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Complete List of Authors:	Clouthier, Samantha; University of North Carolina at Chapel Hill Campus Box 3290 Chapel Hill, NC 27599-3290, USA , Department of Chemistry Tanaka, Joji; University of North Carolina at Chapel Hill, You, Wei; University of North Carolina at Chapel Hill Campus Box 3290 Chapel Hill, NC 27599-3290, USA , Department of Chemistry

COMMUNICATION

Photo-mediated RAFT step-growth polymerization with maleimidic monomers

Samantha Marie Clouthier,[a] Joji Tanaka[a]* and Wei You[a]*

Photo-mediated RAFT step-growth polymerization was performed with and without the presence of a photocatalyst using trithiocarbonate based CTA and maleimidic monomer. Under catalyst free conditions, the polymerization proceeded with appreciable rate under irradiation with blue and green light, which was extended to the red light in the presence of the ZnTPP.

Reversible Addition Fragmentation chain Transfer (RAFT) polymerization, mediated by RAFT agents or Chain Transfer Agents (CTAs) that seed and control the polymerization via chain transfer of the thiocarbonylthiol group, is generally considered as one of the most user friendly and versatile polymerization strategy.[1-3] Traditionally, RAFT polymerization has been driven by exogenous initiators; however, recent years have witnessed a rapid growth in the use of light to directly initiate the RAFT polymerization.[4]

Depending on the chemical nature of the R/Z groups of the CTA, thiocarbonyl thiol group can *directly* absorb appropriate wavelength of light to fragment into radicals to initiate the polymerization.[5] This intriguing photo-induced process was first described by Ostu and coworkers as initiation-chain transfer-terminator (iniferter) using UV irradiation.[6] Later, Zard *et. al.* utilized this photo-induced fragmentation in organic synthesis for insertion process before the invention of RAFT polymerization.[7] More recently, this process been widely exploited with RAFT agents to polymerise under visible light (i.e., RAFT-iniferter polymerization).[8-10]

Scheme 1: Photo-mediated RAFT step-growth polymerization in this work

RAFT Step-growth Polymerization

Previous work

A　RAFT Step-Growth Polymerization initiated by AIBN

This work

B　RAFT-Iniferter Step-Growth Polymerization

C　PET-RAFT Step-growth Polymerization

a. *Department of Chemistry, University of North Carolina at Chapel Hill, Chapel Hill, NC, 27599-3290 USA. E-mail: joji@email.unc.edu, wyou@unc.edu.*
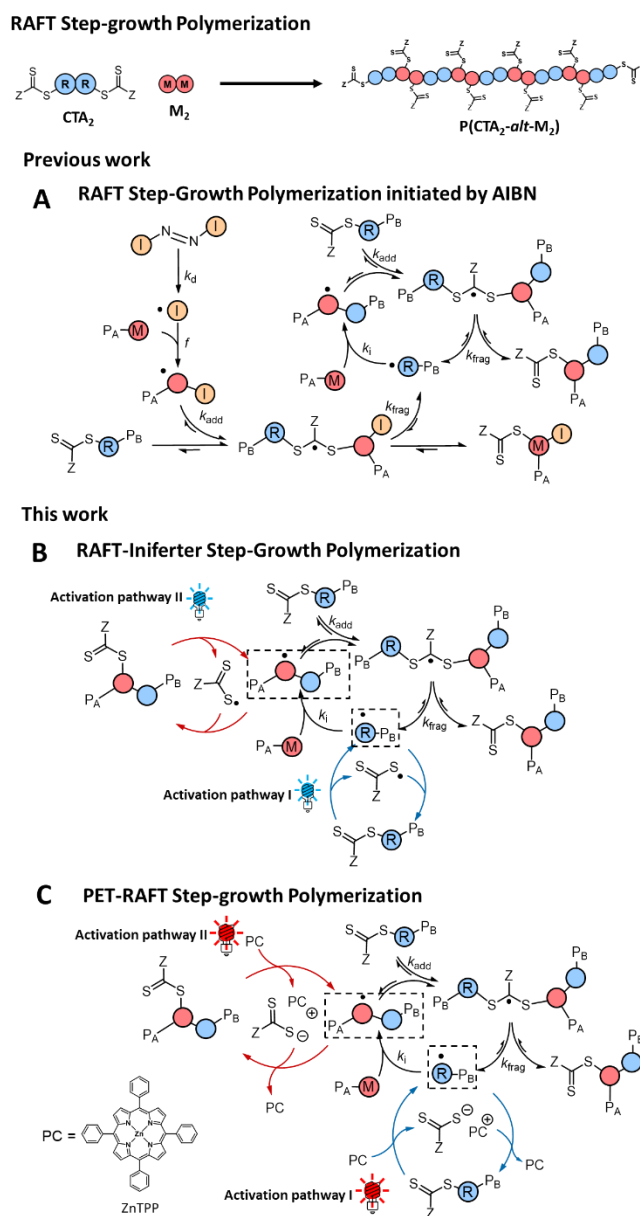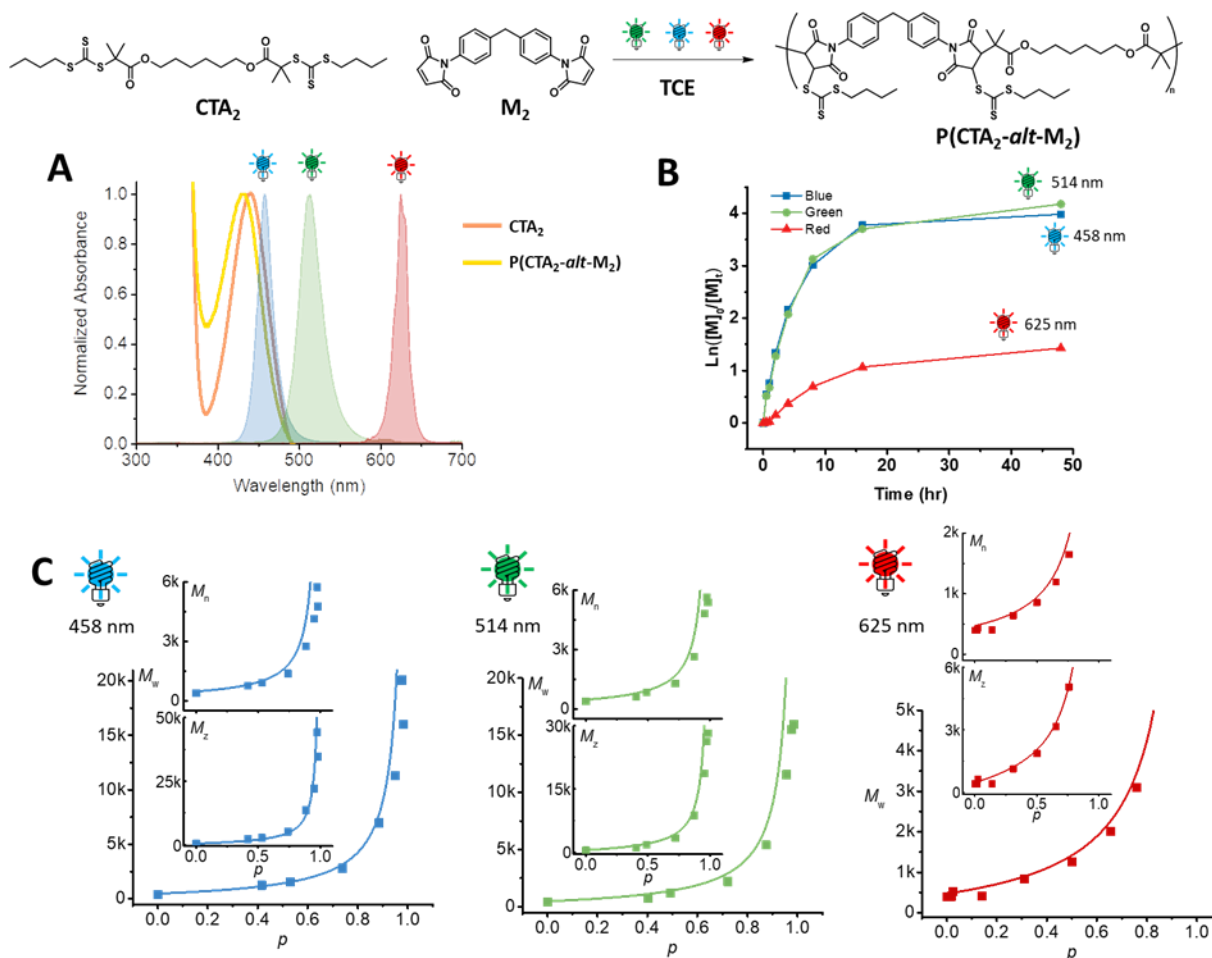
Figure 1: A₂ + B₂ RAFT-iniferter step-growth polymerization. **A**) visible light absorption spectra of bifunctional CTA, CTA₂ (orange line) and the resulting step-growth CTA backbone after polymerization (yellow line). The emission spectra from the LED lights used in the photo-reactor are plotted together. **B**) Semi-logarithmic of polymerization kinetics under different lights. **C**) Evolution of the molecular weight averages (M_w, M_n, M_z) from SEC analysis using polystyrene calibration, plotted together with monomer conversion (p) determined by ¹H-NMR. These are plotted together with theoretical line for step-growth molecular weight evolution which assumes no cyclization.[11]

In contrast to RAFT-iniferter process where light directly fragments the CTA, another recently emerged method relies on photo-induced energy/electron transfer (PET) via photocatalysts to *indirectly* fragment the CTA. While RAFT-iniferter typically requires high energy photons (e.g., UV or blue), PET-RAFT allows versatility in wavelength selection, and oxygen tolerance.[12-15] However, to date, much of the investigations into photo-mediated RAFT polymerization has been focused on controlled chain growth.

We recently reported a step-growth polymerization through RAFT process by utilizing monomer and CTA pairs that selectively and efficiently yield single monomer unit inserted (SUMI) CTA adducts under stoichiometrically balanced conditions.[16] Moreover, we exploited commercially available bifunctional monomers, which were able to undergo RAFT step-growth polymerization, thereby increasing the accessibility to this new polymerization methodology.[17, 18] However, the polymerizations in these reports were all driven by thermal decomposition of exogenous initiators at the cost of end group fidelity (**Scheme 1A**).

In general, high monomer conversion as well as high end-group fidelity is required to obtain high molecular weight through the step-growth mechanism.[19] Therefore, using photo-mediated strategy (e.g., iniferter) that is rapid with limited loss of the end groups is especially desirable for RAFT step-growth polymerization. Moreover, Xu et al. demonstrated quantitative monomer conversion and SUMI-CTA adduct yield via PET-RAFT under balanced stochiometric conditions.[20] Given these desirable features of the light-mediated RAFT polymerizations (iniferter and PET-RAFT), we set our goals to investigate both in our RAFT step-growth system. Importantly, given that different initiating mechanisms between iniferter and PET-RAFT, it would be interesting to compare the difference between these two light-mediated approaches in RAFT step-growth polymerization.

We first investigated RAFT-iniferter step-growth polymerization using three different wavelengths: red (λ_{max} = 625 nm), green (λ_{max} = 514 nm) and blue LED lights (λ_{max} = 458 nm), which overlap with visible light absorbance corresponding to the symmetry forbidden transition (n-π*) of the CTA (**Figure 1A**).[21] In theory, the photoactivation can occur from the end
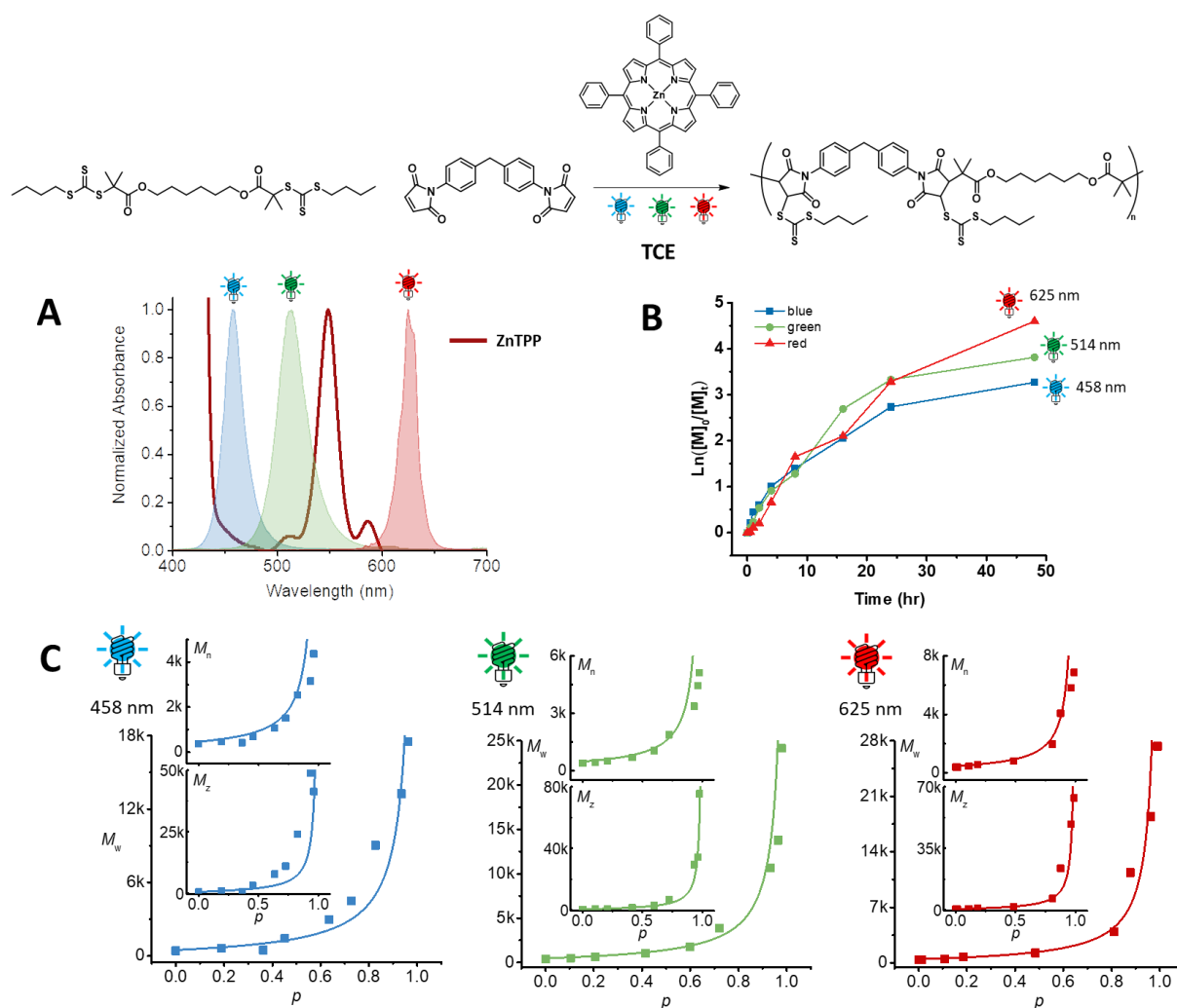
Figure 2: A_2 + B_2 PET-RAFT step-growth polymerization. **A)** visible light absorption spectrum of the photocatalyst, ZnTPP (red line) plotted together with emission spectra from the LED lights used in the photo-reactor. **B)** Semi-logarithmic of polymerization kinetics under different lights. **C)** Evolution of the molecular weight averages (M_w, M_n, M_z) from using polystyrene calibration, plotted together with monomer conversion (p) determined by ^{1}H-NMR. These are plotted together with theoretical line for step-growth molecular weight evolution which assumes no cyclization.[11]

group CTA (activation pathway I, **Scheme 1B**) or from the backbone CTA (activation pathway II, **Scheme 1B**); each pathway would directly generate one of the two radical intermediates required in the RAFT step-growth cycle (dashed line, **Scheme 1**).

Experimentally, the reaction mixture was prepared as previously reported, using commercially available *N,N'*-(1,4-phenylene)dimaleimide as the bifunctional monomer (M_2) in tetrachloroethane (TCE), but without the addition of exogenous initiator.[17] ^{1}H-NMR was used to determine monomer conversion as previously reported [17] and SEC-analysis was used to determine the molecular weights relative to polystyrene standards in THF.

Under our reaction set-up (**Figure S1**), the polymerization proceeded rapidly in the initial 16 hours under blue and green light ($p > 97\%$), though the molecular weight did not increase further beyond 16 hours (**Table S1-S3**, **Figures S2-S4**) despite mild increase in monomer conversion ($p > 98 \%$) was observed. By contrast, under red light, the monomer conversion only

reached 76 % after 48 hours. The observed slower RAFT-iniferter SUMI kinetics with trithiocarbonates under red light was previously observed by others as well despite the minimal overlap of the CTA with the red LED emission spectra.[22] Interestingly, the reaction kinetics significantly deviated from linear trend in the semi-logarithmic plot with increasing conversion (**Figure 1B**). This deviation from first order kinetics can be explained from the blue shift in the n-π* absorbance of the trithiocarbonate (**Figure 1A**), as the end group CTA converts to backbone CTA. Moad et al. reported n-π* absorbance of trithiocarbonates to be blue shifted for less radically stabilized fragmentation;[23] in our case, conversion of the ester stabilised tertiary carbon radical fragmentation (i.e., end group CTA) to maleimidic secondary carbon radical fragmentation (i.e., backbone CTA) would increase energic requirement for homolysis of the latter species, thus the blue-shift as seen in **Figure 1A**. We speculate the preference of photo-induced fragmentation of the end group CTA (activation pathway I, **Scheme 1B**) leads to deviation from the expected first order

kinetics as end group CTAs are consumed during the polymerization.

Nonetheless, the polymerization proceeded with step-growth molecular weight evolution under all wavelengths investigated, as indicated by the molecular weight averages (M_n, M_w and M_z) and conversion following expected trend in accordance with Flory's equations.[11]

Utilising RAFT-iniferter process to mediate RAFT step-growth polymerization was first reported by Zhu et al.[24] In their work, blue light was used to initiate the polymerization with xanthate bearing ester-stabilized secondary carbon fragmentation as the CTA and vinyl ether as the monomer. Though successful step-growth molecular weight evolution was observed in their work, the molecular weight was limited (M_w = 4.2k) at high monomer conversion (p > 99%, $M_{w,th}$ = 57k).[24] In contrast, we obtained higher molecular weight (M_w = 16k); however, it was still lower than expected at high monomer conversion (p = 98%, $M_{w,th}$ = 50k).

We next investigated PET-RAFT step-growth polymerization using the same reaction conditions (**Scheme 1C**). In comparison to RAFT-iniferter, PET-RAFT is known to have superior kinetics especially under irradiation of longer wavelength.[22, 25] We utilized ZnTPP as the photocatalyst in this study as it is affordable and widely used for trithiocarbonate based CTAs (**Figure 2**).[14] In addition, UV-vis of the ZnTPP reveals its Q-band absorbance that overlaps with the LEDs used for our study (**Figure 2A**). In contrast to the iniferter based approach, the photo-activation with ZnTPP photocatalyst is speculated to result in a more stable thiocarbonyl anion via electron transfer (activation pathway I/II, **Scheme 1C**).[26-28] Though this charge transfer-based system has been reported to be optimum in polar solvents such as DMSO,[13, 14] we found our dimaleimide monomer (M_2) insoluble in this solvent. In addition, we previously found DMSO to be incompatible solvent with RAFT step-growth polymerization using maleimidic monomers.[16] Thus, we proceeded to use the TCE as the solvent to favour the solubility of the monomer (M_2). Here, we used molar ratio of CTA functionality to ZnTPP of 200 ($[CTA]_0/[ZnTPP]_0$ = 200) (**Figures S6-S8**). Interestingly, the initial rates were seemingly slower under blue and green light in the PET-RAFT condition when compared to catalyst free conditions (RAFT-iniferter); this observation contrasts to the comparison of kinetics in classical chain-growth systems where PET-RAFT is faster than RAFT-iniferter.[29] Nonetheless, the polymerization rate was significantly improved under red light in the presence of ZnTPP compared to catalyst free conditions under the same irradiation (**Figure 2B**). Interestingly, pseudo-first order kinetics with respect to monomer conversion was observed under blue, green and red light from the semi-logarithmic plot (**Figure 2B**), indicating the number of reactive radical intermediates in the reaction cycle to remain constant, which is consistent with PET RAFT-SUMI kinetics reported in the literature.[25, 30] In contrast to catalyst-free conditions, the activation in PET-RAFT relies on the presence of photocatalyst, which is the limiting reagent. Nonetheless, slight deviation from first order kinetics at high monomer conversion is still apparent, though to lesser extent than iniferter. This observation suggests rate limiting

generation of R•, which could also be attributed to preference of selectivity for photo-activation of the end group CTA. It's noteworthy that, though the initial rates were similar under all three wavelengths of light examined, the highest conversion (p = 99%) and molecular weight (M_w = 27k) was reached under red light, suggesting possibly higher end group fidelity. Nonetheless, under all three wavelengths, we found the
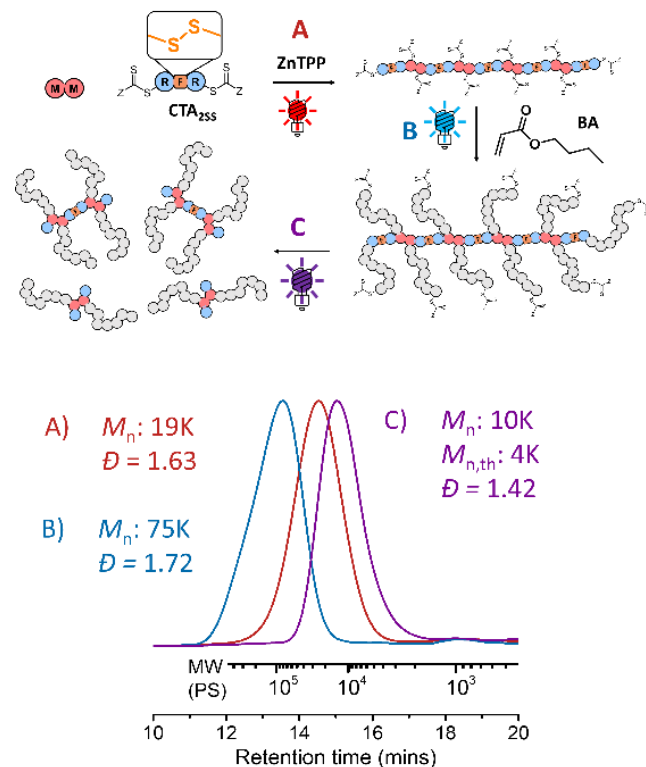

Figure 3: **A)** PET-RAFT step-growth polymerization with disulfide tethered bifunctional CTA_2 using red light. **B)** Grafting PBA from the resulting step-growth backbone via RAFT-iniferter using blue light. **C)** Photo-cleavage of the backbone under ultraviolet light.

polymerization to proceed through step-growth molecular weight evolution (**Figure 2C**, **Figure S9**).

Though we anticipated the molecular weights obtained with the light-mediated RAFT step-growth polymerization to be higher than those of the thermal initiated RAFT step-growth (since no exogenous initiator was used), we did not observe significant improvement in the molecular weight in the light-mediated cases. This observation could be possibly due to the difficulty in balancing the stoichiometry of the starting reagents or presence of impurity in the commercial monomer. To explore the possible improvement in end fidelity with photo-mediated system, we briefly examined the PET-RAFT with an AB RAFT-step growth monomer (**Table S7**, **Figure S10**, **S11**), which would ensure balanced stoichiometry. Interestingly, a difference between the theoretical M_w and the experimental value by a factor of 2 was observed ($M_{w,th}$ = 70k, M_w = 30k, **Table S7**), which was consistent with our previous report when considering initiator derived imbalanced stoichiometry.[16] We speculate this difference is due to the large weight fraction of lower molecular weight cyclic species formed during the polymerization, which inherently occurs more in AB step-growth system.[31] Nevertheless, theoretical M_z follows more

closely to the expected values as lower molecular weight species are weighted less in M_z ($M_{z,th}$ = 112k, M_z = 88k, **Table S7**).

Finally, to demonstrate the mildness and versatility of photo-mediated RAFT step-growth polymerization, we prepared graft copolymers with photo-degradable backbone. Using the same reaction conditions as above, disulfide bond tethered bifunctional CTA (CTA_{2SS}) was polymerized with M_2 via PET-RAFT using red light (**Figure 3A**, **Table S8**, **Figure S12**). Remarkably, despite having relatively labile disulfide bond in each repeat unit, the polymerization proceeded to follow step-growth molecular weight evolution as expected (**Figure S13**). In addition, structural analysis by ^{1}H-NMR spectroscopy was consistent with the intact backbone (**Figure S14**). Unexpectedly, we encountered some difficulty in removing the photocatalyst by precipitation of the polymer from diethyl ether. We have made some attempts to purify the polymer further by passing through aluminium oxide; though there were some visible differences, the presence of the catalyst was still noticeable (**Figure S15**). Nonetheless, we employed this backbone to graft poly(butylacyrlate) (PBA) via RAFT-Iniferter using the same photoreactor with blue light (**Figure S16**). We obtained 40 % conversion after 2 hours, using monomer to CTA ratio of 40 ($[BA]_0/[CTA]_0$ = 40) in dioxane ($[M]_0$ = 3 M), which yields M_n of approximately 2k per PBA side chain (**Figure S16**). Moreover, SEC analysis reveals shift in molecular weight distribution whilst maintaining unimodal shape, indicating a fully intact backbone (**Figure 3B**, **Figure S17**). This is rather remarkable, given that disulfide bonds are classically known to undergo homolytic fission under irradiation with ultraviolet light.[33] We emphasize the mildness of both PET-RAFT and RAFT-iniferter using visible lights, which permits incorporation of relatively photo-labile functional group into the core of a complex structure. Indeed, subjecting the graft copolymer to ultraviolet irradiation results in partial cleavage of the graft copolymer backbone (**Figure 3C**; see **Figure S18** for complete cleavage of the backbone using reducing agent).

In summary, photo-mediated RAFT step-growth polymerization with maleimidic monomers was demonstrated for the first time. The polymerization can be conducted under catalyst free conditions at appreciable rates with green and blue lights, whilst longer wavelength (red light) can be employed in the presence of ZnTPP. The initial rates were comparably faster with green and blue under catalyst free conditions; however, the rate was found to plateau with increasing conversions, deviating from first-order kinetics. In contrast, the rate did not deviate significantly from first order kinetics in the presence of the photocatalyst. Furthermore, the mildness and versatility of this approach was demonstrated by incorporating photo-labile disulfide bond in the step-growth polymer backbone and grafting polymeric side chains with light. It is worth noting that, post polymerization modification is typically required for preparing graft copolymers when using the same polymerization (e.g., RAFT chain-growth) for the side chains as for the main chain;[32] here we use the step-growth CTA backbone to directly graft-from via RAFT chain-growth polymerization without any additional step in between, greatly simplifying the preparation of such complex polymers.

Author Contributions

The manuscript was written through contributions of all authors.

Conflicts of interest

The authors declare the following competing financial interest(s): J.T. and W.Y. are named inventors on the provisional patent application described in this work.

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Notes and references

1. J. Chiefari, Y. K. Chong, F. Ercole, J. Krstina, J. Jeffery, T. P. T. Le, R. T. A. Mayadunne, G. F. Meijs, C. L. Moad, G. Moad, E. Rizzardo and S. H. Thang, *Macromolecules*, 1998, **31**, 5559-5562.
2. N. Corrigan, K. Jung, G. Moad, C. J. Hawker, K. Matyjaszewski and C. Boyer, *Prog. Polym. Sci.*, 2020, **111**, 101311.
3. S. Perrier, *Macromolecules*, 2017, **50**, 7433-7447.
4. M. Hartlieb, *Macromol. Rapid Commun.*, 2022, **43**, 2100514.
5. J. Xu, S. Shanmugam, N. A. Corrigan and C. Boyer, in *Controlled Radical Polymerization: Mechanisms*, American Chemical Society, 2015, vol. 1187, ch. 13, pp. 247-267.
6. T. Otsu and M. Yoshida, *Die Makromolekulare Chemie, Rapid Communications*, 1982, **3**, 127-132.
7. P. Delduc, C. Tailhan and S. Z. Zard, *Journal of the Chemical Society, Chemical Communications*, 1988, DOI: 10.1039/C39880000308, 308-310.
8. S. Shanmugam, J. Cuthbert, J. Flum, M. Fantin, C. Boyer, T. Kowalewski and K. Matyjaszewski, *Polymer Chemistry*, 2019, **10**, 2477-2483.
9. S. Shanmugam, J. Cuthbert, T. Kowalewski, C. Boyer and K. Matyjaszewski, *Macromolecules*, 2018, **51**, 7776-7784.
10. T. G. McKenzie, Q. Fu, M. Uchiyama, K. Satoh, J. Xu, C. Boyer, M. Kamigaito and G. G. Qiao, *Advanced Science*, 2016, **3**, 1500394.
11. P. J. Flory, *J. Am. Chem. Soc.*, 1936, **58**, 1877–1885.
12. J. Xu, C. Fu, S. Shanmugam, C. J. Hawker, G. Moad and C. Boyer, *Angew. Chem. Int. Ed.*, 2017, **56**, 8376-8383.
13. N. Corrigan, D. Rosli, J. W. J. Jones, J. Xu and C. Boyer, *Macromolecules*, 2016, **49**, 6779-6789.

14. S. Shanmugam, J. Xu and C. Boyer, *J. Am. Chem. Soc.*, 2015, **137**, 9174-9185.
15. J. Xu, K. Jung, A. Atme, S. Shanmugam and C. Boyer, *J. Am. Chem. Soc.*, 2014, **136**, 5508-5519.
16. J. Tanaka, N. E. Archer, M. J. Grant and W. You, *Journal of the American Chemical Society*, 2021, **143**, 15918-15923.
17. P. Boeck, N. Archer, J. Tanaka and W. You, *Polymer Chemistry*, 2022, **13**, 2589-2594.
18. N. E. Archer, P. T. Boeck, Y. Ajirniar, J. Tanaka and W. You, *ACS Macro Letters*, 2022, DOI: 10.1021/acsmacrolett.2c00476, 1079-1084.
19. A. Bossion, K. V. Heifferon, L. Meabe, N. Zivic, D. Taton, J. L. Hedrick, T. E. Long and H. Sardon, *Progress in Polymer Science*, 2019, **90**, 164-210.
20. Z. Huang, N. Corrigan, S. Lin, C. Boyer and J. Xu, *Journal of Polymer Science Part A: Polymer Chemistry*, 2019, **57**, 1947-1955.
21. K. Skrabania, A. Miasnikova, A. M. Bivigou-Koumba, D. Zehm and A. Laschewsky, *Polymer Chemistry*, 2011, **2**, 2074-2083.
22. A. Aerts, R. W. Lewis, Y. Zhou, N. Malic, G. Moad and A. Postma, *Macromol. Rapid Commun.*, 2018, **39**, 1800240.
23. L. T. Strover, A. Cantalice, J. Y. L. Lam, A. Postma, O. E. Hutt, M. D. Horne and G. Moad, *ACS Macro Letters*, 2019, **8**, 1316-1322.
24. Z. Li, J. Li, X. Pan, Z. Zhang and J. Zhu, *ACS Macro Letters*, 2022, DOI: 10.1021/acsmacrolett.1c00762, 230-235.
25. Y. Zhou, Z. Zhang, C. M. Reese, D. L. Patton, J. Xu, C. Boyer, A. Postma and G. Moad, *Macromol. Rapid Commun.*, 2020, **41**, 1900478.
26. P. Seal, J. Xu, S. De Luca, C. Boyer and S. C. Smith, *Advanced Theory and Simulations*, 2019, **2**, 1900038.
27. R. N. Carmean, M. B. Sims, C. A. Figg, P. J. Hurst, J. P. Patterson and B. S. Sumerlin, *ACS Macro Letters*, 2020, **9**, 613-618.
28. H. Wang, Q. Li, J. Dai, F. Du, H. Zheng and R. Bai, *Macromolecules*, 2013, **46**, 2576-2582.
29. C. A. Figg, J. D. Hickman, G. M. Scheutz, S. Shanmugam, R. N. Carmean, B. S. Tucker, C. Boyer and B. S. Sumerlin, *Macromolecules*, 2018, **51**, 1370-1376.
30. R. Liu, L. Zhang, Z. Huang and J. Xu, *Polymer Chemistry*, 2020, **11**, 4557-4567.
31. H. R. Kricheldorf, *Macromolecular Rapid Communications*, 2007, **28**, 1839-1870.
32. A. Kerr, M. Hartlieb, J. Sanchis, T. Smith and S. Perrier, *Chem. Commun.*, 2017, **53**, 11901-11904.
33. E. E. Smissman and J. R. J. Sorenson, *The Journal of Organic Chemistry*, 1965, **30**, 4008-4010.