Supplementary material

Photoiniferter-RAFT polymerization mediated by bis(trithiocarbonate) disulfides

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1 Experimental section

1.1 Materials

Methyl acrylate (MA) and methyl methacrylate were obtained from Sigma-Aldrich and passed through neutral alumina column prior to use to remove inhibitor. 2,2'-Azobis(2-methylpropionitrile) (AIBN, $t_{1/2-10h} = 65^{\circ}C$ (toluene), 98%) was obtained from Sigma-Aldrich and recrystalised from hexane prior to use. 4,4'-Azobis(4-cyanovaleric acid) (ACVA, $t_{1/2-10h} = 69^{\circ}C$ (in water, as Na salt), \geq 98%) was obtained from Sigma-Aldrich and used as received. C4 BisTTC was synthesised, details below. All solvents were obtained from either Fisher Scientific, VWR Chemical, or Sigma-Aldrich, and used as received. All deuterated solvents were obtained from or Sigma-Aldrich and used as received. 1,3,5-Trioxane, sodium 1-butanethiolate, carbon disulfide, (dimethylamino)pyridine (DMAP) were obtained from Sigma Aldrich and used as received. N-(3-Dimethylaminopropyl)-N'-ethylcarbodiimide hydrochloride (EDC) was obtained from Carbosynth and used as received. Iodine was obtained from Fisher and used as received.

1.2 Characterisation

1.2.1 Nuclear Magnetic Resonance (NMR) spectroscopy

NMR spectra were recorded on either 300 MHz or 400 MHz Bruker Advanced III systems at 25°C using deuterated solvents – chloroform-d (99,9% D atom) and acetone-d₆ (99.9% D atom). TMS contained in the solvent or solvent itself was used as internal standard and chemical shift values (δ) are reported in ppm.

1.2.2 Size Exclusion Chromatography (SEC)

THF-SEC: Agilent Infinity II MDS instrument equipped with differential refractive index (DRI), viscometry (VS), dual angle light scatter (LS) and multiple wavelength UV detectors. The system was equipped with 2 x PLgel Mixed C columns (300 x 7.5 mm) and a PLgel 5 μ m guard column. The eluent is THF with 0.01 % BHT (butylated hydroxytoluene) as an additive. Samples were run at 1ml/min at 30°C. Poly(methyl methacrylate) standards (Agilent EasiVials) were used for calibration. Analyte samples were filtered through a PTFE membrane with 0.22 μ m pore size before injection. Respectively, experimental molar mass ($M_{n,SEC}$) and dispersity (D) values of synthesized polymers were determined by conventional calibration using Agilent SEC software.

1.2.3 Matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI-ToF-MS)

MALDI-ToF MS was performed on a Bruker Autoflex Speed MALDI-ToF mass spectrometer, equipped with a nitrogen laser delivering 2 ns laser pulses at 337 nm with positive ion ToF detection with an accelerating voltage of 25 kV. Solutions were prepared as follows: trans-2-[3-(4-tert-Butylphenyl)-2-methyl-2-propenylidene] malononitrile (DCTB) as the matrix (40 mg mL⁻¹), sodium trifluoroacetate (NaTFA, 1 mg ml⁻¹) and the polymer sample (10 mg mL⁻¹) were dissolved in spectroscopy grade acetonitrile. 5 μ L of matrix and sample and 1 μ L of salt were mixed and 0.5 μ L of the final solution was applied on the target plate. Spectra recording was made in reflective mode calibrating with PEG 1000, 2000 and 3000 g/mol.

1.2.4 High-performance liquid chromatography (HPLC)

Agilent 1260 infinity system fitted with a binary pump, degasser and variable wavelength UV-Vis detector module. A Luna 5 μ m C18 100 Å (250 x 4.6 mm, Phenomenex) was used with gradients of Acetonitrile (MeCN)/H₂O (+0.04% trifluoroacetic acid (TFA)) at a flow rate of 1ml min⁻¹. Samples were prepared in solvent mixture corresponding to the chromatography starting conditions and injected with a 1260 auto sampler with an injection volume of 20 μ l. UV detection was monitored at λ = 254 or 310 nm. All samples were filtered through 0.4 μ m Nylon membrane prior to injection. Typical solvent conditions were: 80% MeCN for 0 - 5 min, gradient of 80 to 100% MeCN over 5 - 25 min, 100% MeCN 25-35 min, 80% MeCN 35- 40 min.

1.2.5 Ultraviolet/visible (UV-Vis) absorption spectroscopy

UV-Vis absorption spectra were recorded using Agilent Cary 60 UV-Vis spectrometer at 25°C in spectroscopy grade acetonitrile or tetrahydrofuran (THF), scanning rate 600 nm/min, with automatic baseline correction.

1.3 Photoreactor set up



Figure 1 Batch reactor set ups: A multiwell, B test tube.

Lumidox Gen II LED controller was purchased from Analytical Sales equipped with replaceable Gen II 96-Position LED Arrays (λ max 527, 505, 470, 405, 365 nm) with a diffuse mat and solid base. The controller allows for adjusting light intensity, values used are reported in Table 1. Irradiance [mW/cm²] was measured using S142C Integrating Sphere Power Sensor Head with Silicon Detector pointed directly at the LED array, connected to a ThorLabs PM400 optical power meter set at corresponding wavelength. For temperature control, a thermal transfer dock (TTD) was attached to the base of the LED reactor to prevent overheating of the LEDs. The dock was connected to a circular minichiller (Minichiller 600 Ole, Huber UK Temperature Control Ltd) and filled with 30% aqueous solution of ethylene glycol. The reactor was used in two modes: horizontal, with 2 ml screw-cap sample vials placed in a metal multiwell plate holder supplied with Lumidox or vertical, with 5 ml Pyrex test tubes clamped 1 cm away from the LED mat and above a stirring plate. Temperature was recorded during polymerization to ensure no temperature fluctuations were present. Reactions were carried out at T= 45-50°C. For wavelength dependent kinetics, small fan was used, and temperature equilibrated prior to reaction at 45°C (temperature measures inside a 2ml vial) for all wavelengths.

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	Wavelength (nm)	Lumidox setting – total output (W)	Measured light intensity (mW/cm ²)
	527	11.0	82
	527	13.9	102
	505	13.4	120
	470	14.4	115
	470	20.6	170
	365	18.7	160

 Table 1. LED output power as reported by the manufacturer and light intensity as measured

 with the light meter of Lumidox II 96-Well LED arrays with diffuse lens matt and solid base.

1.4 Experimental Procedures

1.4.1 Synthesis of bis(trithiocarbonate butyl) disulfide C4-BisTTC

Scheme 1. Synthesis of C4 BisTTC.



25 ml of 1-butanethiol (1 eq, 0.23 mol) and 350 ml diethyl ether were charged into a round bottom flask equipped with a stirrer bar and a rubber septum. Slowly, aqueous solution of sodium hydroxide (10.21 g, 1.1 eq, 0.26 mol in 40 ml of water) was added and solution was stirred overnight. The solution was cooled down on ice bath and carbon disulfide (14.65 ml, 1.05 eq, 0.24 mol) was added dropwise via syringe over 10 min. The reaction was brought up to room temperature and stirred for further 3 h after which 32.38 g of solid iodine (0.55 eq, 0.128 mol) was added portion-wise and stirred at room temperature for 2 h. The reaction mixture was subsequently washed with thiosulfate, until no further colour changes of the organic layer were observed, water (1x 100 ml) and brine (2 x 100 ml). The organic layer was dried over MgSO₄ and solvent removed under vacuum to give bis(butylsulfanylthiocarbonyl) disulfide as dark orange oil (crude yield 81%, 31.1 g) which was purified in 5 ml batches by isocratic silica flash chromatography using hexane (120 g SiliaSep Flash Cartridge, 60 ml/min, 310 nm detector), concentrated and dried under high vacuum to give dark orange oil, 65% yield.

IR: vmax/cm⁻¹ 2955, 2926, 2869 (C-H stretch), 1459 (C-H bend), 1045 (C=S stretch), 835 (C-S stretch), ¹H NMR: (400 MHz, CDCl₃) δ 3.31 (t, J 7.5 Hz, 4H, SCH₂), 1.69 (quin, J 7.5 4H, SCH₂CH₂), 1.43 (h, J 7.5 Hz, 4H, CH₂CH₃), 0.93 (t, J 7.5 Hz, 6H, CH₃) ppm, ¹³C NMR: (101 MHz, CDCl₃) δ 221.5, 38.1, 29.6, 22.2, 13.7 ppm.



Figure 2 ¹H NMR (top) and ¹³C NMR (bottom) spectra (CDCl₃) of C4 BisTTC

1.4.2 Synthesis of methyl 2-(((butylthio)carbonothioyl)thio)propanoate (PMBTC)

Scheme 2. Synthesis of PMBTC.



2- (((Butylthio)-carbonothioyl)thio)propanoic acid (PABTC) was synthesised according to the literature¹ and recrystallised twice from hexane before use. 10.00 g of PABTC (1 eq, 42 mmol), 0.62 g (0.12 eq, 5 mmol) DMAP and 9.00 g (1.12 eq, 47 mmol) of EDC were dissolved in 100 ml of methanol and vigorously stirred at room temperature for 18 h. Then, methanol was removed in vacuo and the residue was redissolved in 100 ml of DCM and washed twice with water (50 ml each), dried over MgSO₄ and concentrated under vacuum. The crude product was purified by flash column chromatography on a silica column, 80/20 hexanes/ethyl acetate eluent to give pale orange oil (7.30 g, 70% yield).

¹H NMR (400 MHz, CDCl₃) δ 4.85 (q, *J* 7.2, 1H, CS*H*CH₃), 3.75 (s, 3H, OCH₃), 3.37 (t, *J* 7.2, 2H, CH₂S), 1.69 (quin, *J* 7.2, 2H, SCH₂CH₂), 1.60 (d, *J* 8, 3H, CHCH₃), 1.43 (h, *J* 7.2, 2H, CH₂CH₃), 0.94 (t, *J* 7.2, 3H, CH2CH3) ppm. ¹³C NMR (101 MHz, CDCl₃) δ 222.0 (C=S), 171.7 (C=O), 52.9 (OCH₃), 47.73 (CHCH₃), 37.0 (SCH₂), 29.9 (SCH₂CH₂), 22.1 (CH₂CH₃), 17.0 (CHCH₃), 13.6 (CH₂CH₃) ppm. ESI MS +ve: Calculated for C₈H₁₄O₂S₃Na, [M+Na]⁺ 275.02. Found m/z 275.0



Figure 3. ¹H NMR (top) and ¹³C NMR (bottom) spectra (CDCl₃) of PMBTC.

1.4.3 General procedure for thermal polymerization of methyl acrylate

Scheme 3. Thermal polymerization of methyl acrylate.



A 7.5 ml vial was charged with C4 BisTTC (0.33 mmol, 109.4 mg), dioxane (2.1 ml), AIBN (5.4 mg, from 10mg/ml 1,4-dioxane stock solution, 560 mg, 0.033 mmol) and a stirrer bar, was capped with a rubber seal septum and degassed for 10 min. Then, degassed MA (1.5 ml, 16.55 mmol) was added, giving final concentrations [MA] = 4 M and [BisTTC] = 0.08 M, and CTA/I = 10. The vial was then placed in an oil

bath pre-heated to 65°C for 24 h. After this time, the vial was opened to air and samples were taken for ¹H NMR and SEC analysis. Resulting product was precipitated twice in ice cold hexane and dried in vacuo, SEC (THF): D = 1.30, $M_{n, SEC} = 14900$ g/mol.

1.4.4 General procedure for thermal polymerization of methyl methacrylate

Scheme 4. Thermal polymerization of methyl methacrylate



A 10 ml round bottom flask was charged with C4 BisTTC (0.4 mmol, 132.1 mg), dioxane (1.87 ml), ACVA (22.4 mg, 0.08 mmol), methyl methacrylate (2000 mg, 20 mmol) and a stirrer bar, was capped with a rubber seal septum and degassed for 15 min., giving final concentrations [MA] = 4 M and [BisTTC] = 0.08 M, and CTA/I = 5. The vial was then placed in an oil bath pre-heated to 75°C for 24 h. After this time, the vial was cooled down on ice, opened to air and samples were taken for ¹H NMR and SEC analysis, 98% conversion, SEC (THF): D = 1.23, $M_{n, SEC} = 8030$ g/mol. Resulting product was precipitated twice in ice cold diethyl ether and dried in vacuo, SEC (THF): D = 1.17, $M_{n, SEC} = 8640$ g/mol.

1.4.5 General procedure for batch photopolymerization of homopolymers

In a typical procedure targeting PMA₅₀ a 2 ml vial with a screw cap with a rubber seal or a Pyrex test tube fitted with a rubber septum were charged with C4 BisTTC (0.11 mmol, 36.6 mg) and 1,4-dioxane or toluene (0.88 ml) and degassed. Methyl acrylate was degassed separately (to avoid monomer loss due to its volatility) and transferred with a degassed syringe (500 μ l, 5.53 mmol) to the RAFT agent solution, giving final concentrations [MA] = 4 M and [BisTTC] = 0.08 M. DMF or trioxane were added as internal standards for conversion calculations. Reactions with volume exceeding 2 ml were stirred during polymerization. 2 ml vials were placed in the metal holder and irradiated with 150 mW per well 470 nm light for 10 h. Test tubes were clamped 1 cm away from the LEDs and irradiated with 14.4 W 470 nm light for 4 h. Resulting product was precipitated twice in ice cold hexane and dried in vacuo, SEC (THF): D = 1.13, $M_{n, SEC} = 12200$ g/mol.

In a typical procedure targeting PMMA₅₀ a 2 ml vial with a screw cap with a rubber seal was charged with C4 BisTTC (0.08 mmol, 26.4 mg), MMA (400 mg, 4 mmol) and 1,4-dioxane (0.57 ml), giving final concentrations [MMA] = 4 M and [BisTTC] = 0.08 M. The solution was degassed for 5 min and the septum was greased after removal of the needle. The vial was placed in the metal holder (multiwell

set-up) or clamped 1 cm away from the LEDs (vertical set-up) and irradiated with 527 nm light (130 mW/cm²) for 8 h. Reactor was equilibrated for at 30 min before the reaction to reach steady temperature. After reaction time, the vial was opened to air and samples were taken for ¹H NMR and SEC analysis, 91% conversion, SEC (THF): D = 1.46, $M_{n, SEC} = 5$ 440 g/mol. Resulting product was precipitated twice in ice cold diethyl ether and dried in vacuo, SEC (THF): D = 1.20, $M_{n, SEC} = 7$ 700 g/mol.

For kinetic studies, reaction stock solution was prepared and split into multiple 2 ml vials (500 μ l of reaction solution each), degassed and placed in the multiwell plate as above. The vials were removed one each at corresponding time points.



5.2 5.0 4.8 4.6 4.4 4.2 4.0 3.8 3.6 3.4 3.2 3.0 2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8 0.6 Chemical shift (ppm)

Figure 4. ¹H NMR spectrum (CDCl₃) of precipitated PMA₁₂₃ sample, *D* 1.13, *M*_{n, SEC} 12 200 g/mol.



Figure 5. ¹H NMR spectrum of PMMA₅₁ sample, D = 1.20, $M_{n, SEC} = 7700$ g/mol

1.4.6 General procedure for the synthesis of block copolymers

Synthesis of macroCTA was carried out as described in 1.4.3. MacroCTA was precipitated twice in hexane and dried in a vacuum oven at 40°C overnight. Kinetics preceded polymerization to ensure that the reaction was stopped after reaching desired conversion and not left under light for prolonged time. In a typical procedure targeting PMA₁₅₀, macroCTA (0.0294 mmol, ~380 mg) and dioxane (630 μ l) were degassed for 10 min. Separately, MA was degassed for 15 min. After degassing, MA (400 μ l) was transferred with a degassed syringe to the mCTA solution, giving final concentrations [MA] = 4 M and [mCTA] = 0.027 M. Vial was clamped 1 cm away from the LEDs and irradiated with 470 nm, 115 mW/cm² light for 4 h.

Table 2. Reaction set up for screening different wavelength for MA polymerization mediated
with C4 BisTTC in 1,4-dioxane, mutliwell Lumidox Gen II set up.

Light wavelength	Measured light intensity (mW/cm ²)	Reaction time (hours)
365 nm	160	8
470 nm	120	10
505 nm	120	16
527 nm	100	16

1.4.7 Light stability study

The solution of RAFT agent was prepared in a similar manner as described in 1.4.5 but monomer volume was replaced with more solvent, to give final concentration of RAFT agent 0.08 M. Time points were taken under nitrogen blanket. Samples for UV-vis spectroscopy were prepared with

spectroscopy grade acetonitrile were prepared with approximate but accurate concentrations so that absorbance at 310 nm for t₀ sample (before irradiation) was about 0.6. All time points were prepared in the same way and their absorbance was measured with UV-Vis spectrometer. 10 μ l of original solution were diluted in HPLC eluent and run as described in 1.2.4.

For polymer stability study, PMMA (7400 g/mol, D = 1.16) was prepared via thermal polymerization and purified. 700 mg of PMMA were dissolved in 1.75 ml of dioxane and the solution was split into 5 vials and degassed for 5 min and irradiated with light as described in section 1.4.3. Vials were removed at appropriate time points. 5 µl of the solution were diluted in 1 ml THF SEC solvent for SEC analysis.

1.4.8 Isolation of low molecular weight impurities

Impurities from blue light MA polymerization were isolated by precipitating polymer in hexane and concentrating the supernatant.

Impurities from blue light C4 BisTTC degradation were isolated by column chromatography (100% hexane) and HPLC preparatory chromatography. Only one impurity was isolated in quantities sufficient for full analysis and it was identified as S-butyl-S'-butylsulfane trithiocarbonate (Figure 8).

For other impurities ¹H NMR analysis was carried out and obtained spectra were compared with the literature to identify dibutyl trithiocarbonate² and n-butyl disulfide ^{3,4} by comparing shift of the characteristic triplet signal of the CH2 group attached to sulphur (peak d on Figure 6).



Figure 6. ¹H NMR spectra of impurities from blue light polymerization and RAFT agent degradation study.



Figure 7. HPLC chromatograms at 310 nm of C4 BisTTC and sample after 4 h of blue light stability study of neat C4 BisTTC.



Figure 8. ¹H (top) and ¹³C NMR (bottom) spectra one of the isolated impurities - S-butyl-S'butylsulfane.

2 Supplementary figures



Figure 9. Size exclusion chromatograms (THF SEC, PMMA standards) of cyan light (505 nm) polymerization of MA with C4 BisTTC.



Figure 10. (A) Polymerization of methyl acrylate (MA) under green (527 nm) light using C4 BisTTC or control CTA (PMBTC). (B) Size exclusion chromatogram of poly (methyl acrylate) (PMA) prepared using PMBTC. (C) Size exclusion chromatogram of poly (methyl acrylate) (PMA) prepared using C4 BisTTC. (D) UV-Vis absorbance of different RAFT agents.



Figure 11. Comparison of size exclusion chromatograms of PMMA synthesised with C4 BisTTC under green light (102 mW/cm²) in multiwell and test tube set up.



Figure 12. (A) Analysis of green light photoiniferter DP50 MMA polymerization comparing 82 and 102 mW/cm² light intensities. (B) Pseudo-first order kinetic plot. (C, E) THF SEC data – molecular weight and dispersity evolution for 82 mW/cm² polymerization and SEC chromatograms (D, F) THF SEC data – molecular weight and dispersity evolution for 102 mW/cm² polymerization and SEC chromatograms



Figure 13. THF SEC chromatograms for photoiniferter DP500 MA polymerization in test tube set up (A) or multiwell set up (B)



Figure 14. MALDI-ToF analysis of BisTTC-derived poly(methyl acrylate) prepared using 470 nm blue light and proposed structures.



Figure 15. THF SEC chromatograms for thermal synthesis pseudo block copolymers made with purified PMMA (B) and crude PMMA (C) first block.



Figure 16. Photostability of pre-made PMMA polymer under green and blue light



Figure 17 Photodegradation study of C4 BisTTC in the absence of monomer. UV-vis spectra of samples from irradiation of 0.08 M RAFT agent in 1,4-dioxane under 527 nm 505 nm and 470 nm light.



Figure 18. Size exclusion chromatograms of PMA polymers prepared using standard 470 nm photo batch conditions with different amounts of triethylamine; equivalents wrt C4 BisTTC.

References

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