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**Living cationic ring-opening polymerization of 2-oxazolines  
initiated by rare-earth metal triflates**

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**ABSTRACT**

The cationic ring-opening polymerization (CROP) of substituted 2-oxazolines using rare-earth metal triflates (RE(OTf)<sub>3</sub>) as initiator was investigated for the first time. In this effort, we examined the polymerization characteristics of 2-ethyl-2-oxazoline (EtOx) initiated by Sc(OTf)<sub>3</sub> under the conventionally thermal heating and microwave irradiation, and compared the respective outcomes with those obtained with the most frequently used initiator methyl tosylate (MeOTs). The results indicated that Sc(OTf)<sub>3</sub> exhibits a higher catalytic efficiency to the EtOx polymerization than MeOTs under identical conditions. The controlled/living nature for the Sc(OTf)<sub>3</sub>-catalyzed CROP was confirmed by the linear first-order kinetics and narrow molecular weight distribution of the resultant polymers as well as the block copolymerization of EtOx and 2-phenyl-2-oxazoline (PhOx). Based on *in situ* NMR spectroscopic studies and SEC analysis of PEtOx samples obtained from the control termination experiments, a possible initiating/propagating mechanism has been proposed for the living cationic ring-opening polymerization. Moreover, this rare-earth catalytic system also can be

applied to the ring-opening polymerization of some sterically hindered or aryl-substituted 2-oxazolines.

### **Introduction**

Poly(2-oxazoline)s are a class of synthetic polyamides that are receiving considerable attention in the past decade because of their synthetic versatility and potential applications in many fields, especially, in the biomaterials.<sup>1-4</sup> The polymerization of 2-oxazolines usually exhibits controlled and “living” character, i.e. it proceeds in the absence of chain transfer and termination reactions. This feature provides easy access to well-defined polymers with low polydispersity index (PDI) values and adjustable molar masses. Furthermore, a vast variety of substituted 2-oxazoline monomers, as well as functional initiators and terminating agents is available and allows the tuning of the polymer properties.

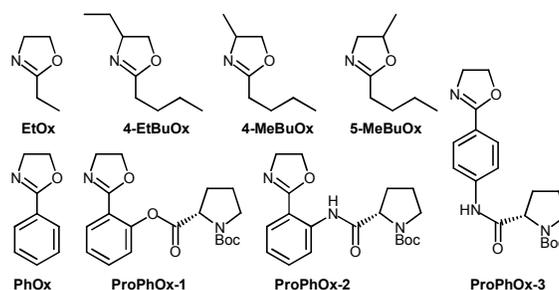
To date, various initiators including Lewis acids, such as boron trifluoride, and alkyl esters such as tosylates, triflates and halides have been reported for the cationic ring-opening polymerization of 2-oxazolines.<sup>5-7</sup> Among them, tosylates and triflates could be particularly effective in combination with microwave irradiation, which enables the polymerization in minutes to a few hours.<sup>8-9</sup> Although such a microwave-assisted polymerization was achieved in a laboratory equipment, the usefulness of this synthesis procedure and its manipulation still remain problematic for a scale up due to the intrinsic limitations of microwave techniques. As for tosylate and triflate, the yet most extensively used initiators, their high toxicity is a relevant key issue that must be taken in consideration in practical applications.<sup>10-13</sup> Therefore,

it is desirable to explore new catalytic systems to alleviate aforementioned problems and permit the CROP of 2-oxazolines to be performed on a normal apparatus. Also, we feel that more fundamental studies on the design and synthesis of polyoxazoline-based materials with new functional properties could be beneficial to the field.<sup>14-17</sup>

On the other hand, rare-earth metal triflates ( $\text{RE}(\text{OTf})_3$ ) as a hard Lewis acid have been applied in the polymer synthesis. For example, Okamoto and his co-workers<sup>18-21</sup> established a general method applicable to some polar monomers such as (meth)acrylamides and methacrylates wherein the added  $\text{RE}(\text{OTf})_3$  catalytically affect the polymerization stereochemistry to isotactic-selective manner, producing corresponding highly stereoregular polymers. With the same protocol, we recently synthesized isotactic-rich polyacrylamide derivatives bearing a chiral oxazoline moiety in the side chain, which can serve as a chemosensor for the enantioselective recognition of 1,1'-bi-2-naphthol.<sup>22-23</sup> More recently,  $\text{RE}(\text{OTf})_3$  has proven to be an efficient catalyst for the ring-opening polymerization of lactones,<sup>24,25</sup> tetrahydrofuran,<sup>26</sup> and amino acid *N*-carboxyanhydrides.<sup>27</sup> In view of this background, it was thought that this kind of rare-earth salts should have potential uses as initiator for the CROP of 2-oxazolines.

The present work aims at examining (i) the catalytic performance of rare-earth metal triflates for the cationic ring-opening polymerization of 2-oxazolines, and (ii) its monomer application scope. For this purpose, we investigated the  $\text{Sc}(\text{OTf})_3$ -catalyzed polymerizations of EtOx under the conventionally thermal heating and microwave

irradiation conditions in comparison with those by using methyl tosylate as initiator. In addition, the influence of the temperature on polymerization kinetics was studied. Based on the observations from *in situ* NMR analyses and control termination experiments, a possible polymerization mechanism was proposed for the rare-earth catalysis. Finally, we briefly screened the polymerization behavior of other substituted 2-oxazolines in the presence of  $\text{Sc}(\text{OTf})_3$ . As depicted in Scheme 1, these monomers can be divided into two categories, namely, the sterically hindered 2-butyl-2-oxazolines bearing an alkyl group at the 4- or 5-position, and 2-phenyl-2-oxazoline derivatives where *t*-butyloxycarbonyl (Boc)-protected L-proline moiety was bound to the benzene ring via amide or ester linkage. Despite some Lewis acids had been utilized as an initiator for the polymerization of 2-oxazolines as early as 1960's,<sup>28</sup> we note that Lewis acidic rare-earth triflates have not yet been reported, to our knowledge.



Scheme 1. 2-Oxazoline monomers tested in this study.

## Experimental section

### Material

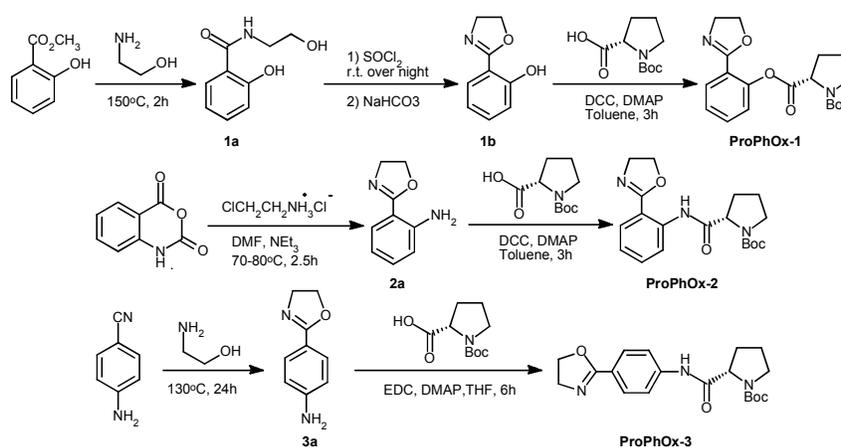
2-Ethyl-2-oxazoline (EtOx) and 2-phenyl-2-oxazoline (PhOx), purchased from Acros Organics, were dried and vacuum-distilled over barium oxide before use. Acetonitrile

(CH<sub>3</sub>CN), dimethyl sulfoxide (DMSO), *N,N*-dimethylformamide (DMF), methyl *p*-tosylate (MeOTs) and piperidine were distilled from calcium hydride. Piperazine (Aldrich) was distilled to use. Other chemicals, such as valeronitrile, 4-aminobenzonitrile, methyl salicylate, isatoic anhydride, dicyclohexylcarbodiimide (DCC), 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDC), 4-dimethylaminopyridine (DMAP), *N*-Boc-L-proline, 2-aminobutanol, 2-aminopropanol, 1-amino-2-propanol, 2-chloroethylamine hydrochloride and ethanolamine (Aldrich) were used as received. Rare-earth metal triflates (RE(OTf)<sub>3</sub>, RE = Sc, Y, La, Dy, Lu) were prepared following the reported method<sup>29</sup> and used after drying in vacuum.

#### **Analytical instrumentation and characterization techniques**

<sup>1</sup>H NMR spectra were recorded on a Bruker Avance DMX-500 spectrometer. The chemical shifts are reported in ppm relative to tetramethylsilane (TMS) as an internal standard. Melting points were taken with a micro melting point apparatus (Shanghai Precision & Scientific Instrument Co. LTD, the accuracy = 0.1°C). Size-exclusion chromatography (SEC) was measured on a Waters-150C apparatus equipped with two PLgel 5 μm MIXED-C 300 × 7.5 mm columns and a differential refractometer detector using DMF with LiBr (0.05 mol L<sup>-1</sup>) as the eluent (flow rate 1 mL min<sup>-1</sup>, 60°C). The number-average molecular weight (*M<sub>n</sub>*) and polydispersity index (PDI) of the polymers were calculated on the basis of a polymethylmethacrylate (PMMA) calibration. Matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectra were acquired on a Bruker Ultraflex extreme mass spectrometer in the

positive reflector mode with an acceleration voltage of 25 kV, using sodium iodide ( $10 \text{ mg mL}^{-1}$  in THF) as ionization salt and dithranol ( $20 \text{ mg mL}^{-1}$  in THF) as matrix. Electrospray ionization-mass spectrometry (ESI-MS) measurements were performed with a Varian 500 mass spectrometer. The X-ray diffraction data for the complex  $\text{Sc}(\text{OTf})_3 \cdot \text{EtOx}$  were measured using an Atlas Gemini Ultima diffractometer (Mo-K $\alpha$  radiation,  $\omega$ -scan technique,  $\lambda = 0.71073 \text{ \AA}$ ) at 170K. The crystal structure was solved by direct methods using SHELXS-97.



Scheme 2. Synthesis of 2-phenyl-2-oxazoline (PhOx) derivatives bearing Boc-protected L-proline moiety.

### Monomer synthesis (Scheme 2)

**2-[2-(*N*-Boc-*L*-prolyloxy)phenyl]-2-oxazoline (ProPhOx-1):** Methyl salicylate (7.6 mL, 59 mmol) was mixed with ethanolamine (3.6 mL, 60 mmol) and stirred for 2h at 150°C. To the reaction mixture was added toluene (3 mL) under stirring. The precipitated product was recrystallized from ethyl acetate to give a white solid (**1a**, 7.25 g, 63%). M.p. = 38.8–39.2°C (lit.<sup>30</sup> 36–37°C). **1a** (3.38 g, 20 mmol) was dissolved in 50 mL of dichloromethane, then to the solution added dropwise 4.5 mL

of  $\text{SOCl}_2$  (62 mmol) at  $0^\circ\text{C}$ . After stirring at room temperature overnight, the reaction mixture was filtered, and the filtrate was concentrated under reduced pressure. The residue was dissolved in water and then saturated with aqueous sodium bicarbonate to precipitate **1b** as a pink solid (2.40 g, 73.7%). To a solution of *N*-Boc-*L*-proline (1.72 g, 8 mmol) and **1b** (0.815 g, 5 mmol) in toluene (25 mL), DCC (1.65 g, 8 mmol) was added followed by DMAP (0.98 g, 8 mmol), and the reaction mixture was stirred at r.t. for 3h. The volatiles were removed under vacuum, and the residue was subjected to silica gel column chromatography (petroleum ether/ethyl acetate, 3:1), giving **ProPhOx-1** (1.55g, 86%) as a white crystal. M.p. =  $123.2\text{--}124.2^\circ\text{C}$ .  $^1\text{H}$  NMR (400 MHz;  $\text{CDCl}_3$ ):  $\delta$  = 1.47 (s,  $\text{OC}(\text{CH}_3)_3$ , 9H), 1.91–2.11 (m,  $\text{N}(\text{CH}_2)_2\text{CH}_2$ , 2H), 2.23–2.59 (m,  $\text{NCH}_2\text{CH}_2\text{CH}_2$ , 2H), 3.41–3.65 (m,  $\text{NCH}_2(\text{CH}_2)_2$ , 2H), 4.02 (t,  $\text{NCH}_2\text{CH}_2\text{O}$ , 2H), 4.35 (t,  $\text{NCH}_2\text{CH}_2\text{O}$ , 2H), 4.51–4.60 (m,  $\text{OCCHN}$ , 1H) 7.08–7.19 (m, Ph, 1H), 7.27–7.32 (m, Ph, 1H), 7.45–7.52 (m, Ph, 1H), 7.91–7.95 (m, Ph, 1H);  $^{13}\text{C}$  NMR (125 MHz;  $\text{DMSO-}d_6$ ):  $\delta$  = 22.9, 23.9, 28.0, 29.3, 46.3, 54.5, 58.8, 66.7, 79.0, 120.9, 123.3, 126.2, 130.3, 132.5, 148.9, 153.7, 160.2, 170.4. MS (ESI+):  $m/z$  (%) = 383.0 (39.6)  $[\text{M}+\text{Na}]^+$ , 743.1 (100)  $[2\text{M}+\text{Na}]^+$ .

**2-[2-(*N*-Boc-*L*-prolinamido)phenyl]-2-oxazoline (ProPhOx-2)**: To a solution of isatoic anhydride (3.26 g, 20 mmol) and 2-chloroethylamine hydrochloride (2.32 g, 20 mmol) in DMF (50 mL) was added 7 mL of  $\text{NEt}_3$ . After stirring for 2.5h at  $80^\circ\text{C}$ , the reaction mixture was poured into 200 mL of water, and then extracted with dichloromethane ( $3 \times 40$  mL). The organic layer was washed successively with water, followed by drying with anhydrous  $\text{MgSO}_4$ . Further purification was performed with

a silica gel column using petroleum ether/ethyl acetate mixture (3:1) as an eluant, and the intermediate **2a** was obtained as a white crystal (1.84 g, 56.7%). M.p. = 53.4–54.3°C (lit.<sup>31</sup> 54.5–55.5°C). The amidation of **2a** was conducted by the same procedure as the esterification of **1b**, and the desired product **ProPhOx-2** was obtained as a white crystal (89.5%). M.p. = 130.3–131.5°C. <sup>1</sup>H NMR (400 MHz; CDCl<sub>3</sub>),  $\delta$  = 1.32 (s, OC(CH<sub>3</sub>)<sub>3</sub>, 9H), 1.91–1.95 (m, N(CH<sub>2</sub>)<sub>2</sub>CH<sub>2</sub>, 2H), 2.13–2.40 (m, NCH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>, 2H), 3.40–3.72 (m, NCH<sub>2</sub>(CH<sub>2</sub>)<sub>2</sub>, 2H), 4.02–4.49 (m, NCH<sub>2</sub>CH<sub>2</sub>O, NCH<sub>2</sub>CH<sub>2</sub>O and OCCHN, 5H), 7.09–7.13 (m, Ph, 1H), 7.46–7.48 (m, Ph, 1H), 7.84–7.87 (m, Ph, 1H), 8.80–8.83 (m, Ph, 1H), 12.79 (s, NHCO, 1H); <sup>13</sup>C NMR (125 MHz; DMSO-*d*<sub>6</sub>):  $\delta$  = 23.2, 23.9, 27.7, 28.0, 30.2, 31.0, 46.4, 54.3, 61.9, 66.3, 78.8, 112.8, 118.5, 122.4, 128.9, 132.5, 139.0, 152.9, 153.9, 163.4, 172.1. MS (ESI+): *m/z* (%) = 382.1 (93.8) [M+Na]<sup>+</sup>, 741.1 (100) [2M+Na]<sup>+</sup>.

**2-[4-(*N*-Boc-*L*-prolinamido)phenyl]-2-oxazoline (ProPhOx-3):** To the melted 4-cyanoaniline (5.91 g, 50 mmol) was added Zn(OAc)<sub>2</sub>·2H<sub>2</sub>O (0.35 g, 1.6 mmol) and ethanolamine (4 mL, 66 mmol), and then the mixture was allowed to stir for 24h at 130°C. The reaction mixture was poured into cold deionized water (200 mL), and the resulted precipitate was purified by chromatography on a silica gel column eluted with THF/petroleum (v/v, 3: 1) to give **3a** as yellowish solid (3.67 g, 45.4%). M.p. = 159.5–160.5°C (lit.<sup>32</sup> 160–161°C). **ProPhOx-3** was prepared by a similar way to that of **ProPhOx-2** except for the use of EDC as the dehydrant and THF as solvent (53.7%, white crystal). <sup>1</sup>H NMR (400 MHz; CDCl<sub>3</sub>):  $\delta$  = 1.44 (s, OC(CH<sub>3</sub>)<sub>3</sub>, 9H), 1.84–1.98 (m, N(CH<sub>2</sub>)<sub>2</sub>CH<sub>2</sub> and NCH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>, 4H), 3.22–3.61 (m, NCH<sub>2</sub>(CH<sub>2</sub>)<sub>2</sub>, 2H), 4.04 (t,

$\text{NCH}_2\text{CH}_2\text{O}$ , 2H), 4.40–4.44 (m,  $\text{NCH}_2\text{CH}_2\text{O}$  and  $\text{OCCHN}$ , 3H), 7.56–7.59 (m, Ph, 2H), 7.88–7.90 (m, Ph, 2H), 9.77 (br,  $\text{NHCO}$ , 1H);  $^{13}\text{C}$  NMR (125 MHz;  $\text{DMSO}-d_6$ ):  $\delta$  = 171.6, 162.6, 153.2, 141.7, 128.5, 122.1, 118.5, 78.5, 67.2, 60.2, 54.3, 46.6, 33.3, 30.9, 30.1, 27.9, 23.6. MS (ESI+):  $m/z$  (%) = 360.1 (100)  $[\text{M}+\text{H}]^+$ , 719.0 (62.6)  $[2\text{M}+\text{H}]^+$ , 741.1 (23.8)  $[2\text{M}+\text{Na}]^+$ .

2-Butyl-2-oxazoline derivatives, including 4-ethyl-2-butyl-2-oxazoline (4-EtBuOx), 2-butyl-4-methyl-2-oxazoline (4-MeBuOx), and 2-butyl-5-methyl-2-oxazoline (5-MeBuOx) were synthesized according to a general procedure described in the literature.<sup>33</sup>

**4-EtBuOx:**  $^1\text{H}$  NMR (400 MHz;  $\text{CDCl}_3$ ):  $\delta$  = 0.88–0.96 (br,  $\text{OC}(\text{CH}_2)_3\text{CH}_3$  and  $\text{NCHCH}_2\text{CH}_3$ , 6H), 1.36–1.61 (br,  $\text{NCHCH}_2\text{CH}_3$  and  $\text{OCCH}_2(\text{CH}_2)_2\text{CH}_3$ , 6H), 2.15 (t,  $\text{OCCH}_2(\text{CH}_2)_2\text{CH}_3$ , 2H), 3.75 (t,  $\text{CH}_2\text{O}$ , 1H), 3.95 (q,  $\text{CHN}$ , 1H), 4.25 (t,  $\text{CH}_2\text{O}$ , 1H).

**4-MeBuOx:**  $^1\text{H}$  NMR (400 MHz;  $\text{CDCl}_3$ ):  $\delta$  = 0.86 (t,  $\text{OC}(\text{CH}_2)_3\text{CH}_3$ , 3H), 1.18 (d,  $\text{NCHCH}_3$ , 3H), 1.32–1.55 (br,  $\text{OCCH}_2(\text{CH}_2)_2\text{CH}_3$ , 4H), 2.20 (t,  $\text{OCCH}_2(\text{CH}_2)_2\text{CH}_3$ , 2H), 3.67 (t,  $\text{CH}_2\text{O}$ , 1H), 4.08 (q,  $\text{CHN}$ , 1H), 4.24 (t,  $\text{CH}_2\text{O}$ , 1H).

**5-MeBuOx:**  $^1\text{H}$  NMR (400 MHz;  $\text{CDCl}_3$ ):  $\delta$  = 0.92 (t,  $\text{OC}(\text{CH}_2)_3\text{CH}_3$ , 3H), 1.29–1.40 (m,  $\text{OC}(\text{CH}_2)_2\text{CH}_2\text{CH}_3$  and  $\text{OCHCH}_3$ , 5H), 1.62 (q,  $\text{OCCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$ , 2H), 2.25 (t,  $\text{OCCH}_2(\text{CH}_2)_2\text{CH}_3$ , 2H), 3.37 (t,  $\text{CH}_2\text{O}$ , 1H), 3.89 (t,  $\text{CHN}$ , 1H), 4.61 (t,  $\text{CH}_2\text{O}$ , 1H).

### Polymerization procedure

All the polymerizations under thermal heating conditions were carried out on the Schlenk line with a predetermined initial monomer concentration. Taking the solution polymerization of EtOx as an example, a typical experimental procedure is as follows.

To a flame dried flask EtOx (1 mL, 9.9 mmol) and 1.2 mL of an acetonitrile solution of  $\text{Sc}(\text{OTf})_3$  ( $8.25 \times 10^{-2} \text{ M}$ ) was added via a syringe under nitrogen atmosphere. The flask was then immersed in a constant-temperature oil bath of  $80^\circ\text{C}$ . After being heated for a definite period of time with magnetic stirring, the reaction was quenched by the addition of deionized water. The resulting solution was left to stir at ambient temperature for 1 h and the crude product was precipitated in diethyl ether. To completely remove the catalyst residue and unreacted monomer, the collected powder matter was redissolved in  $\text{CH}_3\text{CN}$  and then precipitated from  $\text{Et}_2\text{O}$ . This process was repeated three times and the desired polymer PEtOx was dried under vacuum. The polymerization of other 2-oxazoline monomers and the purification are similar to that described above.

For comparison, the polymerization of EtOx with microwave assistance was carried out in a CEM Discover SP microwave synthesizer. In this case, a stock solution of the monomer and  $\text{Sc}(\text{OTf})_3$  or MeOTs as initiator with various monomer-to-initiator ratios was prepared in acetonitrile. The microwave vial was charged with 1–2 mL of this stock solution and heated in the microwave to a certain temperature. After a given time, the reaction mixture was cooled with compressed air and quenched by adding deionized water. The subsequent treatment of the polymerization product is the same as those described above.

#### **Kinetic study of EtOx polymerization initiated with $\text{Sc}(\text{OTf})_3$**

The kinetics of  $\text{Sc}(\text{OTf})_3$ -catalyzed cationic ring-opening polymerization of EtOx was studied under the conventionally thermal heating conditions in acetonitrile. In order

to obtain the monomer conversion, aliquots taken periodically from the reaction mixture were directly subjected to  $^1\text{H}$  NMR analysis in  $\text{CDCl}_3$ . The conversion was determined by comparing the signal intensity from the released  $\text{CH}_2$  of polymer at 3.6–3.3 ppm with that from the remaining  $\text{CH}_2$  of EtOx at 4.3 and 3.8 ppm (see: Fig.S1 in Supporting Inf). Meanwhile, the collected samples were dissolved in DMF containing LiBr (50 mM) for SEC measurement to determine the molecular weight and polydispersity.

## Results and discussion

### Monomer synthesis and polymerization features

Except for EtOx and PhOx, other 2-oxazoline derivatives shown in Scheme 1 were prepared from the commercially available starting materials (nitriles, carboxylates, or isatoic anhydride) by relatively facile functional-group transformations in moderate yields. Details of the synthetic preparations and structural characterization data of these monomers can be found in the experimental part and the Supporting Information.

To evaluate the catalytic performance of rare-earth triflates for CROP of 2-oxazolines, we first investigated the solution polymerization of EtOx under different conditions. The polymerizations with  $\text{RE}(\text{OTf})_3$  ( $\text{RE} = \text{Sc}, \text{Y}, \text{La}, \text{Dy}$  or  $\text{Lu}$ ) were found to proceed smoothly at  $80^\circ\text{C}$  in acetonitrile. As can be seen from Table 1 (runs 1–5), after a reaction period of 2 hours the monomer conversion of 47–84% was observed by  $^1\text{H}$  NMR analysis, yielding corresponding polymers with number-average molecular weight of 5270–8440 and low polydispersity indices (PDI

= 1.09–1.12). Of five triflates tested, Sc(OTf)<sub>3</sub> seems furnish best results in terms of the monomer conversion and PDIs of the resultant PEtOxs. In contrast, methyl tosylate (MeOTs) exhibited a poor initiating efficiency, which gave a monomer conversion of ~16% and a low-molecular-weight polymer under the same conditions (run 6). Noteworthy is also the strong influence of the solvent property on the catalytic activity of Sc(OTf)<sub>3</sub>, with a decrease even deactivation observed when the polymerization was carried out in other solvents such as *n*-BuCl, DMSO or DMF instead of CH<sub>3</sub>CN (runs 7–9).

**Table 1** ROP of 2-ethyl-2-oxazoline (EtOx) under various conditions <sup>a</sup>

| Run             | Catalyst             | Solvent            | [M]:[I] | Temp.<br>(°C)    | Time<br>(min) | PEtOx                |                                    |                  |
|-----------------|----------------------|--------------------|---------|------------------|---------------|----------------------|------------------------------------|------------------|
|                 |                      |                    |         |                  |               | Conv./% <sup>c</sup> | <i>M</i> <sub>n</sub> <sup>d</sup> | PDI <sup>d</sup> |
| 1               | Sc(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 100     | 80               | 120           | 84                   | 5270                               | 1.09             |
| 2               | Y(OTf) <sub>3</sub>  | CH <sub>3</sub> CN | 100     | 80               | 120           | 65                   | 6220                               | 1.12             |
| 3               | La(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 100     | 80               | 120           | 47                   | 8440                               | 1.12             |
| 4               | Dy(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 100     | 80               | 120           | 73                   | 6270                               | 1.10             |
| 5               | Lu(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 100     | 80               | 120           | 71                   | 6290                               | 1.11             |
| 6               | MeOTs                | CH <sub>3</sub> CN | 100     | 80               | 120           | 16                   | 3440                               | 1.18             |
| 7               | Sc(OTf) <sub>3</sub> | <i>n</i> -BuCl     | 100     | 80               | 120           | 48                   | 4230                               | 1.21             |
| 8               | Sc(OTf) <sub>3</sub> | DMSO               | 100     | 80               | 120           | 0                    | –                                  | –                |
| 9               | Sc(OTf) <sub>3</sub> | DMF                | 100     | 120              | 120           | 0                    | –                                  | –                |
| 10 <sup>b</sup> | Sc(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 100     | 80               | 60            | 53<br>(93)           | 4080<br>(7880)                     | 1.09<br>(1.10)   |
| 11 <sup>b</sup> | Sc(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 100     | 90               | 40            | 66<br>(91)           | 4490<br>(8910)                     | 1.10<br>(1.11)   |
| 12              | Sc(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 100     | 140 <sup>e</sup> | 5             | >99                  | 5560                               | 1.14             |

|    |                      |                    |      |                  |    |     |       |      |
|----|----------------------|--------------------|------|------------------|----|-----|-------|------|
| 13 | MeOTs                |                    |      |                  |    | 93  | 5320  | 1.27 |
| 14 | Sc(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 400  | 140 <sup>e</sup> | 20 | >99 | 12210 | 1.31 |
| 15 | MeOTs                |                    |      |                  |    | 69  | 15320 | 1.52 |
| 16 | Sc(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 800  | 140 <sup>e</sup> | 20 | >99 | 19060 | 1.56 |
| 17 | MeOTs                |                    |      |                  |    | 67  | 14850 | 1.97 |
| 18 | Sc(OTf) <sub>3</sub> | CH <sub>3</sub> CN | 1600 | 140 <sup>e</sup> | 20 | 89  | 27240 | 1.67 |
| 19 | MeOTs                |                    |      |                  |    | 44  | 14100 | 2.08 |

<sup>a</sup> The monomer concentration was 3 M for runs 1–9 and 4.5 M for runs 10–19.

<sup>b</sup> The data given in parentheses are values obtained under microwave ( $\mu$ W) radiation.

<sup>c</sup> Monomer conversion was determined by <sup>1</sup>H NMR.

<sup>d</sup> Determined by SEC, PMMA calibration, DMF containing 50 mM LiBr as the eluent.

<sup>e</sup> Under  $\mu$ W conditions.

In a set of comparable experiments, we found that the microwave ( $\mu$ W) irradiation makes Sc(OTf)<sub>3</sub> more effective for the CROP of EtOx compared to the conventional heating, i.e., the rare-earth salt can catalyze the polymerization affording high yields (>90%) of higher-molecular-weight polymers with narrow PDIs under microwave conditions in acetonitrile at 80 or 90°C (runs 10 and 11). Such a significant improvement in catalytic efficiency pointed to the existence of a non-heat microwave effect in the Sc(OTf)<sub>3</sub>-catalyzed polymerization. Nevertheless, for the reported  $\mu$ W-assisted CROPs of 2-oxazolines there seemed to be no distinct correlation between the accelerated polymerization rate and the microwave effect, as demonstrated by Hoogenboom and Schubert et al.<sup>34</sup>

It is also interesting to note that Sc(OTf)<sub>3</sub> always exhibited higher catalytic

efficiency than MeOTs in the  $\mu$ W-assisted polymerization process (runs 12–19). For example, the  $\text{Sc}(\text{OTf})_3$ -catalyzed reaction came to completion within 5–20 minutes at  $140^\circ\text{C}$  in the cases of monomer-to-initiator ratio of 100, 400 and 800, even at a  $[\text{M}]/[\text{I}]$  of 1600 the monomer conversion reached  $\sim 90\%$  yielding  $M_n$  as high as 27000. However, with decreasing of the catalyst loading a relatively broad molecular-weight distribution was observed for the resultant PEtOxs (PDI value changing from 1.14 to 1.67), which may be attributed to chain transfers during the CROP.<sup>35</sup>

Table 2 summarizes the bulk polymerization results of EtOx using  $\text{Sc}(\text{OTf})_3$  as the initiator under conventionally thermal heating. It can be seen that this bulk polymerization process allowed the synthesis of polymers with molar masses in the range  $5\,400\text{ g}\cdot\text{mol}^{-1} < M_n < 18\,800\text{ g}\cdot\text{mol}^{-1}$  (PMMA standard) through regulation of reaction parameters. In experimenting we found that with the proceeding of polymerization the reaction mixture became highly viscous and later solidified. It usually occurred at the point that the monomer conversion was 70–80%. Most likely, the presence of such a viscous or heterogeneous system at the late stage of polymerization is responsible for the broader molecular weight distributions (PDI = 1.27–1.37). This speculation is supported by the data from Table 2. More specifically, in the polymerization with a monomer-to-initiator ratio of 100 (runs 1–3), elongating the reaction time from 30 min to 60 min resulted in a distinct increase in both  $M_n$  and PDI; however, both the values almost remained constant when further extending periods of time. From the results shown in runs 6–8 of Table 2, it appears that the combination of a lower temperature and longer reaction time is beneficial to the

improvement of molar masses while keeping narrower polydispersity for the case of high  $[M]/[I]$  ratio.

**Table 2** Bulk polymerization of 2-ethyl-2-oxazoline with  $\text{Sc}(\text{OTf})_3$

| Run | [M]:[I] | Temp./°C | Time/min | PEtOx                 |         |                  |
|-----|---------|----------|----------|-----------------------|---------|------------------|
|     |         |          |          | Yield <sup>a</sup> /% | $M_n^b$ | PDI <sup>b</sup> |
| 1   | 100     | 80       | 30       | 34.2                  | 5450    | 1.09             |
| 2   | 100     | 80       | 60       | 89.0                  | 12040   | 1.29             |
| 3   | 100     | 80       | 90       | 89.4                  | 12920   | 1.29             |
| 4   | 100     | 100      | 30       | 86.4                  | 8860    | 1.28             |
| 5   | 200     | 100      | 30       | 86.1                  | 9030    | 1.37             |
| 6   | 500     | 100      | 30       | 70.1                  | 13800   | 1.26             |
| 7   | 500     | 100      | 180      | 97.8                  | 12410   | 1.64             |
| 8   | 500     | 80       | 180      | 85.0                  | 18730   | 1.32             |

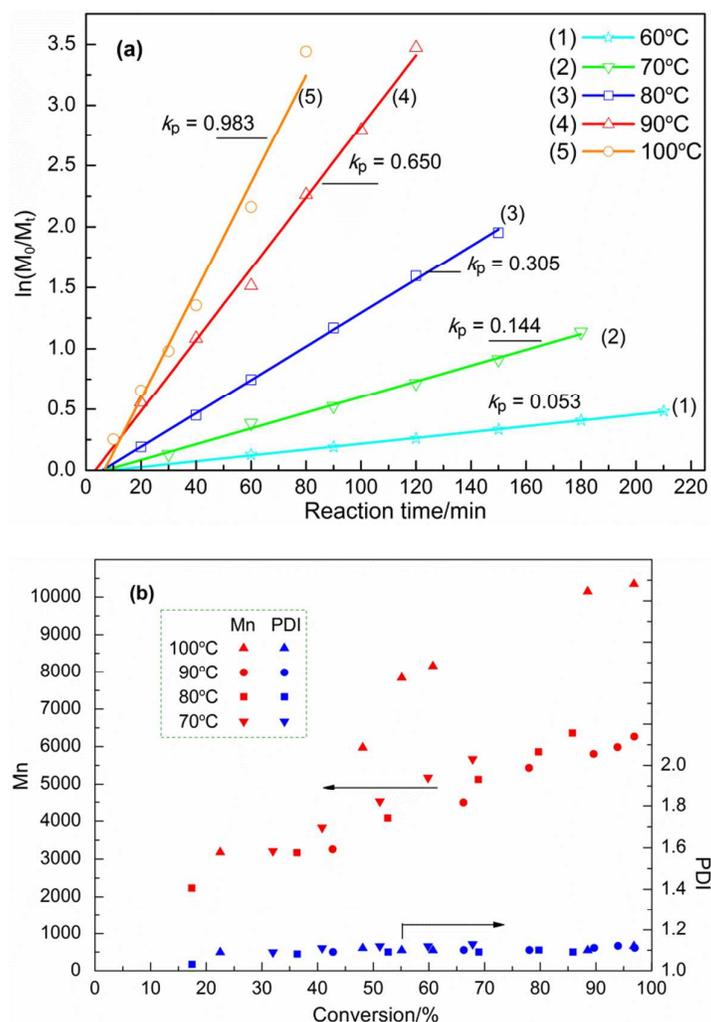
<sup>a</sup> Isolated yield determined by gravimetry.

<sup>b</sup> Determined by GPC, PMMA calibration, DMF containing 50 mM LiBr as the eluent.

### Kinetic studies of EtOx polymerization with $\text{Sc}(\text{OTf})_3$

The polymerization kinetics of EtOx were determined in acetonitrile with  $\text{Sc}(\text{OTf})_3$  as the initiator under conventional conditions, using an initial monomer concentration of 4.5 M and a monomer-to-initiator ratio of 100. The resulting kinetic plots at five different polymerization temperatures are depicted in Figure 1a. It can be seen that at 100°C or 90°C the monomer revealed linear first-order kinetics up to ~90% conversion ( $\ln([M]_0/[M]_t) \approx 2.3$ ) in less than 2 h. For the polymerization conducted at

80°C and 70°C, this linear relationship was observable in the range of 86% and 68% conversion within 3 h, respectively. In all experiments, SEC analyses of the obtained polymers gave unimodal traces. As shown in Figure 1b, the number-average molecular weight ( $M_n$ ) increased linearly in proportion to the conversion, while the PDIs remained around 1.10. As such, it can be concluded that the polymerizations proceeded in a controlled/living manner.



**Fig. 1** (a) Kinetic plots for 2-ethyl-2-oxazoline polymerizations initiated with  $\text{Sc}(\text{OTf})_3$  ( $[\text{M}]_0/[\text{I}]_0 = 100$ ) in acetonitrile ( $[\text{M}]_0 = 4.5 \text{ M}$ ) at 60, 70, 80, 90, and 100°C under thermal heating; the apparent rate constants ( $k_p$ ) are expressed in  $\text{L mol}^{-1} \text{ min}^{-1}$ .

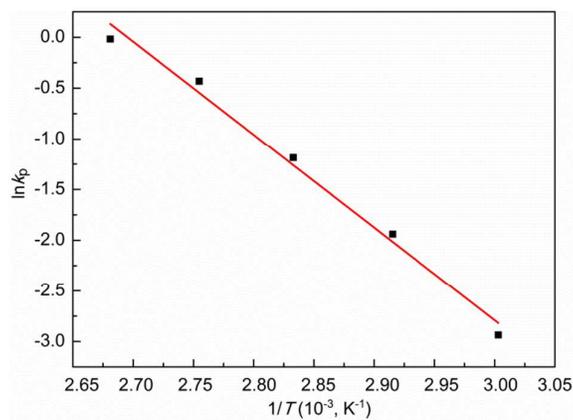
(b) Evolution of the molar mass ( $M_n$ ) and the PDI value with monomer conversion (determined by SEC, RI detection, PMMA calibration, DMF containing 50 mM LiBr as the eluent. See: Fig. S2 in Supporting Information).

The fact that  $\ln([M]_0/[M]_t)$  increased linearly with reaction time (Fig. 1a) indicates that the concentration of propagating species remained constant throughout the polymerization. Assuming that the concentration of the active species  $[P^*]$  was equal to the initial initiator concentration  $[I]_0$ , the formula (eq 1) for determining the apparent rate constant ( $k_p$ ) was integrated in eq 2. Then,  $k_p$  values can be deduced by the slope of the  $\ln([M]_0/[M]_t)$  versus time, as shown in Fig. 1a. From the graphical resolution of the Arrhenius equation (eq 3 and Fig. 2), the activation energy ( $E_a$ ) and the frequency factor ( $A$ ) are calculated as  $69.54 \text{ kJ mol}^{-1}$  and  $9.77 \times 10^7 \text{ L mol}^{-1} \text{ s}^{-1}$ , respectively. The  $E_a$  value is comparable to that obtained in the MeOTs initiating system.<sup>8</sup>

$$-\frac{d[M]}{dt} = k_p [P^*][M] \quad (1)$$

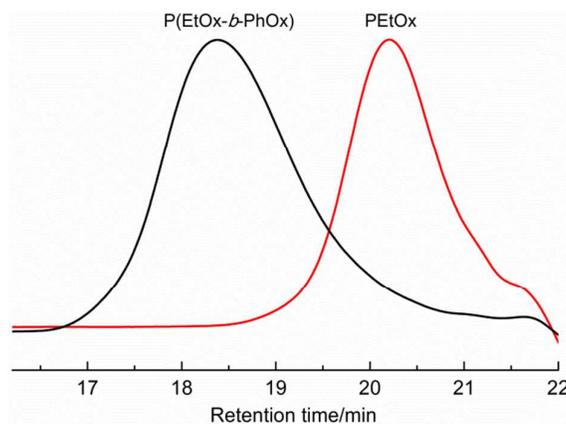
$$\ln \frac{[M]_0}{[M]_t} = k_p [I]_0 t \quad (2)$$

$$k_p = A e^{-E_a/RT} \quad (3)$$



**Fig. 2** Arrhenius plot for the polymerizations of 2-ethyl-2-oxazoline with  $\text{Sc}(\text{OTf})_3$  in acetonitrile (see Fig. 1a for  $k_p$  values).

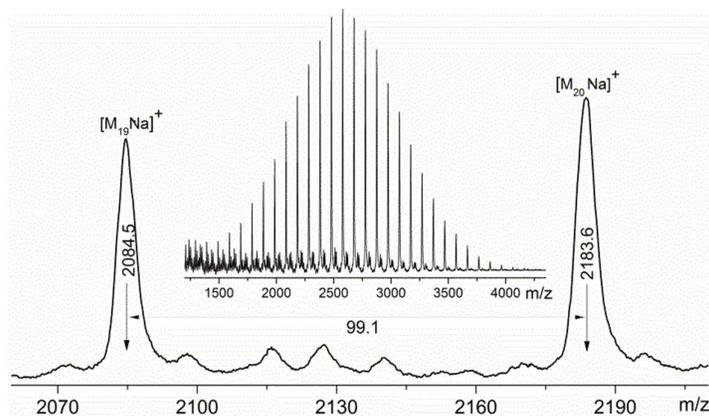
As evidenced by the kinetic results, Lewis acidic  $\text{Sc}(\text{OTf})_3$  is more reactive towards EtOx polymerization than other existing initiators such as methyl tosylate<sup>8</sup> and alkyl iodides.<sup>36</sup> With the rare-earth catalyst the high yield synthesis of PEtOx was achieved in a rapid manner (within several hours) under mild conditions. Furthermore, this living system can be expected for the preparation of block copolymers with a well-defined structure. For instance, we have successfully synthesized a diblock polymer comprised of PEtOx and PPhOx segments via a sequential polymerization route, wherein the formation of copolymer was confirmed by the observed SEC analyses of a peak shift from 20.3 to 18.4 min elution time from the first (PEtOx) to second block growth profiles and a narrow molecular weight distribution (PDI = 1.18) (Fig.3).



**Fig. 3** SEC profiles of PEtOx and the *in situ* prepared poly(EtOx-*b*-PhOx) by using the sequential addition method (SEC: RI detection, PMMA calibration, THF as eluent, with a flow rate of 1 mL min<sup>-1</sup>, 40°C). Copolymerization:  $\text{Sc}(\text{OTf})_3/\text{EtOx}/\text{PhOx}$  = 1:28:60 (molar ratio),  $[\text{M}]_{\text{total}} = 4.5$  M, acetonitrile, 90°C; the second monomer was added when EtOx conversion reached >99% (traced by <sup>1</sup>H NMR). The  $M_n$ 's of PEtOx and poly(EtOx-*b*-PhOx) were 1190 and 3340, respectively.

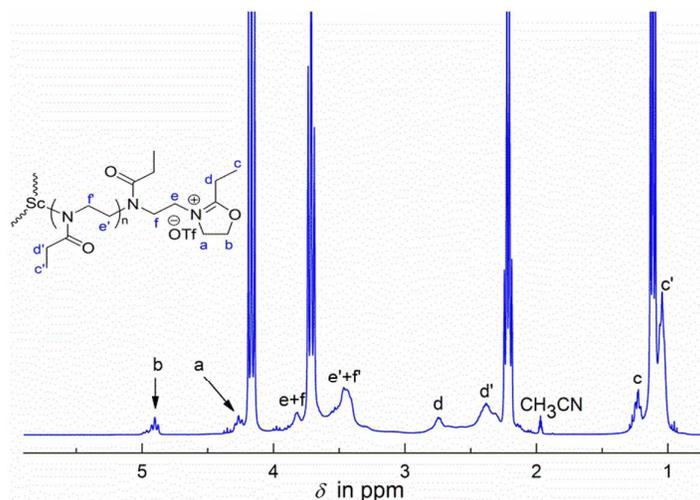
### Mechanistic aspects

The cationic ring-opening polymerization of 2-oxazolines proved to proceed via two different types of active species, i.e. ionic and covalent types, depending on the nature of the initiator and on the monomer.<sup>5</sup> For the present system, the ionic polymerization mechanism seems to be most possible because the counteranion  $^-OTf$  is of poor nucleophilicity. Moreover, judging from the low polydispersity (PDIs  $\leq 1.10$ ) of the purified kinetic samples, the cationic species of an oxazolinium is likely to be the only propagating end existed during the polymerization. Further support to this speculation was given by analysis of the MALDI-TOF mass spectrum of PEtOx with piperidine terminals. These polymer samples were obtained by end-termination of the living oxazolinium species resulting from the CROP of EtOx with excess piperidine. As can be seen from Fig. 4, the mass difference in the series of signals ( $m/z$  99.1) agrees well with the mass of one EtOx repeating unit, confirming that the sodium adducts form a homologue series originating from end-functionalized polymers. Similar results observations were made for the higher molecular weight polymers, shown in Fig. S3 in the Supporting Information.



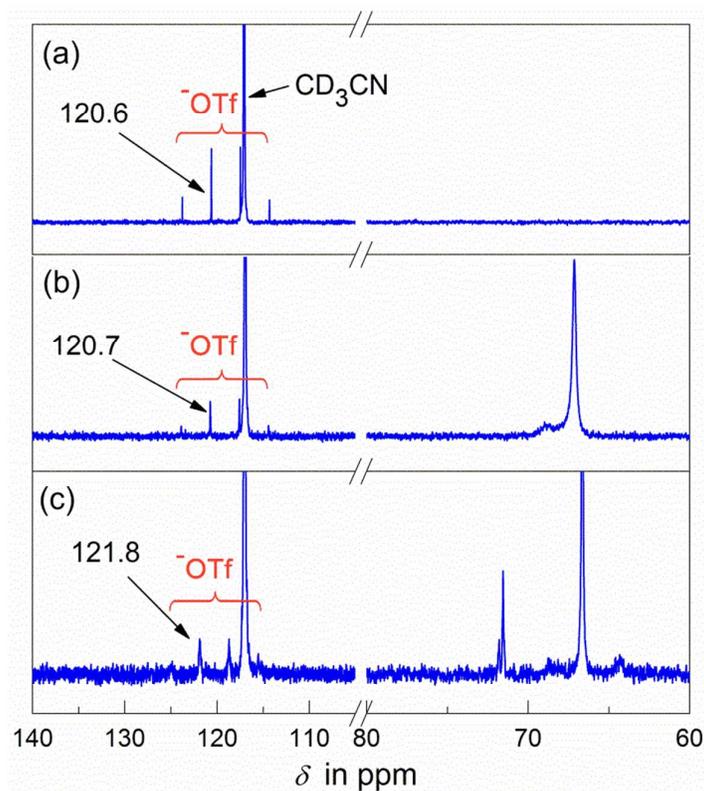
**Fig. 4** A typical MALDI-TOF mass spectrum of PEtOx having a piperidine group at the  $\omega$ -terminal end ( $M_{n,SEC} = 3560$ ,  $M_{w,SEC}/M_{n,SEC} = 1.11$ ; PMMA standard, eluent: DMF with 50 mM LiBr). The inset shows the corresponding full spectrum. Polymerization conditions:  $[M]_0 = 4.5$  M,  $[M]_0/[I]_0 = 100$ ,  $CH_3CN$ ,  $Sc(OTf)_3$  initiator,  $90^\circ C$ , 1h, piperidine terminator.

Single-crystal X-ray diffraction analysis of  $Sc(OTf)_3/EtOx$  complex revealed extensive coordinative interactions between the imine units of the monomer and the scandium cation (Fig. S4 in the Supporting Information). It is conceivable that the coordination would promote the nucleophilic attack of free monomers at the C-5 position of the bound oxazoline unit to generate an oxazolinium propagating species, which has been confirmed by *in situ* NMR spectroscopic studies. As shown in Fig. 5, the EtOx polymerization system before being subjected to the termination (i.e. a living polymer) displays the weak proton signals at 4.26 and 4.90 ppm (denoted as *a* and *b*). The two peaks should come from the active oxazolinium units, because they are different from those due to methylene protons of monomer ( $\delta$ : 3.71, 4.17 ppm) and those of the polymer main chain ( $\delta$ : 3.6–3.3 ppm) as well; furthermore, they vanished totally upon addition of terminating agents such as piperidine (see: Fig. S1 in the Supporting Information).



**Fig. 5**  $^1\text{H}$  NMR spectrum of a living polymer sample formed in the EtOx polymerization in  $\text{CD}_3\text{CN}$  at  $80^\circ\text{C}$  for 30 min ( $[\text{EtOx}]/[\text{Sc}] = 30$ ).

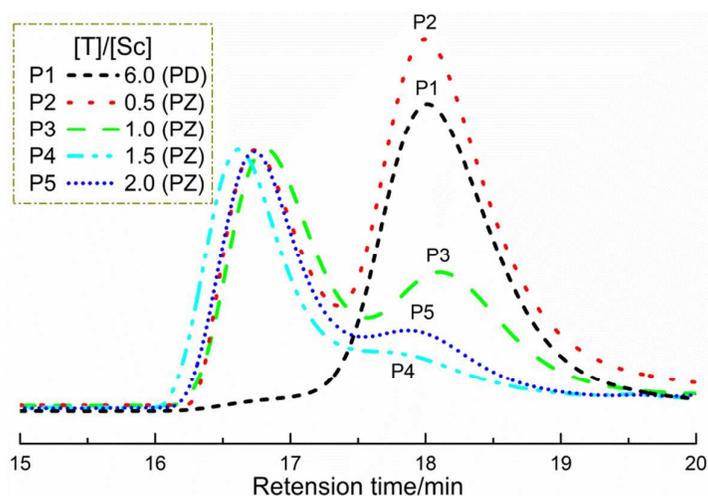
Simultaneously,  $^{13}\text{C}$  NMR spectroscopy provides us with more information about the propagating species. In the  $^{13}\text{C}$  NMR spectra of  $\text{Sc}(\text{OTf})_3$ , the anionic ligand displays a characteristic quartet at 114.4–123.8 ppm, and the position of these signals does not change distinctly in the presence of EtOx at ambient temperature (Fig. 6a,b). However, a *ca.* 1.2 ppm downfield shift was observed upon heating the mixture at  $80^\circ\text{C}$  for 30 min (Fig. 6c), indicating that the ligand moved to the propagating ends as a bound counterion with the polymerization went on. This situation is similar to that seen in the ligand exchange of rare-earth triflates reported by Ling et al.<sup>37</sup>



**Fig. 6**  $^{13}\text{C}$  NMR spectra in  $\text{CD}_3\text{CN}$  of (a)  $\text{Sc}(\text{OTf})_3$ , (b)  $\text{Sc}(\text{OTf})_3 + \text{EtOx}$  (30 eq.),  $25^\circ\text{C}$ , and (c) the mixture composed of  $\text{Sc}(\text{OTf})_3$  and  $\text{EtOx}$  (30 eq.) after heating for 30 min at  $80^\circ\text{C}$ .

It is noteworthy that the  $^{13}\text{C}$  NMR signal of the ligand  $^-\text{OTf}$  still remained its intrinsic quartet feature in the living polymerization system (Fig.6), which means they are in the identical chemical environments as counterions. Hence we presume that every metallic active species *in situ*-generated from the  $\text{Sc}(\text{OTf})_3$ - $\text{EtOx}$  complexation may possess three identical chain-growing sites, in other words, one  $\text{Sc}(\text{OTf})_3$  initiated three equivalent  $\text{PEtOx}$  chains. To clarify this point, we devised a set of control experiments, in which the parallel  $\text{EtOx}$  polymerizations initiated with  $\text{Sc}(\text{OTf})_3$  under the same conditions ( $[\text{M}] = 4.5 \text{ M}$ ,  $[\text{M}]/[\text{I}] = 100$ ,  $90^\circ\text{C}$ , 60 min) were terminated by two kinds of terminating agents, the monofunctional piperidine and the bifunctional

piperazine. Rather, the termination reaction was conducted at a predetermined terminator-to-initiator molar ratio ( $[T]/[Sc]$ ) to prepare the desired polymers (**P1–P5**) for SEC analysis. Among them, **P1**, as a reference, was obtained by using intentionally excess piperidine ( $[T]/[Sc] = 6$ ) in the termination step, while **P2–P5** resulted from the piperazine termination with  $[T]/[Sc]$  of 0.5, 1.0, 1.5, and 2.0, respectively.

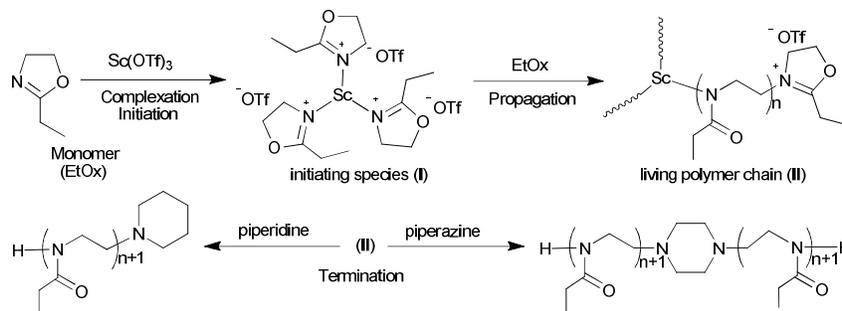


**Fig. 7** Normalized SEC traces (THF, RI detection) of PETox samples obtained by terminating the EtOx polymerization with piperidine (**P1**) and piperazine (**P2–P5**); the added amounts of terminators ( $[T]/[Sc]$ ) are noted in the inset (PD = piperidine, PZ = piperazine).

As shown in Fig.7, **P1** gives a unimodal molecular weight distribution with  $M_n = 3310$  (PDI = 1.09) in THF. In contrast, the SEC traces of **P2–P5** exhibit a bimodal shape and the peak of low molecular weight components (LMW, arbitrarily defined as  $M_n \approx 3$  kD) was found to decrease in going from **P2** to **P4** in concert with an increase in the terminator amount used in termination reactions. The  $M_n$  values of high molecular weight (HMW) polymers are roughly twice  $M_n$ 's of LMW parts. These

observations may be explained by the idea proposed above that one  $\text{Sc}(\text{OTf})_3$  leads to three living polymer chains combination with Scheme 3 illustrating the initiating/propagating mechanism. In the piperazine-termination with  $[\text{T}]/[\text{Sc}] = 0.5$ , the nucleophilic sites (secondary amino groups) were not in sufficient quantities to stop all the living chains and thereby the resultant polymer **P2** is composed of the piperazine-coupled HMW PEtOx and non-coupled LMW PEtOx, as evidenced by its SEC curve (Fig.7). It was also the case for the termination with  $[\text{T}]/[\text{Sc}] = 1.0$ , but the relative content of LMW components in **P3** decreased remarkably compared with **P2**.

Interestingly, the SEC elution trace of **P4** is close to a unimodal shape, indicative of this sample consisted of the coupled polymers predominantly. This result seems to be understandable, because in the case of  $[\text{T}]/[\text{Sc}] = 1.5$  the bifunctional terminator just provides equivalent nucleophilic sites relative to the cationic propagating ends, whereby every piperazine molecule can catch two active chains in average during the termination process yielding the coupled product. The very minor distribution occurred in the SEC profile reveals the presence of a few PEtOx polymers resulting from chain transfer to the moisture or/and nucleophilic impurity that enter reaction vessel. On the other hand, an excess of piperazine would retard such coupling reactions owing to partial terminators is bound to serve as the monofunctional capping agent in this case, which increasing the content of LMW polymers, as shown in SEC curve of **P5** (Fig.7).



**Scheme 3** Schematic representation of the cationic ring-opening polymerization of 2-ethyl-2-oxazoline (EtOx) with  $\text{Sc}(\text{OTf})_3$  as the initiator.

### Extension of $\text{Sc}(\text{OTf})_3$ -catalysis to other substituted 2-oxazolines

Finally, we tried to extend the rare-earth catalysis to CROPs of some sterically hindered and functional 2-oxazoline derivatives. The preliminary results suggest that 4/5-alkylated 2-butyl-2-oxazolines (i.e., 4-EtBuOx, 4-MeBuOx and 5-MeBuOx) as well as 2-phenyl-2-oxazoline (PhOx) can be polymerized in a thermal heating process using  $\text{Sc}(\text{OTf})_3$  as the initiator, leading to corresponding polymers with low molecular weights and a relatively narrower polydispersity (runs 1–4, Table 3). At a high catalyst loading ( $[\text{M}]/[\text{I}] = 20$ ), the polymerization of ProPhOx-1 containing ester linkage was achieved at  $90^\circ\text{C}$ , while its amide analogs (ProPhOx-2 and ProPhOx-3) did not give the desired polymers (runs 5–7). Different from ProPhOx-2, however, ProPhOx-3 can be polymerized at  $140^\circ\text{C}$  under microwave irradiation resulting in the polymer with  $M_n$  of  $\sim 6.0$  kD and a narrower molecular weight distribution ( $\text{PDI} \sim 1.4$ ). The poor polymerizability of ProPhOx-2 is probably attributed to the fact that the intramolecular hydrogen bonding interaction between the adjacent oxazoline unit and amide group decreases the cyclic-imine basicity to such an extent that the oxazolinium initiating species failed to form. However, a relevant case was reported

by Jordan and coworkers,<sup>13</sup> who showed that methyl triflate did not efficiently initiate the ring-opening polymerization of a kind of 2-oxazoline monomer with a Boc protected amino function (2-[*N*-Boc-5-aminopentyl]-2-oxazoline). They presumed the initiator does not only attack the 2-oxazoline ring, but mainly attacks the secondary amide group in the monomer side chain.

**Table 3** Polymerization of various substituted 2-oxazoline monomers with Sc(OTf)<sub>3</sub>

| Run | Monomer   | [M]<br>(mol·L <sup>-1</sup> ) | [M]:[I] | Solvent            | T/°C             | t/min | Polymer <sup>a</sup>  |                             |                  |
|-----|-----------|-------------------------------|---------|--------------------|------------------|-------|-----------------------|-----------------------------|------------------|
|     |           |                               |         |                    |                  |       | Yield <sup>b</sup> /% | M <sub>n</sub> <sup>c</sup> | PDI <sup>c</sup> |
| 1   | 4-EtBuOx  | neat                          | 60      | bulk               | 120              | 180   | 48                    | 4650                        | 1.13             |
| 2   | 4-MeBuOx  | neat                          | 60      | bulk               | 120              | 180   | 38                    | 4530                        | 1.15             |
| 3   | 5-MeBuOx  | neat                          | 60      | bulk               | 120              | 180   | 26                    | 4230                        | 1.20             |
| 4   | PhOx      | 4.5                           | 100     | CH <sub>3</sub> CN | 90               | 180   | 31                    | 5510                        | 1.21             |
| 5   | ProPhOx-1 | 1.0                           | 20      | CH <sub>3</sub> CN | 90               | 180   | 85                    | 2460                        | 1.14             |
| 6   | ProPhOx-2 | 1.0                           | 20      | CH <sub>3</sub> CN | 90               | 180   | –                     | –                           | –                |
| 7   | ProPhOx-3 | 1.0                           | 20      | CH <sub>3</sub> CN | 90               | 180   | –                     | –                           | –                |
| 8   | ProPhOx-2 | 1.0                           | 20      | CH <sub>3</sub> CN | 140 <sup>c</sup> | 20    | –                     | –                           | –                |
| 9   | ProPhOx-3 | 1.0                           | 20      | CH <sub>3</sub> CN | 140 <sup>c</sup> | 20    | 46                    | 5840                        | 1.42             |

<sup>a</sup> The structural characterization of polymers are given in Supporting Information.

<sup>b</sup> Isolated yield.

<sup>c</sup> Determined by SEC, PMMA calibration, DMF containing 0.05 M LiBr as the eluent.

<sup>d</sup> Under μW conditions.

## Conclusions

In summary, we have demonstrated that rare-earth metal triflates could be used as an efficient catalyst for the cationic ring-opening polymerization of 2-oxazolines under

mild conditions. As evidenced by linear first-order kinetics, the polymerization of 2-ethyl-2-oxazoline with Sc(OTf)<sub>3</sub> in acetonitrile proceeded in a living/controlled manner, which was also supported by unimodal molar mass distribution for the resultant polymers with PDI values below 1.15. *In situ* NMR spectroscopic studies in combination with SEC analysis of PEtOx samples obtained from the control termination experiments showed strong evidence that during the Sc(OTf)<sub>3</sub>-catalyzed polymerization every *in situ*-formed metallic active species consists of three identical onium sites and therefrom initiates simultaneously three equivalent propagating chains. Such a multi-site propagating mechanism seems to be consistent with the higher polymerization reaction rate observed in the Sc(OTf)<sub>3</sub>-catalysis. In comparison with other initiating systems, the rare-earth catalysis has the advantage of no requirement for microwave assistance, which would allow the whole polymerization process to be easily scaled up. We expect that the polyoxazolines bearing a chiral L-proline moiety in the side-chain synthesized herein will find potential applications in asymmetric catalysis, the related research is currently underway.

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### Notes and references

- 1 R. Hoogenboom, *Macromol. Chem. Phys.*, 2007, **208**, 18–25.
- 2 R. Hoogenboom, *Angew. Chem. Int. Ed.*, 2009, **48**, 7978–7994.

- 3 H. Schlaad, C. Diehl, A. Gress, M. Meyer, A. L. Demirel, Y. Nur and A. Bertin, *Macromol. Rapid Commun.*, 2010, **31**, 511–525.
- 4 R. Luxenhofer, Y. Han, A. Schulz, J. Tong, Z. He, A. V. Kabanov and R. Jordan, *Macromol. Rapid Commun.*, 2012, **33**, 1613–1631.
- 5 K. Aoi and M. Okada, *Prog. Polym. Sci.*, 1996, **21**, 151–208.
- 6 C. Giardi, V. Lapinte, C. Charnay and J. J. Robin, *React. Funct. Polym.*, 2009, **69**, 643–649.
- 7 R. Luxenhofer, M. Bezen and R. Jordan, *Macromol. Rapid Commun.*, 2008, **29**, 1509–1513.
- 8 F. Wiesbrock, R. Hoogenboom, C. H. Abeln and U. S. Schubert, *Macromol. Rapid Commun.*, 2004, **25**, 1895–1899.
- 9 F. Wiesbrock, R. Hoogenboom, M. A. M. Leenen, M. A. R. Meier and U. S. Schubert, *Macromolecules*, 2005, **38**, 5025–5034.
- 10 H. M. L. Lambermont-Thijs, H. P. C. v. Kuringen, J. P. W. v. d. Put, U. S. Schubert and R. Hoogenboom, *Polymers*, 2010, **2**, 188–199.
- 11 K. Kempe, S. Jacobs, H. M. L. Lambermont-Thijs, M. M. W. M. Fijten, R. Hoogenboom and U. S. Schubert, *Macromolecules*, 2010, **43**, 4098–4104.
- 12 M. M. Bloksma, U. S. Schubert and R. Hoogenboom, *Polym. Chem.* 2011, **2**, 203–208.
- 13 S. Cesana, J. Auernheimer, R. Jordan, H. Kessler and O. Nuyken, *Macromol. Chem. Phys.*, 2006, **207**, 183–192.

14. J.-S. Park, Y. Akiyama, F. M. Winnik and K. Kataoka, *Macromolecules*, 2004, **37**, 6786–6792.
15. M. Bortenschlager, N. Schöllhorn, A. Wittmann, R. Weberskirch and R. Weberskirch, *Chem. Eur. J.*, 2007, **13**, 520–528.
16. K. Kempe, S. L. Ng, K. F. Noi, M. Müllner, S. T. Gunawan and F. Caruso, *ACS Macro Lett.* 2013, **2**, 1069–1072.
17. C. Legros, M.-C. De Pauw-Gillet, K. C. Tam, S. Lecommandoux and D. Taton, *Polym. Chem.*, 2013, **4**, 4801–4808.
- 18 Y. Isobe, D. Fujioka, S. Habaue and Y. Okamoto, *J. Am. Chem. Soc.*, 2001, **123**, 7180–7181.
- 19 Y. Isobe, Y. Suito, S. Habaue and Y. Okamoto, *J. Polym. Sci. Part A: Polym. Chem.*, 2003, **41**, 1027–1033.
- 20 H. Baraki, S. Habaue and Y. Okamoto, *Macromolecules*, 2001, **34**, 4724–4729.
- 21 K. Morioka, Y. Suito, Y. Isobe, S. Habaue and Y. Okamoto, *J. Polym. Sci. Part A: Polym. Chem.*, 2003, **41**, 3354–3360.
- 22 W. Lu, L. P. Lou, F. Y. Hu, L. M. Jiang and Z. Q. Shen, *J. Polym. Sci. Part A: Polym. Chem.*, 2010, **48**, 5411–5418.
- 23 G.X. Liu, W. Lu, L. M. Jiang, W. L. Sun and Z. Q. Shen, *Acta Polym. Sinica.*, 2009, 775–780.
- 24 J. Ling, Z.Q. Shen and Q. H. Huang, *Macromolecules*, 2001, **34**, 7613–7616.
- 25 J. Ling, Y. F. Zhang and Z. Q. Shen, *Chin. Chem. Lett.*, 2001, **12**, 41–42.
- 26 L. X. You, T. E. Hogen-Esch, Y. H. Zhu, J. Ling and Z.Q. Shen, *Polymer*, 2012, **53**,

4112–4118.

27 H. Peng, J. Ling and Z. Q. Shen, *J. Polym. Sci. Part A: Polym. Chem.*, 2012, **50**, 1076–1085.

28 T. Kagiya, *J. Polym. Sci. Part B: Polym. Lett.*, 1966, **4**, 441–445.

29 S. Kobayashi and I. Hachiya, *J. Org. Chem.*, 1994, **59**, 3590–3596.

30 J. Lustoň, J. Kronek and F. Böhme, *J. Polym. Sci. Part A: Polym. Chem.*, 2006, **44**, 343–355.

31 K. Hioki, Y. Takechi, N. Kimura, H. Tanaka, and M. Kunishima, *Chem. Pharm. Bull.*, 2008, **56**, 1735–1737.

32 M. T. Leffler and R. Adams, *J. Am. Chem. Soc.*, 1937, **59**, 2252–2258.

33 M. M. Bloksma, S. Rogers, U. S. Schubert and R. Hoogenboom, *Soft Matter* 2010, **6**, 994–1003.

34 R. Hoogenboom, M. A. M. Leenen, F. Wiesbrock and U. S. Schubert, *Macromol. Rapid Commun.*, 2005, **26**, 1773–1778.

35 A. Baumgaertel, C. Weber, K. Knop, A. Crecelius, U. S. Schubert, *Rapid Commun. Mass Spectrom.*, 2009, **23**, 756–762.

36 Q. Liu, M. Konas and J. S. Riffle, *Macromolecules*, 1993, **26**, 5572–5576.

37 L. X. You, Z. Q. Shen, J. Kong and J. Ling, *Polymer*, 2014, **55**, 2404–1410.

Lewis acidic rare-earth metal triflates were found to efficiently initiate the cationic ring-opening polymerization of 2-oxazolines in a multi-site propagating fashion.

