Organocatalytic Stereoselective Ring-Opening Polymerization of Lactide with Dimeric Phosphazene Bases

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Supporting Information

Materials. L-Lactide (L-LA, 99%, Purac) and *rac*-lactide (*rac*-LA, 99%, Purac) were recrystallized three times from toluene and dried in vacuum prior to use. 1-Pyrenebutanol (PB, 99%, Aldrich) was dissolved in THF over CaH_2, filtered after an overnight stir, and collected by evaporation of the solvent. 1-*tert*-Butyl-2,2,4,4,4-pentakis(dimethylamino)-2Λ^5,4Λ^5-catenadi(phosphazene) THF solution (P_2-*t*-Bu, ~2.0 mole/L, Fluka), benzyl alcohol (BAol, 99.9%, J. T. Baker) and toluene-d8 ($C_6D_5CD_3$, D 99.6%, Aldrich) were stirred over CaH_2 overnight and filtered prior to use. Dry toluene solvent was obtained from Innovative Systems with drying columns. Chloroform-d ($CDCl_3$, D 99.8%, Cambridge Isotope Laboratories, Inc.), methanol (100.0%, J. T. Baker) and benzoic acid (99.5%, Aldrich) were used as received. Hydroxyl functional poly(styrene) (PS_{100}-OH, Mn=10000 g mol^{-1}, PDI = 1.08, polymerized using nitroxide mediated polymerization techniques[1-3] was dried by azeotropic distillation with toluene prior to use.

Instruments. One dimensional ^1H (400 MHz) and ^{13}C (75 MHz) nuclear magnetic resonance (NMR) spectra were recorded on Bruker Avance 400 or Avance 300

instruments using the deuterated solvent $CDCl_3$ or $C_6D_5CD_3$ as an internal standard. Gel permeation chromatography (GPC) was carried out with a Waters chromatograph calibrated with polystyrene standards (750 - 2 × 10^6 g mol^{-1}) using THF as solvent. A Waters 410 differential refractometer and a 996 photodiode array detector were installed for detection. Four 5 μm Waters columns (300 mm × 7.7 mm) with pore sizes of 10, 100, 1000, 10^5, and 10^6 Å were connected in series in the chromatograph. GPC using chloroform solvent was performed on a Waters Alliance 2695 Separations Module equipped with three Polymer Labs PLgel 5 m mixed-C columns (300 x 7.5 mm) in series, a Waters Model 2414 Refractive Index detector, a Waters Model 2996 Photodiode Array detector, a Wyatt Technology miniDAWN multi-angle light scattering (MALS) detector, and a Wyatt Technology ViscoStar viscometer. Waters Empower™ 2 Software was used to generate a conventional calibration curve based on low PDI polystyrene standards (162 – 6.04 x 10^6 g mol^{-1}) and subsequently evaluate molecular weight characteristics. Differential scanning calorimetry (DSC) was performed using a TA differential scanning calorimeter 1000 that was calibrated using high purity indium at a heating rate of 5 °C/min. Melting temperature were determined from the second scan at a heating rate of 5 °C/min following a slow cooling rate of 3 °C/min to remove the influence of thermal history. Matrix assisted laser desorption ionization time-of-flight mass spectrometry (MALDI TOF MS) data was collected using a Bruker Daltonics Autoflex II mass spectrometer. The instrument is equipped with a N_2 laser (λ=337 nm) with a pulse width of 3 ns, a 2 GHz acquisition digitizer, and a pulsed ion extraction (PIE) source operated using flexControl 2.4 software. *trans*-Indole-3-acrylic acid (IAA) was used as the matrix in all MALDI TOF MS measurements. IAA was dissolved in THF (anhydrous, inhibitor removed)

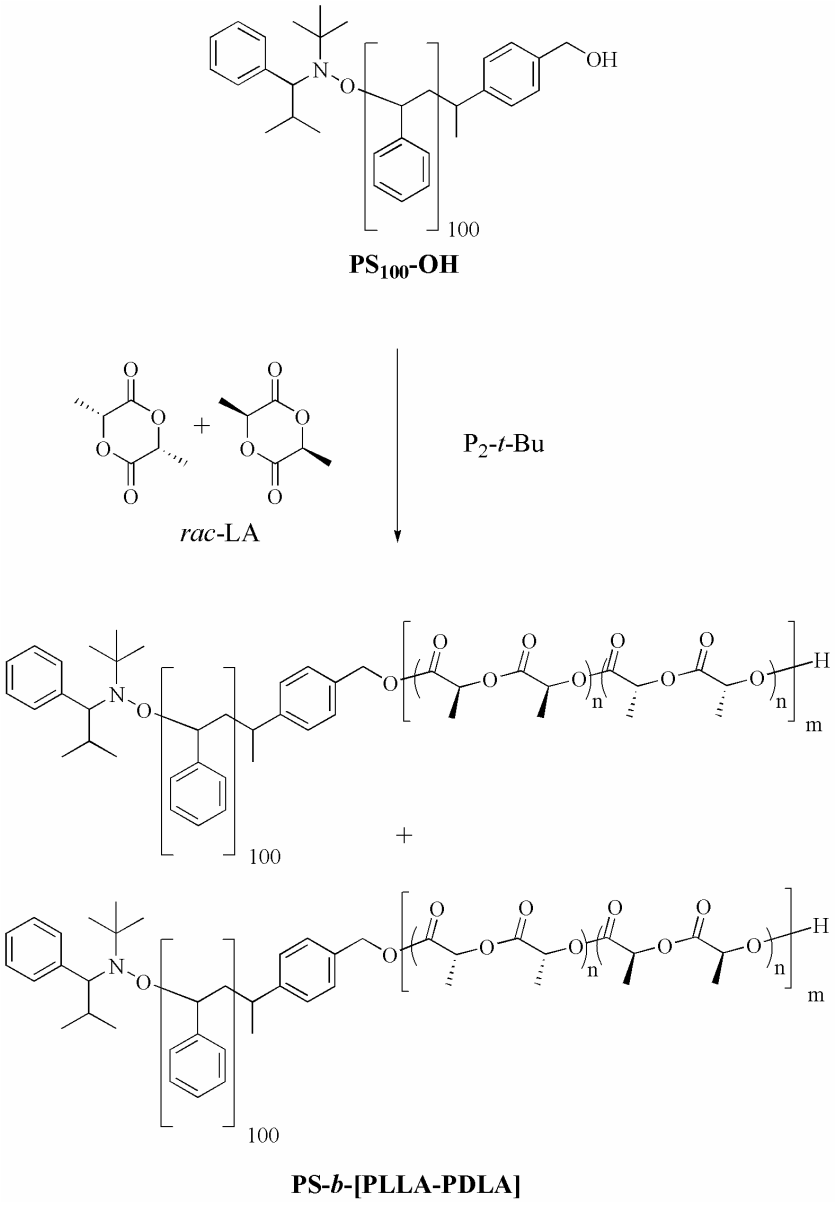
where [IAA] = 25 mg/mL. PLA samples were dissolved in anhydrous methylene chloride where [PLA] = 5.0 mg/mL. IAA and PLA solutions were mixed in a 2:1 v/v ratio and subsequently spotted onto a stainless steel target. All measurements were made in the positive linear mode and the mass scale was calibrated externally using peptide and protein standards.

Polymerization of L-LA using P_2-*t*-Bu as catalyst (Table 1, entry 1)**.** In a glove-box, L-LA (430 mg, 3.0 mmol) and 1-pyrenebutanol (8.2 mg, 0.03 mmol) were dissolved in toluene (7.5 g). A solution of P_2-*t*-Bu (11.0 mg, 0.03 mmol) in 0.5 g of toluene was added to initiate the polymerization. After continuously stirring at room temperature for 10 seconds, reaction was quenched by addition of benzoic acid. Thereafter, part of the solution was diluted with chloroform-d for NMR analysis to determine the conversion. The remaining solution was poured into a large excess of cool methanol to precipitate PLLA, which was then isolated by vacuum filtration. The obtained white solid was characterized by GPC (for molecular weight and polydispersity) and NMR (for degree of polymerization). ^{1}H NMR ($CDCl_3$): 8.28-7.83 (m, 9H, aromatic), 5.27-5.07 (m, C<u>H</u> PLLA backbone), 4.36(m, 1H, C<u>H</u>-OH), 4.21 (t, 2H, pyrene-$CH_2CH_2CH_2C\underline{H}_2OC(=O)$), 3.38 (t, 2H, pyrene-C<u>H_2</u>-), 1.70-1.40 (m, C<u>H_3</u> PLLA backbone, pyrene-$CH_2C\underline{H}_2C\underline{H}_2$). GPC (RI): Mn = 25800 g mol^{-1}, PDI = 1.23.

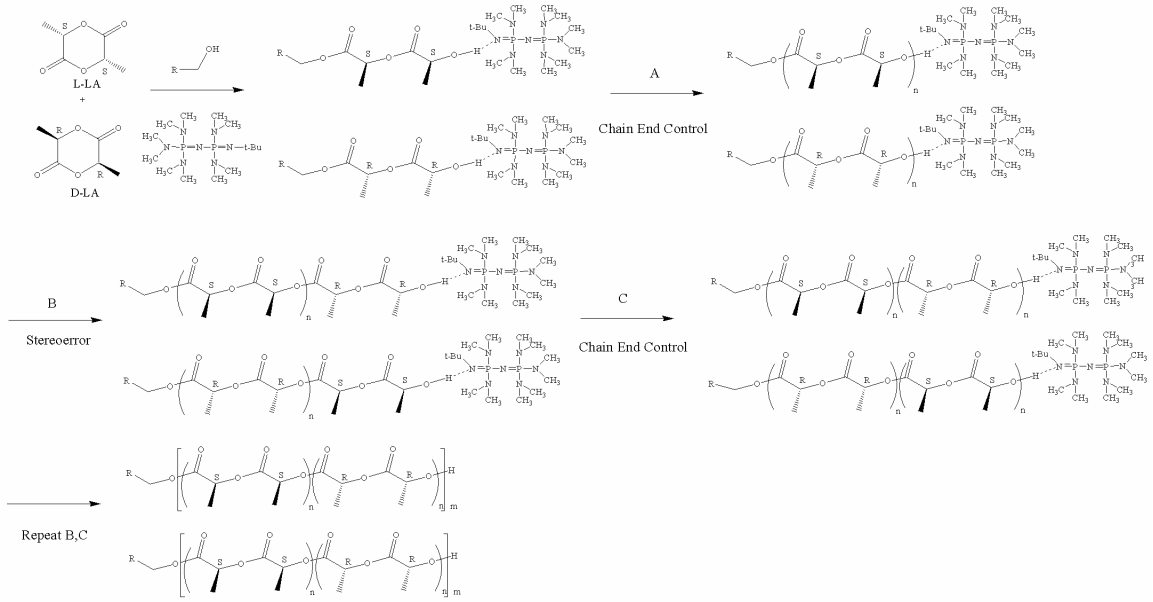
Polymerization of *rac*-LA using P_2-*t*-Bu as catalyst (Table 1, entry 4)**.** In a glove-box, *rac*-LA (108 mg, 0.75 mmol) and 1-pyrenebutanol (2.1 mg, 7.5 μmol) were dissolved in toluene (8 g) in a flask sealed with a rubber cap. The solution was then cooled to -75°C in

an acetone-dry ice cooling bath (some *rac*-LA was precipitated at low temperature). A solution of P_2-*t*-Bu (2.8 mg, 7.5 μmol) in 0.5 g of toluene was then added through a needle to initiate the polymerization. After continuously stirring at -75°C for 3 hours, benzoic acid was added to quench the reaction and the viscous solution was precipitated in cool methanol. ^{1}H NMR ($CDCl_3$): 8.28-7.82 (m, 9H, aromatic), 5.25-5.09 (m, C<u>H</u> Poly(*rac*-LA) backbone), 4.36(m, 1H, C<u>H</u>-OH), 4.21 (t, 2H, pyrene-$CH_2CH_2CH_2C\underline{H}_2OC(=O)$), 3.38 (t, 2H, pyrene-C<u>H</u>$_2$-), 1.78-1.38 (m, C<u>H</u>$_3$ Poly(*rac*-LA) backbone，pyrene-$CH_2C\underline{H}_2C\underline{H}_2$). GPC (RI): Mn = 27200 g mol^{-1}, PDI = 1.11.

Synthesis of poly(styrene)-block-poly(*rac*-lactide) stereoblock (Table 1, entry 5)**.** In a glove-box, *rac*-LA (108 mg, 0.75 mmol) and hydroxyl functional poly(styrene) (75mg, 7.5μmol, Mn=10000g mol^{-1}, PDI = 1.08) were dissolved in toluene (8 g) in a flask sealed with a rubber cap. The solution was then cooled to -75°C in an acetone-dry ice cooling bath (some *rac*-LA was precipitated at low temperature). A solution of P_2-*t*-Bu (2.8 mg, 7.5 μmol) in 0.5 g of toluene was then added through a needle to initiate the polymerization. After continuously stirring at -75°C for 3.6 hours, benzoic acid was added to quench the reaction and the viscous solution was precipitated in cool methanol. ^{1}H-NMR ($CDCl_3$): δ = 7.25-6.30 (m, 5H, Ar<u>H</u>$_{PS}$), 5.30-5.10 (m, H, C<u>H</u>$_{PLA}$), 4.40-4,30 (q, H, C<u>H</u>-OH), 2.40-1.20 (m, H: C<u>H</u> $_{PS}$, C<u>H</u>$_{2\ PS}$, C<u>H</u>$_{3\ PLA}$). GPC (RI): M_n = 30700 g mol^{-1}, PDI = 1.10.



Scheme S1. Chain extension of PDMA-OH with *rac*-LA using P_2-*t*-Bu catalyst to prepare PS-*block*-PLA stereoblock.



Scheme S2. Postulated mechanism for the stereoselective ROP of *rac*-LA with P_2-*t*-Bu catalyst.

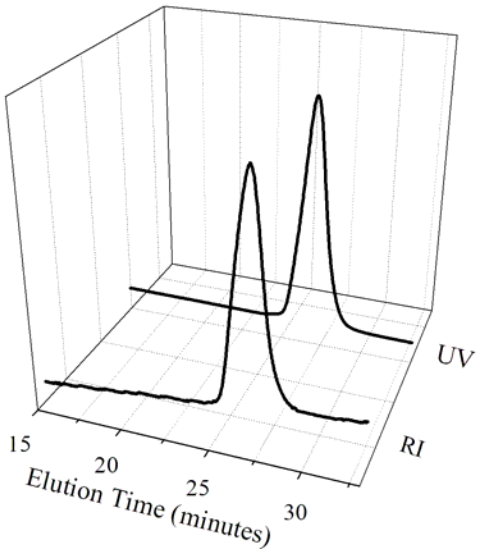


Figure S1. GPC traces simultaneously collected by refractive index (RI) and UV detectors (at 254 nm) show the complete incorporation of UV-active 1-pyrenebutanol initiator into the polymer chain (Table 1, entry 1), demonstrating the high end-group fidelity.

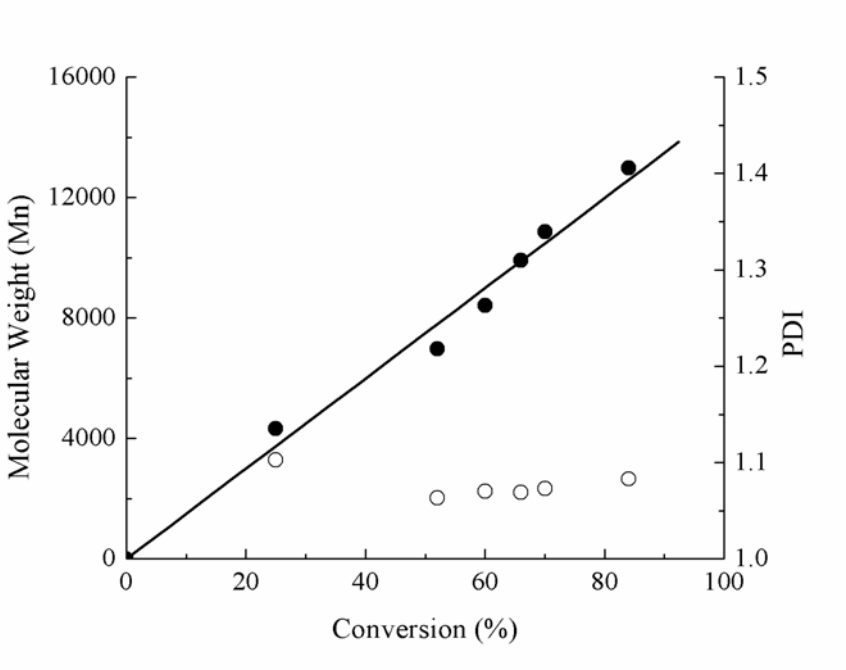


Figure S2. Evolution of molecular weight, Mn, and polydispersity with percent conversion for the polymerization of L-lactide in the presence of P_2-*t*-Bu. The reactions were carried out with an initial monomer concentration of 0.08 mol/L and a monomer to initiator to catalyst molar ratio of 100:1:1 at room temperature. The reaction times were 0.2, 0.5, 0.83, 1, 2, and 25 min, respectively.

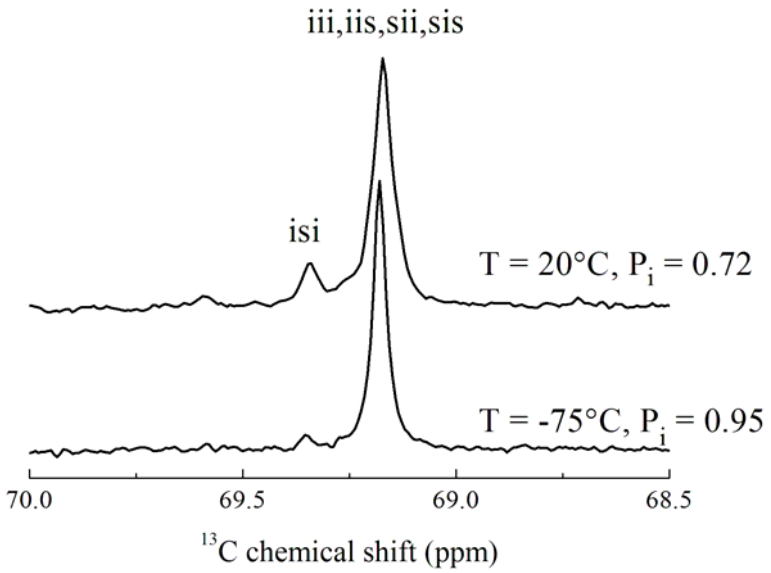


Figure S3. ^{13}C NMR spectra (75 MHz, $CDCl_3$) of the methine region of PRLAs prepared using P_2-*t*-Bu catalyst at 20 °C (Table 1, entry 3) and -75 °C (Table 1, entry 4).

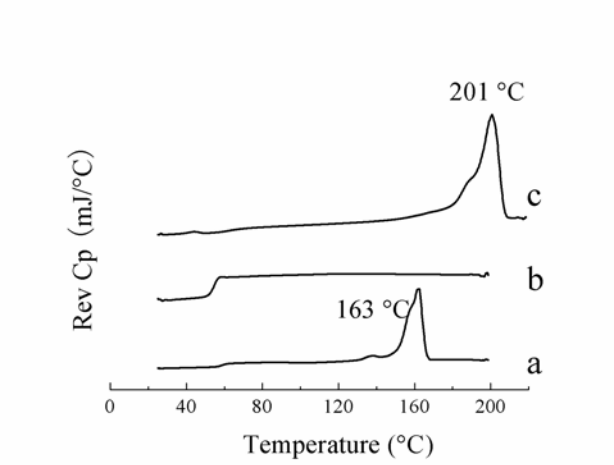


Figure S4. Thermal analysis (heating rate of 5 °C/min, 2nd scan) of a) PLLA (Table 1, entry 1), b) PRLA prepared at 20 °C (Table 1, entry 3), and c) PRLA prepared at -75 °C (Table 1, entry 4).

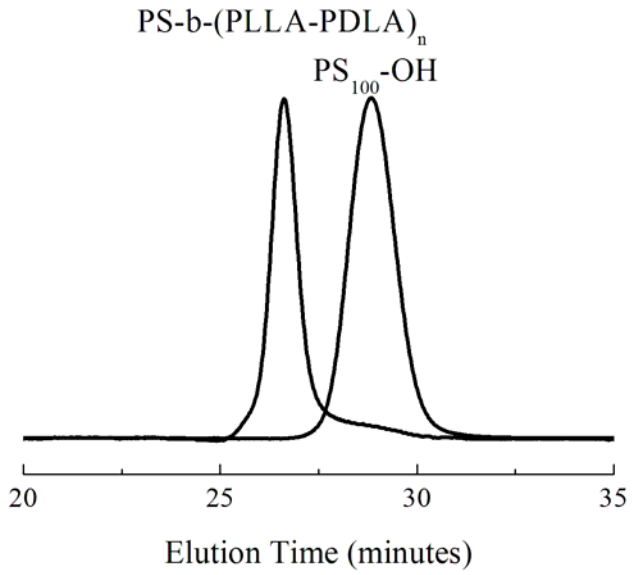


Figure S5. GPC traces showing the chain extension of polystyrene macroinitiator (PS_{100}-OH) with *rac*-LA using P_2-*t*-Bu catalyst at 75 °C to produce polystyrene-*block*-polylactide stereoblock (Table 1, entry 5).

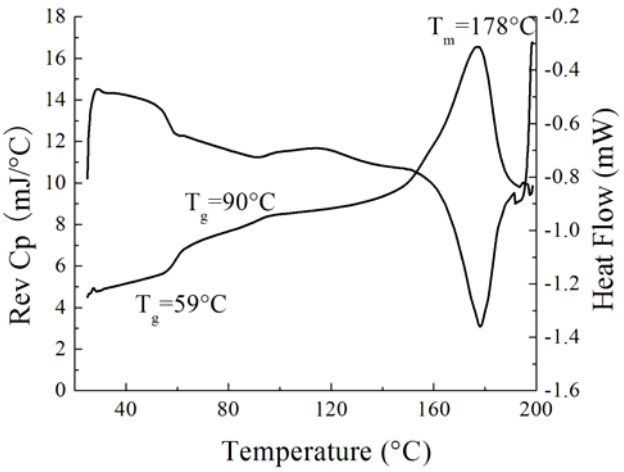


Figure S6. Thermal analysis (heating rate of 5 °C/min, 2nd scan) of the polystyrene-*block*-polylactide stereoblock (Table 1, entry 5).

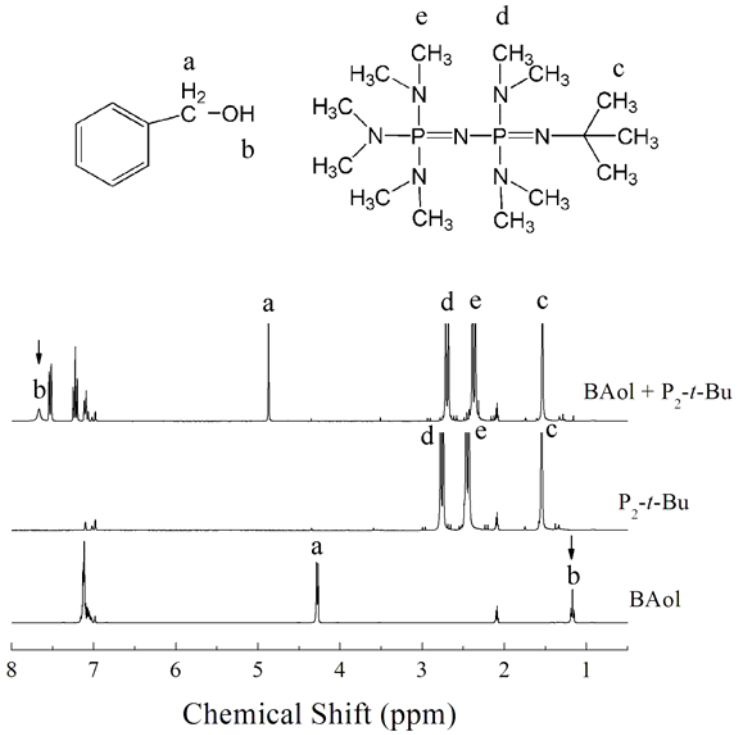


Figure S7. ^{1}H NMR spectra (toluene-d8) of 1: BAol, 2: P_2-*t*-Bu, and 3: BAol with P_2-*t*-Bu.

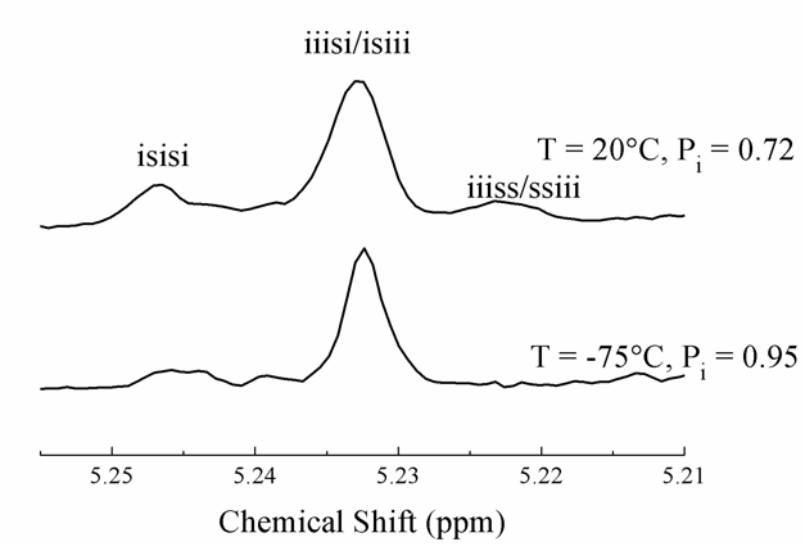


Figure S8. Homonuclear decoupled ^{1}H NMR spectra (400 MHz, $CDCl_3$) of the methine region of PRLAs prepared using P_2-*t*-Bu catalyst at 20 °C (Table 1, entry 3) and -75 °C (Table 1, entry 4).

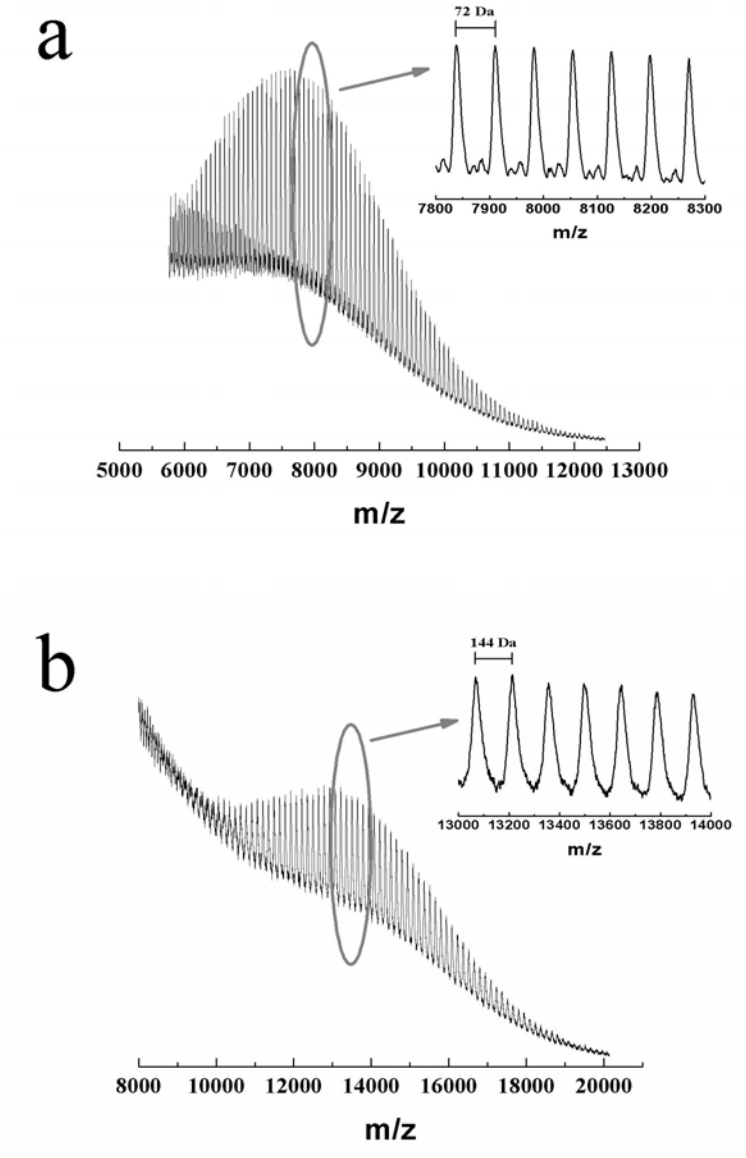


Figure S9. MALDI TOF mass spectra of a) PRLA prepared at 20 °C (Table 1, entry 3), and b) PRLA prepared at -75 °C (Table 1, entry 4). For PRLA prepared at 20 °C, the repeating unit is 72 Da (half lactide repeat unit), which suggests severe transesterification reaction happens during the ROP of *rac*-lactide. However, for poly(*rac*-LA)s prepared at -75 °C, only peaks corresponding to lactide repeat units (144 Da) are present, which suggests the complete depression of transesterification reaction at -75 °C.

References

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(3) Hawker, C. J.; Hedrick, J. L.; Malmstrom, E. E.; Trollsas, M.; Mecerreyes, D.; Moineau, G.; Dubois, P.; Jerome, R. *Macromolecules* **1998**, *31*, 213