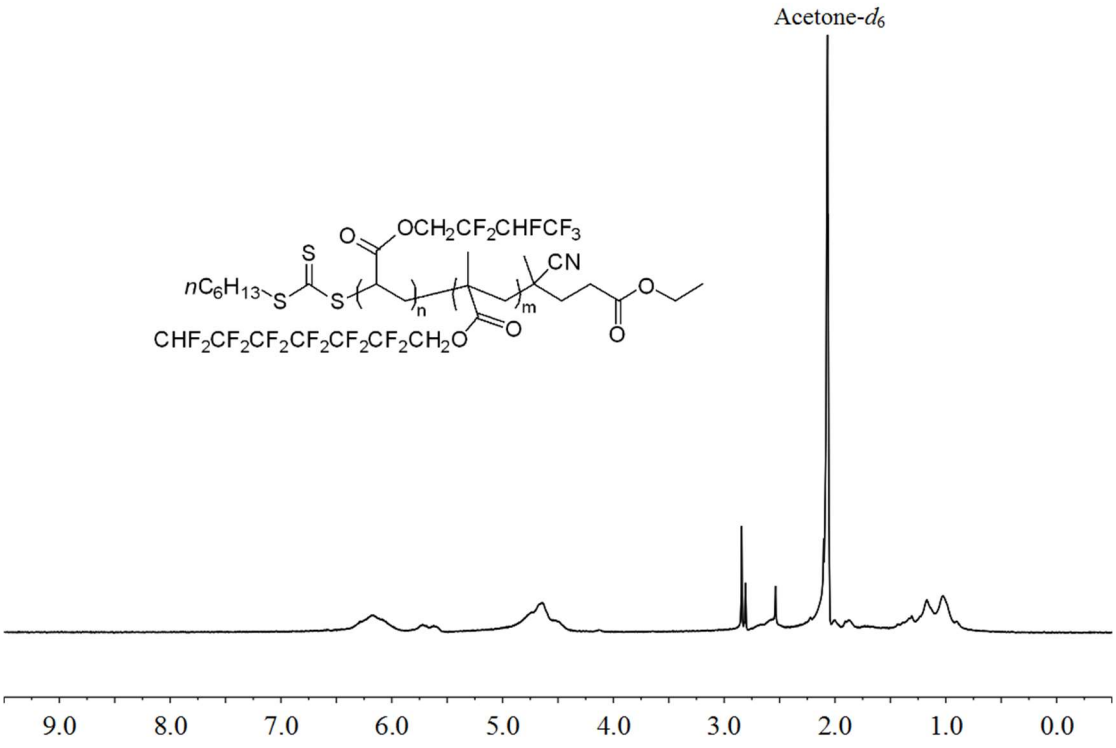


Figure S23. ^{1}H NMR Spectra of block polymer (PHFBA-*b*-PDDFHMA)

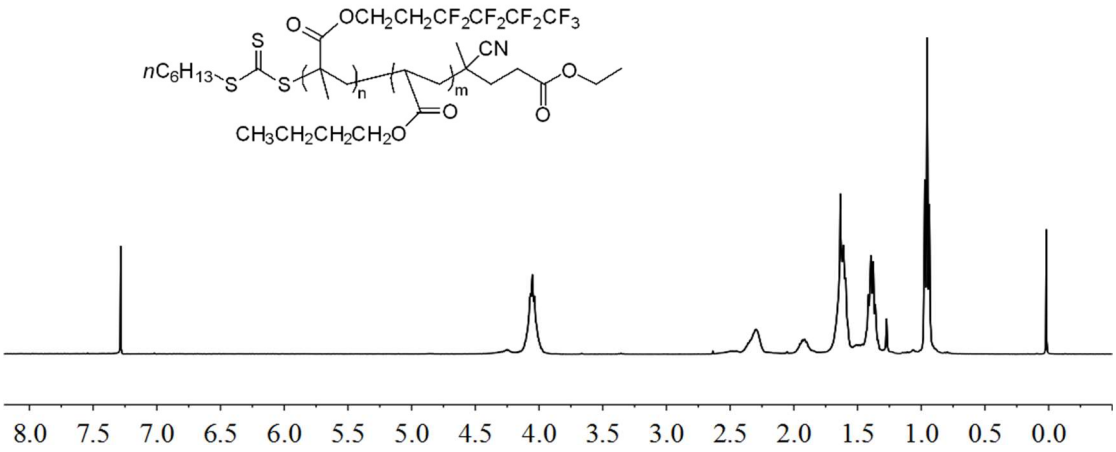


Figure S24. ^{1}H NMR Spectra of block polymer (PNFHMA-*b*-P*n*BA)

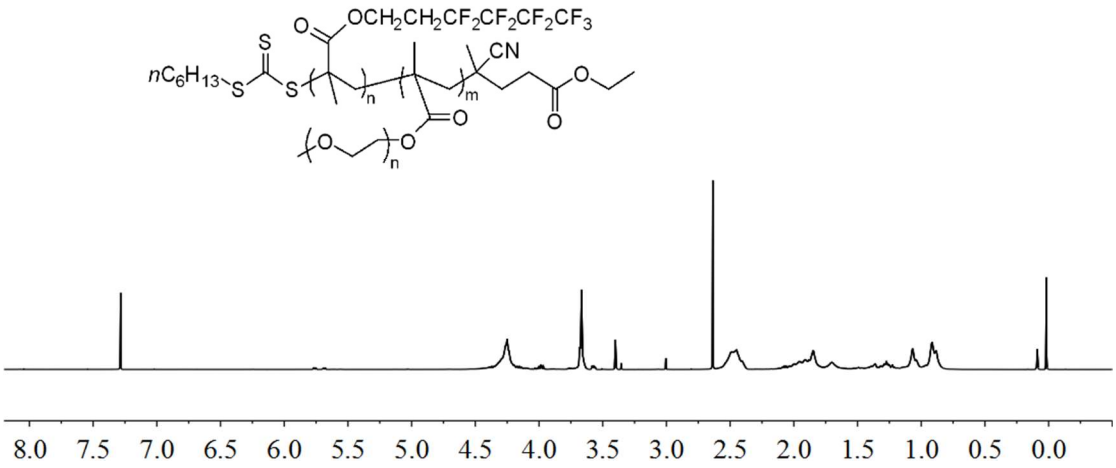


Figure S25. ^{1}H NMR Spectra of block polymer (PNFHMA-*b*-PPEGMMA)

Reference

[1] Fu, L.; Sun, C.; Yan, L., Galactose Targeted pH-Responsive Copolymer Conjugated with Near Infrared Fluorescence Probe for Imaging of Intelligent Drug Delivery. *ACS Appl. Mater. Interfaces.* **2015,** *7*, 2104.

[2] Mitsukami, Y. Donovan, M. S. Lowe, A. B. McCormick, C. L. *Macromolecules,* **2001***, 34, 2248.*

[3] Lal, N. Jangir, S. Bala, V. Mandalapu, D. Sarswat, A. Kumar, L. Jain, A. Gupta, G. Sharma, V. L. *Eur. J. Med. Chem.* **2016***, 115, 275.*

[4] Shi, L. Chapman, T. M. Beckman, E. J. *Macromolecules,* **2003***, 36, 2563.*