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Metal-Free Ring-Opening Metathesis Polymerization: From Concept to Creation

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Cite This: *Acc. Chem. Res.* 2020, 53, 2325−2335 Read Online

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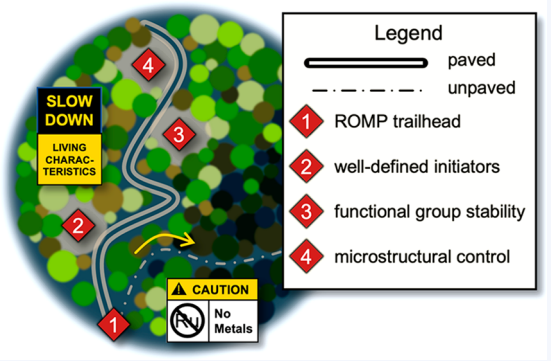
CONSPECTUS: Ring-opening metathesis polymerization (ROMP), which is derived from transition-metal-based olefin metathesis, has evolved into one of the most prevalent technologies for making functional polymeric materials in academia and in industry. The initial discovery of and advances in ROMP used ill-defined mixtures of metal salts to initiate polymerization. The initiators most commonly used today, developed with tremendous efforts, are well-defined metal−alkylidene complexes that have enabled a good mechanistic understanding of the polymerization as well as improvement of the initiators' activity, stability, and functional group tolerance.



The evolution of ROMP has been decidedly metal-centric, with the path to accolades being paved primarily in ruthenium-, molybdenum-, and tungsten-based systems. Our departure from the ROMP trailhead was inspired in part by recent breakthroughs in radical-mediated polymerizations, whereby their mechanisms were leveraged to develop metal-free reaction conditions. Inventing a metal-free complement to traditional ROMP would essentially involve stepping away from decades of inorganic and organometallic developments, but with the promise of crossing new synthetic capabilities and curiosities.

Driven by this motivation, as well as a community-inspired desire to develop "greener" controlled polymerizations, our team pioneered the search for, and discovery of, a wholly organic alternative to traditional metal-mediated ROMP. In this Account, we review our recent efforts to develop metal-free ring-opening metathesis polymerization (MF-ROMP), which is inspired by previous reports in electro- and photo-mediated organic transformations.

This work began with an exploration of the direct oxidation of enol ethers and the propensity of the ensuing radical cations to initiate ROMP. To overcome limitations of the electrochemical conditions, a photoredox-mediated method was investigated next, using photoexcited pyrylium salts to oxidize the enol ethers. With this system, we demonstrated the ability to produce ROMP products and temporally control the polymerization.

Further investigations into different aspects of the reaction included monomer scope, functional group tolerance, the impact of changing photocatalyst properties, and the ability to control molecular weight. The unique mechanism of MF-ROMP, along with the relative ease of synthesizing enol ether initiators, enabled the preparation of numerous polymeric materials that are hard to access through traditional metal-mediated pathways. At the end of this Account, we provide a perspective on future opportunities in this emerging area.

KEY REFERENCES

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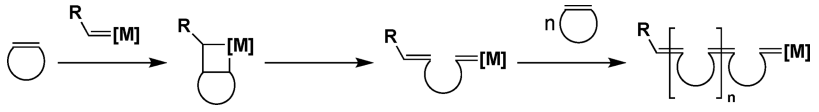
- Goetz, A. E.; Boydston, A. J. Metal-Free Preparation of Linear and Cross-Linked Polydicyclopentadiene. *J. Am. Chem. Soc.* **2015**, *137*, 7572−7575.[2] *This reference highlights the method for producing linear and cross-linked polyDCPD without the use of transition metals. Insight into mechanistic details of metal-free (MF) ROMP is also provided.*
- Goetz, A. E.; Pascual, L. M. M.; Dunford, D. G.; Ogawa, K. A.; Knorr, D. B.; Boydston, A. J. Expanded Functionality of Polymers Prepared Using Metal-Free Ring-Opening

Received: July 3, 2020
Published: September 22, 2020

Scheme 1. Generalized Mechanism of Traditional ROMP Using Metal Initiators



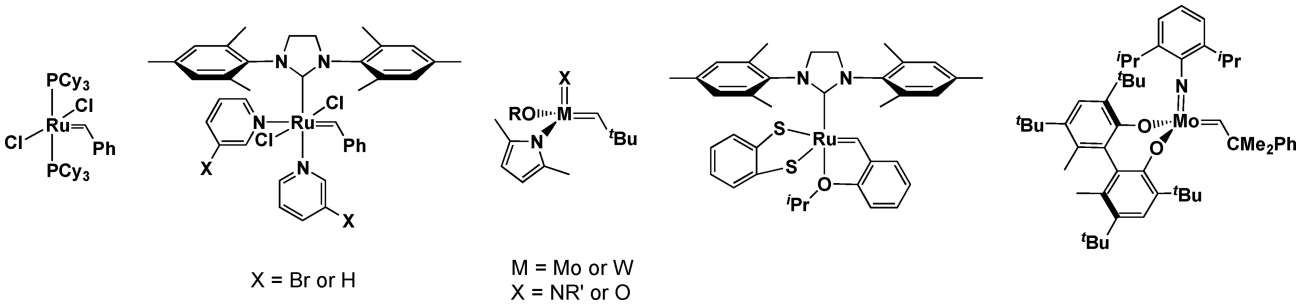


Figure 1. Select examples of well-defined metal-based ROMP initiators.

Metathesis Polymerization. *ACS Macro Lett.* **2016**, *5*, 579−582.[3] *The effect of various additives on MF-ROMP, the optimization of reaction protocols, and the use of functionalized monomers are explored in this reference.*

- Kensy, V. K.; Tritt, R. L.; Haque, F. M.; Murphy, L. M.; Knorr, D. B.; Grayson, S. M.; Boydston, A. J. Molecular Weight Control via Cross Metathesis in Photo-Redox Mediated Ring-Opening Metathesis Polymerization. *Angew. Chem. Int. Ed.* **2020**, *59*, 9074−9079.[4] *A simple, inexpensive method of controlling molecular weight in MF-ROMP, using alpha olefins as chain transfer agents is investigated in this reference. The regioselectivity of the chain transfer event is also studied.*

INTRODUCTION

Ring-opening metathesis polymerization (ROMP) has emerged as a powerful and broadly applicable technique for synthesizing polymeric materials. The origins of ROMP date back to the 1950s, when mixtures of metal salts were recognized for their ability to accomplish olefin metathesis, albeit without a corresponding mechanistic understanding.[5] That understanding came in the latter half of the twentieth century with work by Casey,[6,7] Grubbs,[8,9] and Katz,[10−13] which revealed that a metallacyclobutane intermediate was responsible for the carbon−carbon double bond exchange process, which was based on an earlier proposal by Chauvin.[14] ROMP monomers are cyclic alkenes, and the release of their ring strain is often the driving force for the polymerization. Due to the metathesis mechanism, the final ROMP polymer retains the level of unsaturation present in the original monomer (Scheme 1).

While other transition metals have been used to initiate ROMP, initiators based on Ru and Mo (Figure 1) are the most widely used due to their excellent functional group tolerance, which has greatly expanded the monomer scope of the reaction.[15] Importantly, careful adjustment of reaction conditions and initiator selection can achieve living polymerization characteristics that afford polymers with a controlled number-average molecular weight (M_n), a narrow dispersity ($Đ$), and a high chain-end fidelity.

Living ROMP is commonly terminated by the addition of a specialized chemical reagent, which selectively removes the transition metal from the chain end and deactivates it from further propagation. Removal of this residual metal, however, is challenging, and standard chromatographic methods are often not helpful. This is problematic because it limits the applications for ROMP polymers as metal contamination is unacceptable in the biomedical and microelectronics fields, for example. Although there has been much effort devoted to improving purification methods, these extra processes increase the length and cost of polymer production.[16] Moreover, the removal of metal from cross-linked thermosets is practically impossible.

To address the need for metal-free alternatives and to contribute to broader community efforts to develop "greener" controlled polymerizations, our team envisioned an organic alternative to metal-mediated ROMP. There is precedence for metal-catalyzed polymerizations being adapted for organocatalyzed conditions. For example, the Hawker and Miyake groups independently initiated the development of organocatalyzed atom transfer radical polymerization (o-ATRP).[17,18] There, photoredox catalysis took center stage in the mechanistic schemes. Similarly, the Boyer group led efforts to evolve reversible addition−fragmentation chain transfer (RAFT) polymerization into photo-induced electron-transfer (PET-RAFT) techniques, including organocatalyzed variants.[19] In this Account, we provide an overview of the evolution of metal-free (MF) ROMP, beginning with its inception, inspired by pioneering electrochemical and photochemical work. We then summarize recent efforts on the expansion of this method, including an investigation of monomer scope, photocatalyst effects, functional group tolerance, modulation of molecular weight, and preparation of block copolymers.

AN ELECTROCHEMICAL APPROACH TO MF-ROMP

When approaching the task of developing a metal-free ROMP method, there is not an immediately obvious substitute for a metal alkylidene. However, inspired by the Chiba group's electrochemical intermolecular cross coupling and cross metathesis of enol ethers and terminal olefins,[20,21] we envisioned a new mechanistic approach to ROMP. Chiba and co-workers proposed that the oxidation of enol ethers in the presence of excess olefin leads to the formation of a cyclobutane radical cation, geometrically reminiscent of the metallacyclobutane intermediate in metal-mediated ROMP. Depending on the coupling partners,[21] the radical cation complex can undergo reduction to a cyclobutane or fragmentation to give an olefin and an enol ether radical cation that have been metathesized (Scheme 2).

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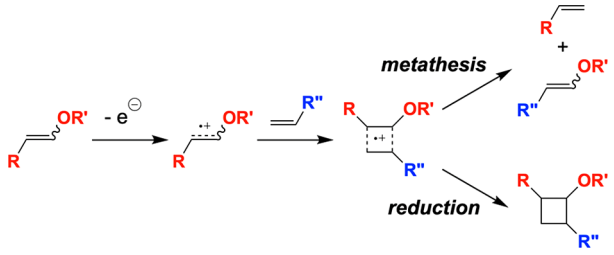
Scheme 2. Electrochemical Olefin Metathesis and Cyclobutane Formation



As shown in Scheme 3, we postulated that, for our purposes, an enol ether radical cation (**b**) could engage a strained cyclic olefin and that the reduction of the resulting radical cation complex (**c**) would be outcompeted by the rapid ring-opening of the strained monomer to form a propagating species (**d**).

To investigate the possibility of initiating ROMP with an enol ether radical cation, we conducted bulk electrolysis on solutions of norbornene (**1a**), a common ROMP monomer with relatively high ring strain, and readily available enol ether initiators (Scheme 4).[1] Initial results were discouraging, as there was no detection of polymer in solution after 3 h of bulk electrolysis. A closer examination of the carbon fiber (CF) anode, however, revealed that the surface was coated with a white precipitate that was insoluble in methanol.

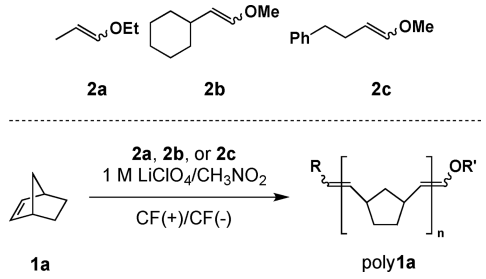
Using ^{1}H NMR spectroscopy, this residue was found to be consistent with polynorbornene (poly**1a**) prepared via metal-mediated ROMP. The polymer end group was also identified in this way and found to be consistent with an enol ether. A further analysis of the sample via gel-permeation chromatography (GPC) demonstrated that the residue was indeed macromolecular (M_n = 11.8 kDa, $Đ$ = 2.2). Although the most optimistic take on the reaction yield (approximately 3%) for attempts with each initiator (**2a**–**c**) was that it was nonzero, these initial results confirmed that the anodic oxidation of enol ethers could initiate a polymerization of **1a**. Additionally, the assessment of the poly**1a** structure was consistent with a ROMP-type mechanism.

The low yields were attributed to the poor solubility of both **1a** and poly**1a** in the requisite electrolyte system: 1 M lithium perchlorate ($LiClO_4$) in nitromethane (CH_3NO_2). During electrolysis, the insolubility of poly**1a** led to its deposition on the surface of the anode, resulting in a rapid decrease in the current and preventing further oxidation of the enol ether. Screens of different electrode materials and electrolyte/solvent combinations demonstrated that the CF/$LiClO_4$/CH_3NO_2 system was crucial to the success of the polymerization. Attempts to increase the monomer conversion within those parameters, such as with the use of an ultrasonic bath, only afforded small improvements (yields up to 14%).

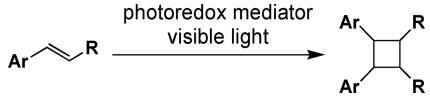
A PHOTOCHEMICAL APPROACH TO MF-ROMP

To circumvent the solubility issues encountered in the electrochemical setup, we proposed an alternate method of generating the radical cation. In general, photoredox processes are compatible with a broader range of solvents than their electrochemical counterparts and have the advantage of often being homogeneous. The Nicewicz[22] and Yoon[23,24] groups have each demonstrated the synthesis of cyclobutanes (Scheme 5)

Scheme 4. Electro-Mediated MF-ROMP and Select Enol Ether Initiators



Scheme 5. Photoredox-Mediated Cyclobutane Formation

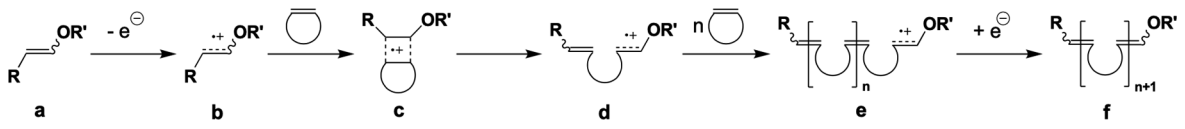


using photoredox mediators like 2,4,6-tri(4-methoxyphenyl)-pyrylium and ruthenium tris(bipyrimidine). Our perspective was that the envisioned intermediates were reminiscent of those we had proposed for MF-ROMP.

In keeping with the desire to be metal-free, 2,4,6-tri(4-methoxyphenyl)pyrylium (**3a**) was selected for screening. The calculated excited state reduction potential of **3a** is 1.89 V versus a saturated calomel electrode (SCE) and therefore high enough to oxidize enol ethers **2a**–**c**, which have oxidation potentials ranging from 1.30 to 1.43 V versus SCE. A blue LED bulb (2 W, λ_{em} = 450–480 nm) was used to excite **3a** in a polymerization of **1a**. All three initiators gave poly**1a** with good monomer conversion (87–92%), with **2a** being selected for further screens due to its commercial availability. Control experiments confirmed that the initiator, photoredox mediator, and light source were all required for successful polymerization. Over the course of the polymerization, M_n gradually increased with monomer conversion, showing characteristics desirable in living polymerizations (Figure 2a, b); however, the linearity was not as precise as in traditional "living" ROMP.

The use of a photocatalyst also enabled a high degree of temporal control over the polymerization due to the reversibility of the enol ether activation as well as deactivation of the chain ends. This ability was illustrated with "light on/light off" experiments (Figure 2c, d) that show no significant change in monomer conversion in the dark but additional chain growth during irradiation. This level of temporal control has not been accomplished with traditional ROMP initiators. Also of mechanistic interest is the appearance of bimodal GPC traces at a higher loading of photo-oxidant, which we attribute to

Scheme 3. Hypothesized Mechanism of Redox-Mediated MF-ROMP



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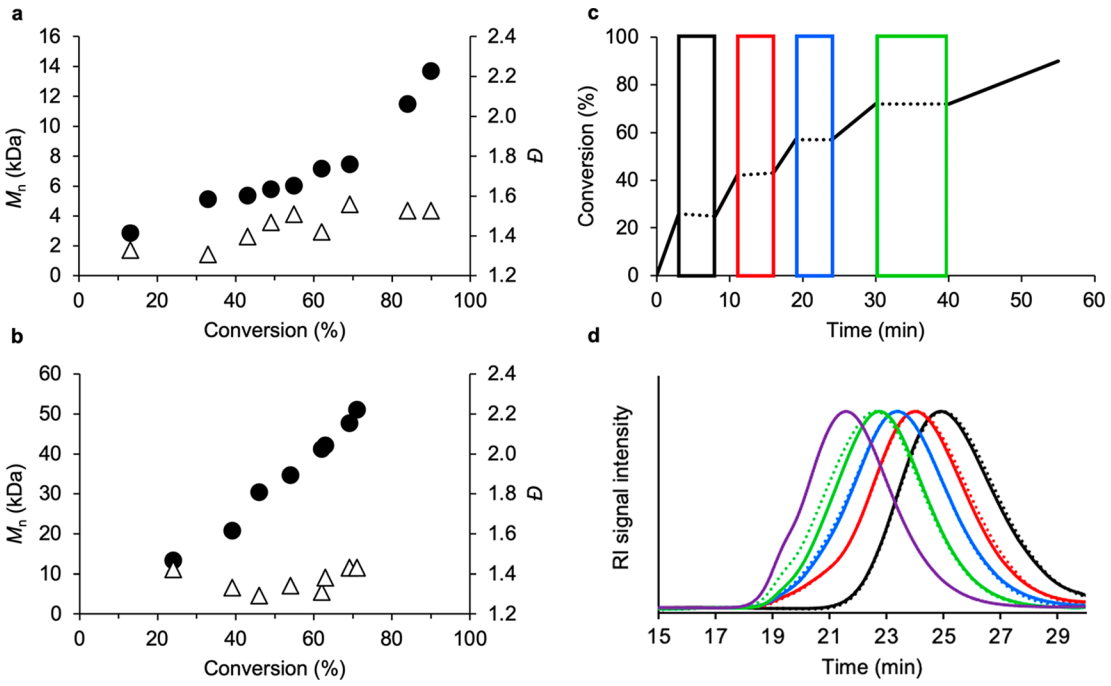

Figure 2. Plot of M_n (black dot) and Đ (white triangle) vs % monomer conversion using an initial ratio of **1a**:**2a** of 100:1 (a) and 500:1 (b). (c) Plot of % monomer conversion vs time; periods of dark are highlighted with boxes. (d) GPC traces for dark/light cycles; dotted traces are for the dark period indicated by the box in the top plot, and solid traces are for the light period immediately preceding. The purple trace is for the final polymer product. Adapted with permission from ref 1. Copyright 2015 American Chemical Society.

increased instance of chain−chain coupling due to an increased concentration of active chain ends.

Significantly, while initial screens were conducted under an inert atmosphere, monomer conversion was found to be slightly higher in ambient conditions (80 ± 1% in nitrogenous atmosphere versus 87 ± 2% in air).[3] An atmosphere higher in oxygen content, however, resulted in a slightly worse conversion (70 ± 4%). The origins of this behavior are currently unknown but are under investigation. Importantly however, these results mean MF-ROMP can be conducted without the additional considerations necessary for polymerizations that require an inert atmosphere, expanding its ease of use.

SCREENING PHOTOREDOX CATALYSTS

Early experimental results showed the propagating radical chain end in MF-ROMP likely forms a dynamic redox couple with the reduced pyrylium salt. To discern if there were any trends between photo-oxidant performance in MF-ROMP and excited state reduction potential (E^*_{red}), a screen of pyrylium (**3a**−**d**) and thiopyrylium (**4a**−**d**) salts was conducted.[25] These experiments revealed that increasing E^*_{red} resulted in a lower monomer conversion (Table 1).

It is possible that photo-oxidants with higher oxidizing potentials may lead to overoxidation of enol ether initiators and even **1a** and poly**1a** main chain olefins. Between pyrylium and thiopyrylium salts with identical substituents (e.g., **3a** and **4a**), the thiopyrylium salt gave a higher monomer conversion than the corresponding pyrylium salt. These results suggest that the careful selection of photo-oxidants should be critical to establishing precise control over the polymerization.

Monitoring monomer conversion over the course of the polymerization facilitated direct comparison of the best-performing photo-oxidants (**3a** and **4a**). Although both consistently led to high conversion over a standard polymerization time frame, **4a** reached high conversions faster than **3a** (Figure 3). As it requires one fewer synthetic step to prepare, **3a** has emerged as our workhorse catalyst.

Table 1. Results of MF-ROMP Using Pyrylium and Thiopyrylium Photo-Oxidants

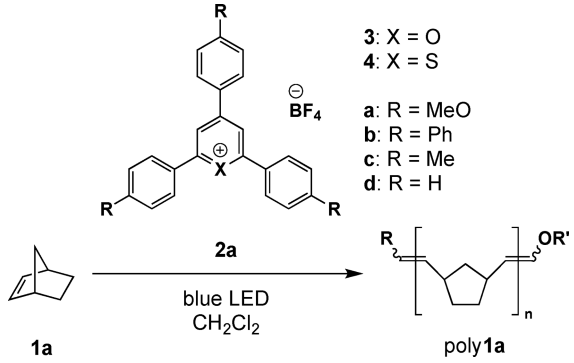

photo-oxidant	E^*_{red} (V vs SCE)	conversion[a] (%)	M_w[b] (kDa)	Đ[c]
3a	1.89	75 ± 4	20.0	1.5
4a	1.86	84 ± 1	36.3	1.6
3b	2.02	31 ± 1	7.4	1.4
4b	2.02	52 ± 3	13.3	1.4
3c	2.23	12 ± 1	5.5	1.2
4c	2.20	26 ± 1	7.3	1.5
3d	2.46	9 ± 1	n.d.	n.d.
4d	2.41	<5	n.d.	n.d.

[a]Conversion of **1a** as determined by ^{1}H NMR spectroscopy. [b]Weight average molecular weight determined by multiangle laser light scattering (MALLS). [c]Dispersities determined by GPC. Reproduced with permission from ref 25. Copyright 2016 Georg Thieme Verlag KG.

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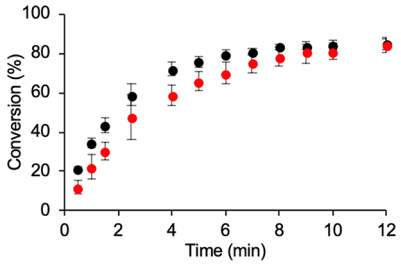


Figure 3. Plot of % monomer conversion vs time in MF-ROMP of **1a** with photo-oxidants **3a** (red) and **4a** (black) Reproduced with permission from ref 25. Copyright 2016 Georg Thieme Verlag KG.

MOLECULAR WEIGHT CONTROL VIA CROSS-METATHESIS

In general, demonstrating good control over molecular weight is a key element in developing new polymerization methods, both from a fundamental perspective and in order to study the correlation between structure and property in final polymer products. In particular, low molecular weight polymers, including precise oligomers, have a number of applications in the industrial sector, e.g., viscosity modulation in resin formulations or as nonvolatile substitutes for small molecules. In metal-based ROMP, high loadings of initiator were traditionally required to achieve lower molecular weights. In MF-ROMP, with high loadings of the monomer relative to the initiator, M_n values of up to 60 kDa were observed. However, the lower limit for M_n was around 8 kDa because at high loadings of enol ether initiator, it was prone to cationic homopolymerization.

With the motivations of potential broadened utility for MF-ROMP products and the synthetic challenge of achieving efficient production of oligomeric materials, we set our sights on expanding MF-ROMP into the low molecular weight regime.[4] Cross metathesis is commonly used in metal-mediated ROMP, both as a method of controlling molecular weight, and as a means of end-group functionalization. This prompted us to propose a mechanism whereby an olefin could engage a radical cation chain end, which would result in a dead chain and a new radical cation species (Scheme 6).

With this in mind, a small set of alkenes was screened as potential chain transfer agents (CTAs), and while internal olefins did not show evidence of cross-metathesis in the MF-ROMP of **1a**, the terminal alkenes 1-hexene and 4-phenyl-1-butene did show evidence of this. Indeed, by varying the equivalents of the terminal alkene from 5 to 400 relative to the initiator, polymers with molecular weights ranging from 27 down to 4 kDa were able to be synthesized.

Olefinic chain ends were identified using matrix-assisted laser-desorption ionization time-of-flight mass spectrometry (MALDI-TOF MS), but the regioselectivity of the chain transfer event was still undetermined. To this end, we attempted to initiate MF-ROMP with ethyl vinyl ether (EVE, Scheme 7, bottom) and found that it did not perform as well as **2a** (EVE, 12% monomer conversion and 2.8% initiator efficiency; **2a**, > 80% monomer conversion and 66% initiator efficiency). This suggested that the chain transfer event was regioselective for the path that would generate a more highly substituted, and therefore more electronically stable, radical cation (Scheme 7, top). This path would also go through an intermediate in which the polymer chain and the alkyl chain of the CTA were in a trans orientation, making it more sterically favored as well. Also of note in Scheme 7 is the generation of such species as **P2** and **P4**, which, while macromolecular, have terminal olefin chain ends and could be supposed to act as macro CTAs. Indeed, when low loadings of CTA are used (<25:1 CTA:**2a**), the bimodality of the GPC traces increased with monomer conversion, suggesting chain−chain coupling was occurring.

Under chain transfer conditions, the monomer conversion in MF-ROMP tended to be lower when run for the same amount of time as MF-ROMP without a CTA. To investigate this, the conversion of **1a** over time was tracked via ^{1}H NMR spectroscopy, and indeed, it was slower compared to the standard polymerization. The radical cation species in solution should be sensitive to the solution dielectric constant (ε), and adding up to 400 equiv CTA relative to the initiator would greatly affect ε. This hypothesis was tested by running a polymerization with *n*-hexane ($\varepsilon = 1.89$) in lieu of 1-hexene ($\varepsilon = 2.05$), and indeed, the reaction rate was similarly decreased (Figure 4), indicating that ε affects propagation.

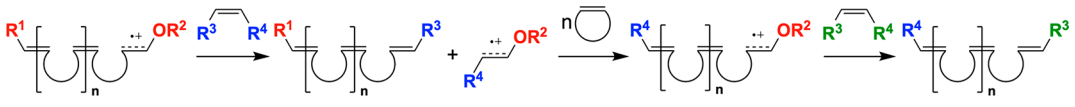
EXPANDING MONOMER SCOPE

As stated previously, the development of well-defined metal catalysts has transformed traditional ROMP into an extraordinary polymerization technique with remarkable functional group tolerance and monomer scope.[5] Since our initial investigation into MF-ROMP was limited to **1a**, we sought to explore the polymerization of monomers with more complex structure and functionality. Dicyclopentadiene (DCPD), a monomer commonly used in metal-based ROMP, was investigated first.[2] When polymerized with metal alkylidene initiators, *endo*-DCPD (**5a**) affords cross-linked thermoset materials with excellent properties such as high chemical- and impact-resistance that make it valuable for use in industrial equipment such as vehicle body panels and wind turbine blades.

Under MF-ROMP conditions, poly**5a** was synthesized with about a 15% monomer conversion (M_n = 3.8 kDa, $Đ$ = 1.1). Notably, poly**5a** was linear, not cross-linked; due to the high activity of metal-based initiators, the cross-linking of polyDCPD in traditional ROMP is essentially unavoidable, so MF-ROMP has thus provided access to a previously inaccessible material with a much broader range of processing options than its cross-linked counterpart. Poly**5a** could, however, be cross-linked, also without the use of metals, by subjecting linear poly**5a** to thiol−ene reaction conditions.

Optimization of the polymerization of **5a** to achieve higher monomer conversion was attempted. However, varying both the monomer concentration and photocatalyst loading did not result in a significant improvement; decreasing the polymerization temperature and initial ratio of monomer to initiator gave a slight improvement in the conversion (up to about 20% in both

Scheme 6. Cross Metathesis in MF-ROMP



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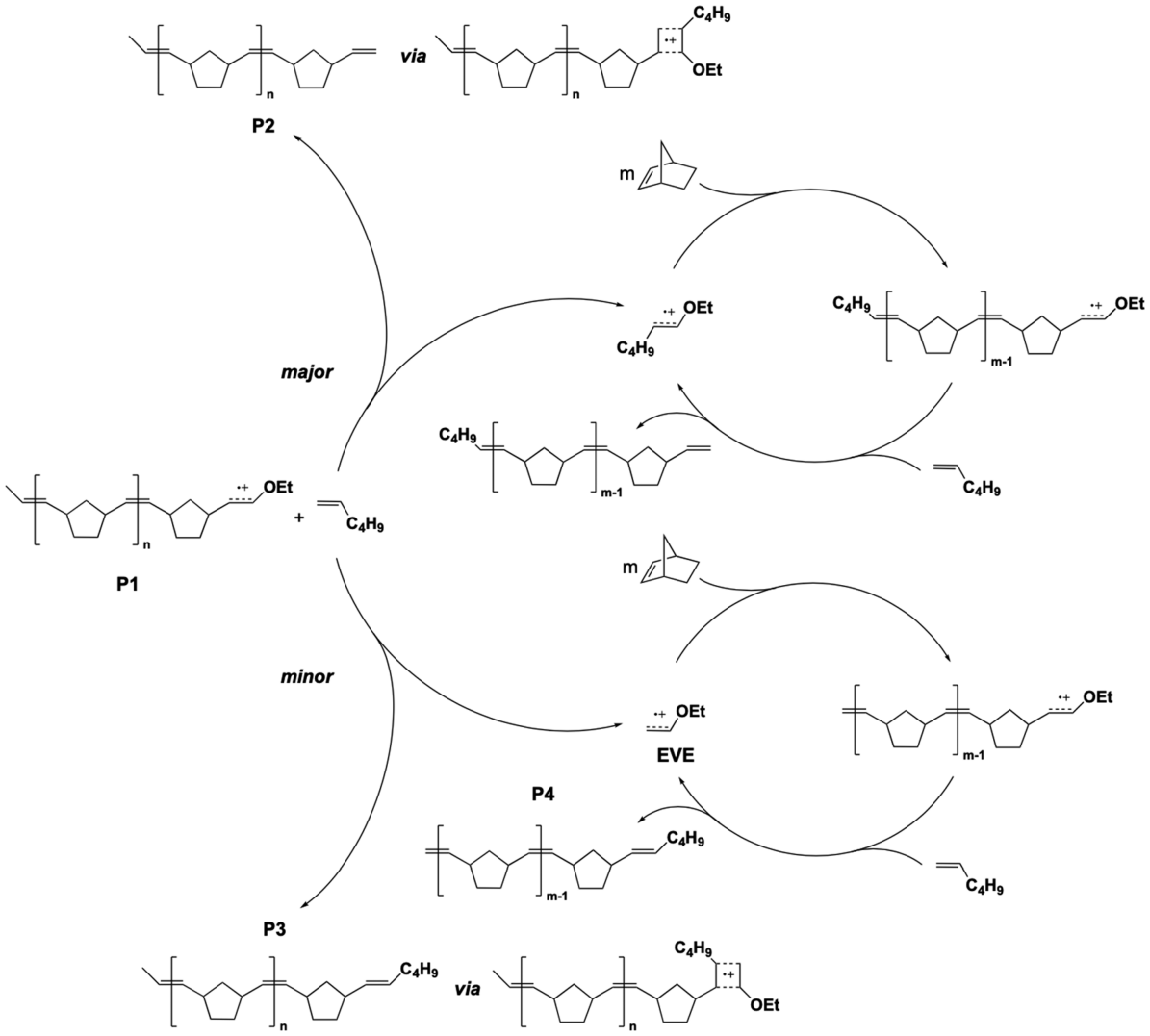
Scheme 7. Possible Pathways of Cross Metathesis



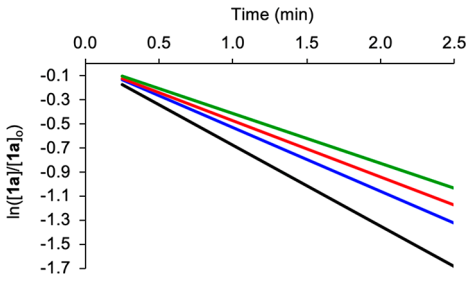


Figure 4. Plot of $\ln([\mathbf{1a}]/[\mathbf{1a}]_0)$ versus time for MF-ROMP of **1a** (CH_2Cl_2, 25 °C, $[\mathbf{1a}]_0 = 0.5$ M); no additive (black), 50 equiv. *n*-hexane (blue), 50 equiv. 1-hexene (red), 50 equiv. 4-phenyl-1-butene (green). Adapted with permission from ref 4. Copyright 2020 John Wiley and Sons.

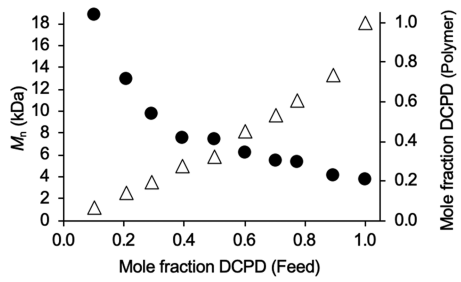


Figure 5. Plot of M_n (black dot) and **5a** incorporation in final polymer (white triangle) vs **5a** loading for a copolymerization of **5a** and **1a**. Adapted with permission from ref 2. Copyright 2015 American Chemical Society.

cases). The ^{1}H NMR spectrum revealed the presence of multiple enol ether species, possibly signifying the presence of deleterious side reactions of the enol ether radical cations, thus limiting monomer conversion.

While the homopolymerization of **5a** had been met with limited success, copolymerization with varying feed ratios of **1a** and **5a** resulted in a corresponding variation in the final polymer composition (Figure 5). As expected, a higher initial loading of **5a** corresponded to a lower overall monomer conversion and thus a lower final M_n. Since moderate conversion (50−60%) of **5a** was achieved at low loading, it was concluded that the lower reactivity of **5a** compared to **1a** was not responsible for the poor homopolymerization results. Two additional hypotheses were thus proposed, the first being that the steric bulk of the additional ring in **5a** might attenuate the rate of new monomer incorporation. The second was that the proximity of the pendant cyclopentene ring to the propagating radical cation chain end

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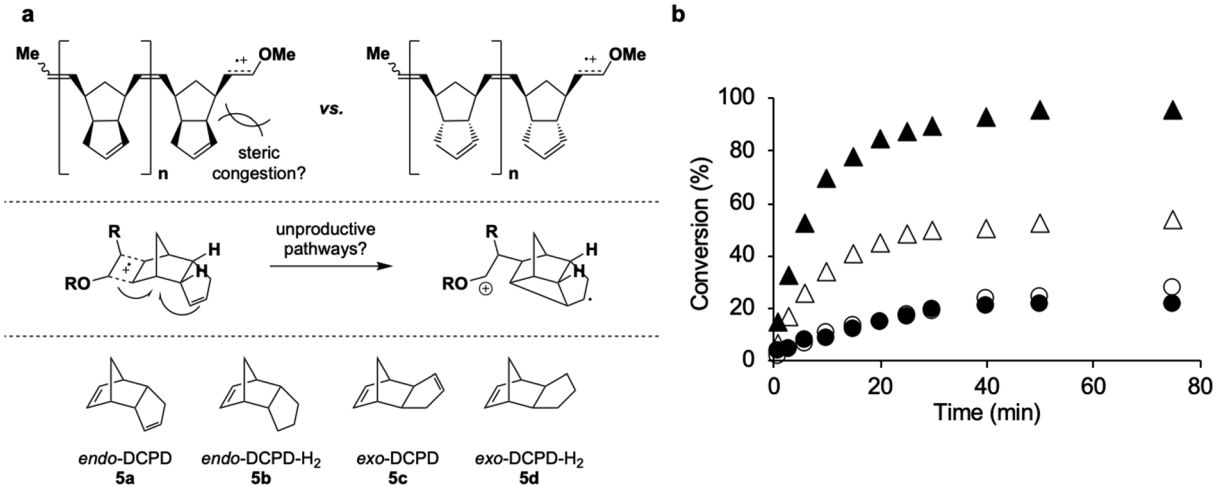


Figure 6. (a) Potential reasons for decreased conversion of **5a** and scope of monomers examined. (b) Plot of monomer conversion vs time for MF-ROMP of **5a** (white dot), **5b** (white triangle), **5c** (black dot), and **5d** (black triangle). Adapted with permission from ref 2. Copyright 2015 American Chemical Society.

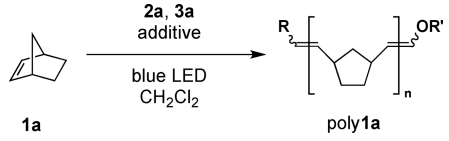
may result in undesired side reactions since intramolecular reactions of olefins and radical cations are well-documented. To probe these possibilities, monomers **5b–d** were prepared in order to compare their behavior under MF-ROMP conditions. Monomers **5b** and **5d** avoid the possibility of undesired side reactivity, while monomer **5c** would be expected to perform well if the issue was related strictly to sterics (Figure 6a).

Monomers **5a–d** underwent MF-ROMP with varying degrees of success (Figure 6b). Similar to what was observed for **5a**, monomer **5c** performed poorly with about 20% conversion. However, for monomers **5b** and **5d** with saturated pendant rings, the conversion was much higher (55 and 90%, respectively). These results suggest that the poor performance of **5a** and **5c** likely arise from the pendant cyclopentene, since the steric impedance in **5b** did not diminish its reactivity. Cyclopentene, which is unreactive toward MF-ROMP homopolymerization, did not affect polymerizations of **1a** or **2a** when used as an additive. Taken together, these control experiments confirmed that it is some intramolecular interaction between the propagating radical cation chain end and the pendant cyclopentene that is hindering conversion.

To further expand the monomer scope of MF-ROMP, we became interested in exploring the functional group tolerance of the reaction in order to identify functionalized monomers compatible with this methodology, specifically the incorporation of alcohol functional groups, in which we had a vested interest.[3] The effect of small molecule additives on the polymerization of **1a** was investigated first. The loading of these additives was varied from 1 to 100 equiv. versus the enol ether initiator. The difference in the monomer conversion for the series of alcohol additives was ascribed to their relative nucleophilicity since the radical cation intermediates are highly reactive. This is consistent with the fact the sterically hindered *tert*-butanol performed relatively well compared to the less hindered alcohols (Table 2). Less nucleophilic additives like electron-deficient hexafluoroisopropanol (HFIP) and sterically hindered methyl *tert*-butyl ether (MTBE) had little impact on the MF-ROMP of **1a**, even up to 100 equiv.

After observing the tolerance toward some alcohols and ethers, monomers with similar functionalities were screened. Norbornenes **6** and **7**, which have unprotected alcohol functionalities, unsurprisingly did not undergo homopolymerization. Among a series of norbornenes with protected alcohol groups (**8a–d**), only that with a *tert*-butyldimethylsilyl (TBS) group, **8d**, was successfully homopolymerized (50% conversion). However, each monomer underwent successful copolymerization with **1a**, with **8d** still showing the best MF-ROMP compatibility. To investigate additional functional group compatibility, monomers **8e–g** were investigated. Neither **8e** nor **8f** showed any ability to be homopolymerized but were successfully incorporated into a copolymer with **1a**, albeit at a low incorporation and overall conversion (Table 3). Surprisingly, **8g** was successfully homopolymerized but did not inhibit or react in a copolymerization with **1a**, likely due to the much more rapid polymerization of **1a** compared to **8g**. In addition to demonstrating several new monomers that perform well for MF-ROMP, these investigations also provide insight into considerations for future monomer design.

Table 2. Effect of Additives on MF-ROMP of 1a



additive	equivalents[a]	conversion[b] (%)
none		80
H_2O	1	53
MeOH	1	40
i-PrOH	1	68
t-BuOH	1	80
t-BuOH	100	0
HFIP	100	72
MTBE	100	78

[a]Relative to vinyl ether initiator. [b]Conversion of **1a**, as determined by ^{1}H NMR analysis. Adapted with permission from ref 3. Copyright 2016 American Chemical Society.

SYNTHESIZING BLOCK COPOLYMERS VIA MF-ROMP

The synthesis of ROMP copolymers is an area of both academic and industrial interest due to the nature of the products' structural difference from polymers produced through other

https://dx.doi.org/10.1021/acs.accounts.0c00427
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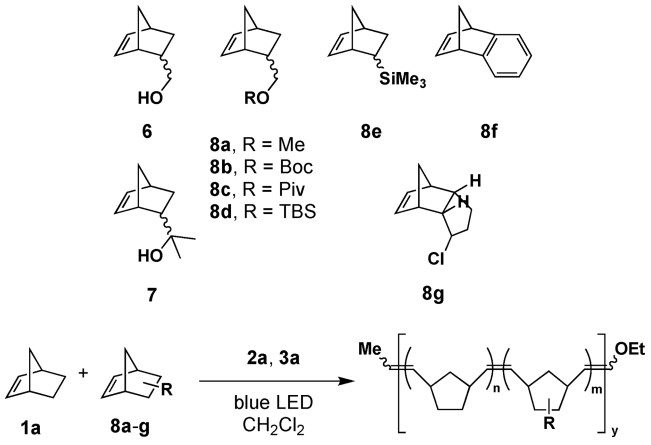
Table 3. Results of Copolymerizations Between 1a and Functional Monomers



comonomer	conversion[a] (%)	1a:8[b] (polymer)	M_w[c] (kDa)	$Đ$
8a	77 (34)	82:18	20.3	1.4
8b	70 (30)	88:12	95.0	3.7
8c	74 (55)	89:11	37.2	2.2
8d	78 (71)	80:20	27.0	1.5
8e	47 (9)	90:10	5.3	1.3
8f	34 (19)	74:26	7.9	1.2
8g	87 wrt 1a	100:0	24.0	1.5

[a]Determined by ^{1}H NMR analysis of a reaction aliquot. The yield is in parentheses after isolation of the polymer. wrt = with respect to. [b]Determined by ^{1}H NMR spectroscopy of the isolated polymer; reaction feed ratios were 75:25 **1a**:**8**. [c]Weight-average molecular weight determined by GPC using MALLS. Dispersities ($Đ$) determined by GPC. Adapted with permission from ref 3. Copyright 2016 American Chemical Society.

means. For example, polymers produced via alkene addition as compared to ring-opening polymerization have structural differences that can lead to different mechanical and physicochemical properties.

Thus, we were interested in determining the feasibility of preparing block copolymer structures via MF-ROMP. In a tandem copolymerization, chain end stability is critical for the living characteristics that enable successful chain extension from one block to another. For MF-ROMP, the stability of the reactive radical cation chain end during sequential monomer addition was a central concern, so we sought to determine the parameters that would facilitate successful block copolymerization.

A cursory study of varying reaction times and the order of addition in a copolymerization of **1a** and **5d** was conducted (Figure 7).[26] These experiments revealed that the chain extension of poly**1a** was more successful with shorter reaction times, consistent with irreversible termination of chain ends. In contrast, **5d** demonstrated more complete chain extension, potentially due to greater steric shielding around the active chain end. More detailed investigations in this area are warranted and are currently underway.

As block copolymerization using only MF-ROMP conditions was relatively limited, integrating this method with other types of polymerizations became key to expanding the structural variety of MF-ROMP block copolymers. The expedient synthesis of macroinitiators was facilitated by the general ease of installing enol ether moieties. Thus, difunctional macroinitiators **9** and **10** were readily prepared from commercially available polyethylene glycol and polypropylene glycol.[27] Successful initiation under MF-ROMP conditions resulted in triblock copolymers **12** and **13**. Polymerization off the side chain of **11** was also demonstrated, prepared through controlled radical polymerization, resulting in **14** with moderate to high monomer conversion (Figure 8).

Mechanism-switch dual polymerization was also attempted, which could be used to access additional diverse structures.[28] Bifunctional initiator **15**, which possesses both an enol ether and an alcohol end group, was prepared to first produce polylactide (**16**), polycaprolactone (**17**), and polytrimethylene carbonate (**18**) with controlled M_n and narrow $Đ$ values via organocatalyzed ring-opening polymerization (*o*-ROP). An analysis of these polymers via ^{1}H NMR spectroscopy confirmed the retention of the enol ether chain ends. These macroinitiators were then put under MF-ROMP conditions and both polynorbornene and polydicyclopentadiene blocks were successfully synthesized (Figure 9). The applicability of this method was then expanded by developing conditions for a one-pot sequential polymerization; in that case, it is necessary for the *o*-ROP block to be made first and for excess **3a** to be used in the MF-ROMP step in order to quench the *o*-ROP catalyst, triazabicyclodecene.

CONCLUSIONS AND OUTLOOK

This Account has highlighted the evolution of MF-ROMP, ranging from its initial motivation and conception to the expansion of monomer scope and early mechanistic investigations. After optimization, we were able to carry out MF-ROMP using both electro- and photoredox-mediated pathways; however, the photoredox method resulted in dramatically higher monomer conversion. With a pyrylium salt as the photocatalyst, we were able to gain excellent temporal control over MF-ROMP. Compared to traditional metal-mediated ROMP, MF-ROMP currently has limited functional group tolerance, which likely originates from the high reactivity of radical cation chain ends. However, the ability to conduct the polymerization under ambient conditions is a significant advantage. Successful MF-ROMP from macroinitiators to make block copolymers has further expanded the structural variety of polymers we are able to access.

While we have made important advances in the development and general parametrization of this method, there are several areas that we are currently exploring. First, the mechanistic details of MF-ROMP are not completely understood. Expanded structure−function studies for both the initiator and photocatalyst are necessary, as well as an acquisition of information about their interplay. Thus, exciting opportunities may arise to expand the functional groups tolerated by MF-ROMP, broaden the solvent compatibilities, and establish stereocontrol during polymerization. Though molecular weight control has been established via chain transfer, finer control over other aspects of polymer structure, such as tacticity and molecular weight dispersity, remains elusive; the effects that the photophysical and electrochemical properties of the catalyst have on these mechanistic artifacts are being explored. Investigations into the behavior of small molecules in this system also have exciting potential.

The development of far-red or near-IR absorbing systems, similar to those in use for photocontrolled RAFT polymerizations, could make MF-ROMP suitable for biological applications. MF-ROMP products in general are already positioned for ease of application in industrial settings, as the

https://dx.doi.org/10.1021/acs.accounts.0c00427
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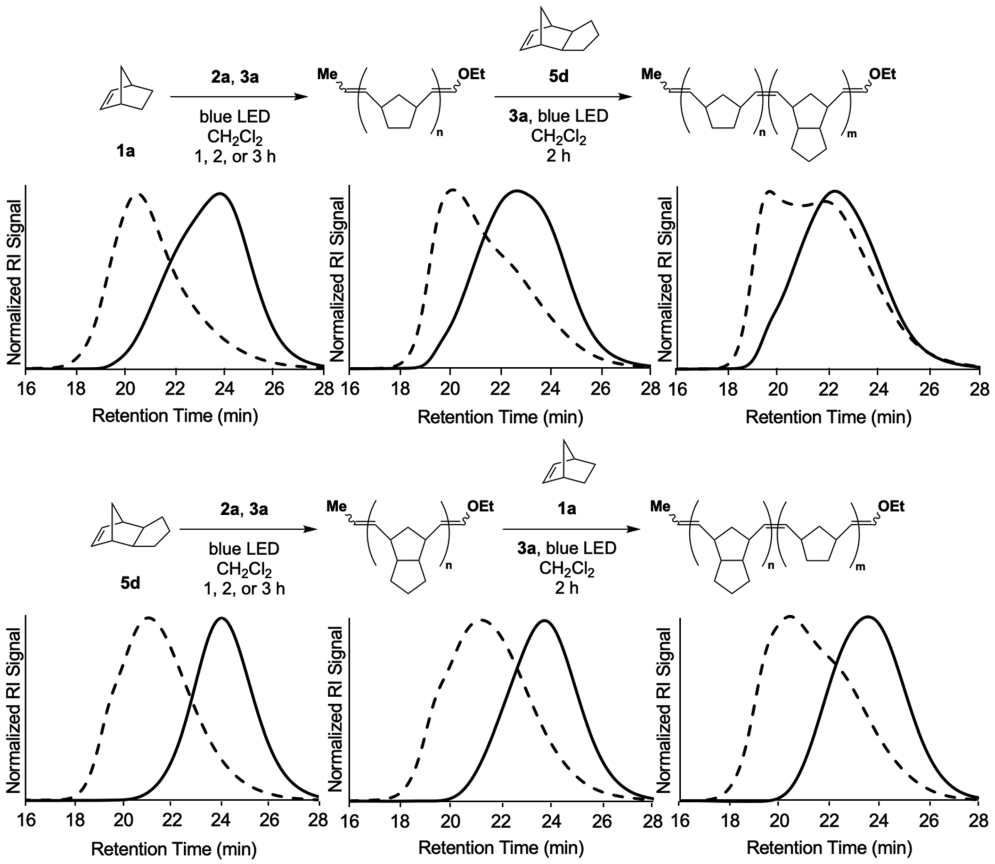

Figure 7. GPC traces for block copolymers (solid line = trace after first block formation; dashed line = trace after diblock formation). From left to right: first block reaction times = 1, 2, and 3 h; reaction time of second block = 2 h. Adapted with permission from ref 26. Copyright 2017 John Wiley and Sons.

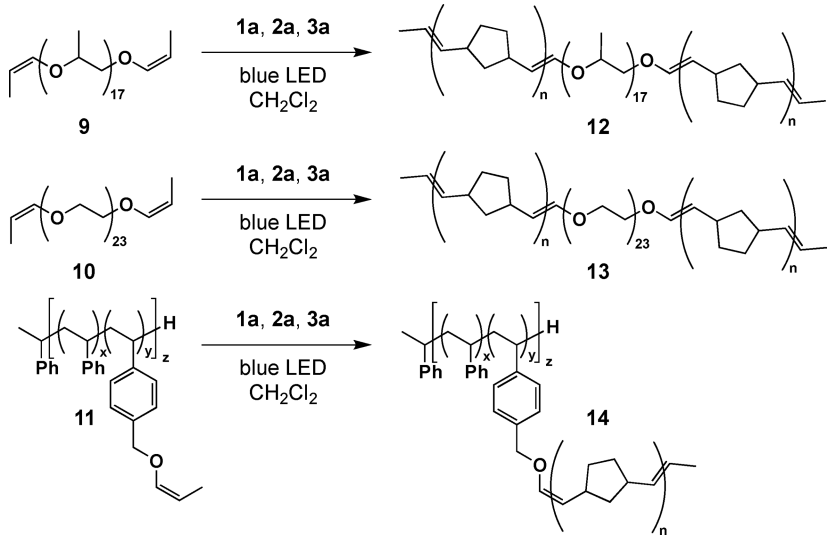

Figure 8. Block copolymers made from MF-ROMP off macromolecular initiators. Adapted with permission from ref 27. Copyright 2017 John Wiley and Sons.

polymerization's ability to be temporally controlled lends itself well to the adoption of a flow reactor setup for accelerated polymer preparation on a large scale. Finally, apart from its metal-free merits, the synthetic utility of MF-ROMP should not be overlooked. The distinct mechanism of this polymerization may also allow it to be compatible with monomers that are difficult to polymerize through metal-mediated ROMP. Compared to metal alkylidene species, the relative ease of installing enol ether groups will facilitate the synthesis of multifunctional initiators, which provide expedient access toward polymers with unique architectures. Additionally, the use of chain transfer in MF-ROMP to functionalize polymer chain ends is currently under investigation. We believe that these future developments will eventually transform MF-ROMP into a

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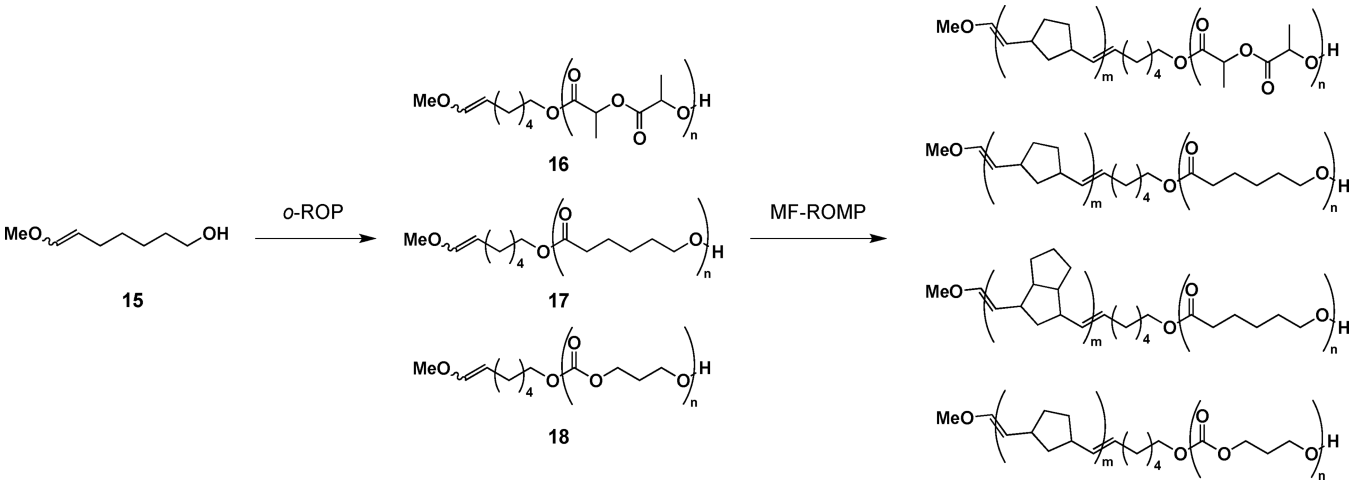

Figure 9. Block copolymers made from sequential *o*-ROP and MF-ROMP.

significant complement to traditional metal-mediated ROMP, even as a competitive alternative in many cases.

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Notes

The authors declare the following competing financial interest(s): A.J.B. has an ownership interest in Boydston Chemical Innovations, Incorporated, which has licensed the technology reported in this publication.

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Daniel T. Seidenkranz received his B.A. in chemistry from the University of Minnesota, Morris in 2013. He earned his Ph.D. in 2018 in Prof. Michael Pluth's group at the University of Oregon, developing new supramolecular Hamilton receptors for material and sensing applications. He then joined Prof. A. J. Boydston's group as a postdoctoral researcher to develop new photoredox catalysts for metal-free ring-opening metathesis polymerization. He is currently a Senior Chemist at Cascade Chemistry in Eugene, Oregon.

A. J. Boydston began studying chemistry as an undergraduate at the University of Oregon under the guidance of Prof. Michael M. Haley. After completing B.S. and M.S. degrees, he began his doctoral research at the University of Texas at Austin. In 2005, Dr. Boydston joined the group of Prof. Christopher W. Bielawski and was coadvised by Prof. C. Grant Wilson. After graduating in 2007, he moved to Pasadena, CA to take a National Institutes of Health postdoctoral position at the California Institute of Technology. There, he worked under the mentorship of Prof. Robert H. Grubbs. He returned to the Pacific Northwest as an assistant professor of chemistry at the University of Washington in the summer of 2010. In the summer of 2018, he moved to the University of Wisconsin−Madison where he is a full professor in the Department of Chemistry with additional appointments in the Department of Chemical and Biological Engineering and the Department of Materials Science and Engineering. His research group currently focuses on developments in the areas of polymer synthesis, additive manufacturing, mechanochemical transduction, electro-organic synthesis, and triggered depolymerization.

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