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Ru-Catalyzed Isomerization Provides Access to Alternating Copolymers via Ring-Opening Metathesis Polymerization

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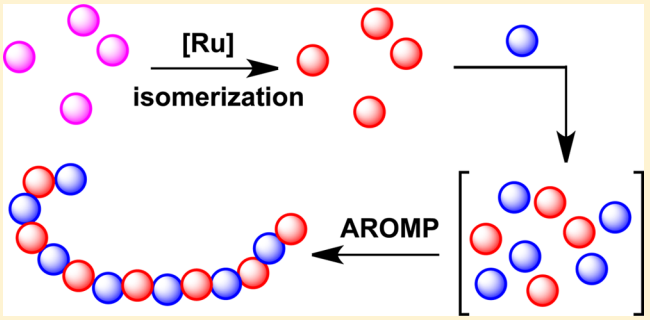
Supporting Information

ABSTRACT: We describe an isomerization–alternating ROMP protocol that gives linear copolymers with rigorous sequence alternation. Bicyclo[4.2.0]oct-7-ene-7-carboxamides of primary amines are isomerized in the presence of (3-BrPyr)$_2$Cl$_2$(H$_2$IMes)Ru=CHPh to the corresponding bicyclo[4.2.0]oct-1(8)-ene-8-carboxamides in which the olefinic bond is tetrasubstituted. The *isomerized* amides undergo alternating ring-opening metathesis polymerization with cyclohexene to provide soluble and linear copolymers with molecular weights up to ~130 kDa. This process provides efficient entry to strictly alternating copolymers that can display diverse functional groups.



Sequence-controlled polymers have the potential to provide high-density information storage.[1] In addition, they offer control of folding and macroscopic properties such as conductivity or rigidity.[2−4] Currently, polymer sequence is best controlled by utilizing nature's machines, which are themselves composed of sequence-controlled polymers. Although nature's approach can be coopted to introduce non-natural monomers, it is limited to biopolymer-type backbones.[5]

Chemists have sought ways to prepare more diverse polymer structures. Iterative chain extension is the most advanced method for controlling monomer sequence in a synthetic polymer,[6] but lengths become limited by reaction yields and repeated purification steps.

For alternating polymers, chain-growth or step-growth polymerizations could bypass these shortcomings. Step-growth approaches necessarily afford alternation, but chain-growth methods require a mechanism that regulates the alternation. This requirement is satisfied by methods that rely on radical intermediates[7] or on metal-mediated polymerizations in which one of the monomers is carbon monoxide or carbon dioxide.[8−10] However, both of these classes of reactions are limited with respect to the introduction of side-chain functionality, the former because many functional groups react with radicals and the latter because, by definition, one of the monomers has no side chain.

The "living" ring-opening metathesis polymerization (ROMP) has great potential for control of alternating sequence and of molecular weights[11−23] and can be catalyzed by functional group tolerant ruthenium complexes.[24−26] However, there are few examples of high accuracy and/or efficient monomer incorporation. Furthermore, molecular weight measurements require that the polymer products be soluble.

Cyclobutene-1-carboxylic acid derivatives exhibit selective reactivities in ruthenium-catalyzed ring-opening metathesis.[22,27,28] For example, the ROMP of the secondary amides of cyclobutene-1-carboxylic acid provides regioregular polymers that contain *E*-olefins and that have low molar mass dispersities.[27,28]

Although neither a cyclobutenecarboxylic acid ester nor a cyclohexene undergoes ROMP on its own, the two copolymerize to produce precisely alternating copolymers.[22] This iterative process, initiated when the benzylidene Ru carbene undergoes ROM with the cyclobutene ester and enabled when the resulting enoic Ru carbene undergoes ROM with cyclohexene, provides a perfectly alternating copolymer in a single reaction. We named this process AROMP, for alternating ring-opening metathesis polymerization.

The strict alternation obtained in cyclobutenecarboxylic acid ester/cyclohexene AROMP suggests interesting applications.[29,30] However, because the lengths of the resulting linear polymers have been limited by intramolecular cross-metathesis (backbiting) reactions,[22,31] we designed bicyclic olefinic esters as AROMP substrates.[32] We found that methyl bicyclo[4.2.0]-oct-7-ene-7-carboxylic ester and cyclohexene provide linear, alternating copolymers without competing inter- or intramolecular cross-metathesis reactions, although their length was limited by slow propagation.

Recognizing the interesting architecture of polymers that have rings fused to their backbones, we tested the corresponding bicyclo[4.2.0]oct-7-ene-7-carboxamides **1a–f** in ROMP reactions with the Grubbs III catalyst **2** (Scheme 1). To

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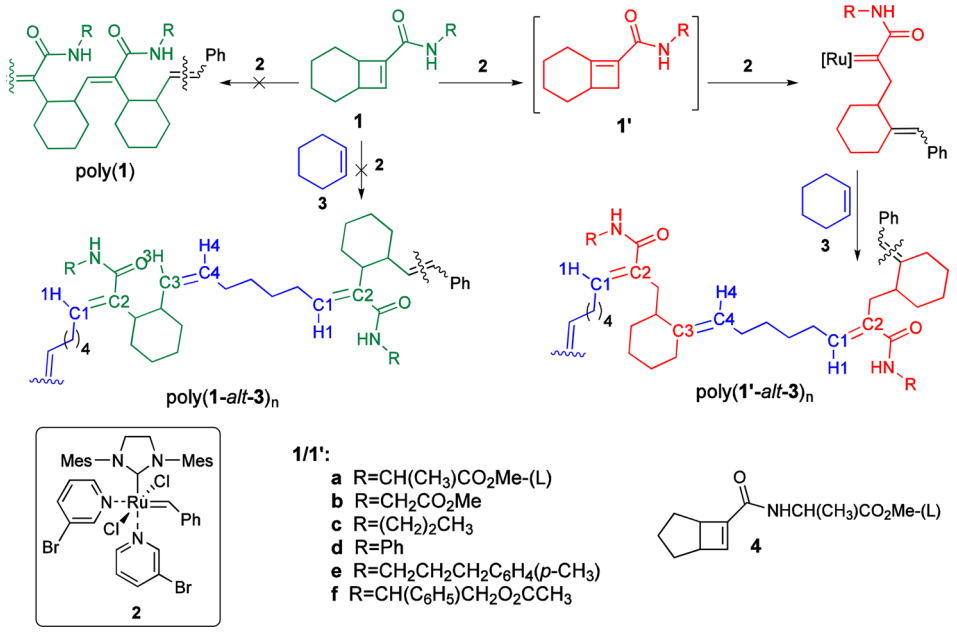
Scheme 1. Synthesis of Alternating Copolymers with Bicyclo[4.2.0]oct-7-ene-7-carboxamides 1 and Cyclohexene 3



our surprise, under ROMP conditions, each of the amides **1** isomerized to the bicyclo[4.2.0]oct-1(8)-ene-8-carboxamide **1′**. None of the amides showed evidence of homopolymerization in the presence of catalyst **2**. Notably, addition of cyclohexene **3** to isomerized amides **1′** in the presence of catalyst **2** provided a reaction manifold for the isomerized amides that led to linear, alternating copolymers, poly(**1′**-*alt*-**3**)$_n$, of extensive length. Herein, we describe the AROMP of the isomerized monomers bearing functional groups, which provides long, soluble, and perfectly alternating copolymers.

EXPERIMENTAL METHODS

All metathesis reactions were performed under an N_2 atmosphere. Solvents, e.g. CH_2Cl_2 and THF, were purified with Pure Process Technology (PPT). Deuterated solvents for all ring-opening reactions were degassed and filtered through basic alumina before use. Catalyst $Cl_2(H_2IMes)(PCy_3)Ru{=}CHPh$ and poly(styrene) standards were purchased from Aldrich. Cyclohexene-D_{10} was purchased from CDN Isotope Inc. The synthesis of catalyst $(3\text{-Br-Pyr})_2Cl_2(H_2IMes)Ru{=}CHPh$, **2**, was performed according to the procedure of Love et al.[33] Experimental procedures for the preparation of amides **1** and **4** are in the Supporting Information.

Mallinckrodt silica gel 60 (230−400 mesh) was used for column chromatography. Analytical thin layer chromatography (TLC) was performed on precoated silica gel plates ($60F_{254}$), flash chromatography on silica gel-60 (230−400 mesh), and Combi-Flash chromatography on RediSep normal phase silica columns (silica gel-60, 230−400 mesh). Bruker Nanobay 400, Avance III 500, and Avance III 700 NMR instruments were used for analysis. Chemical shifts were calibrated from residual undeuterated solvents; they are denoted in ppm (δ). Molecular weights and molar mass dispersities except poly(**1c′**-*alt*-**3**)$_{420}$ and poly(**1b′**-*alt*-**3**)$_{260}$ were measured on a Phenogel 5 μm MXL LC column (300 × 7.8 mm, 100 kDa exclusion limit, Phenomenex) with a chromatography system constructed from a Shimadzu pump coupled to a Shimadzu UV detector. Methylene chloride served as the eluent with a flow rate of 0.700 mL/min. Molecular weights and molar mass dispersities of poly(**1c′**-*alt*-**3**)$_{420}$ and poly(**1b′**-*alt*-**3**)$_{260}$ were measured on a Phenogel 5 μm 10E4A LC column (300 × 7.8 mm, 500 kDa exclusion limit, Phenomenex) on the same chromatography system. THF served as the eluent with a flow rate of 1.00 mL/min. Both GPCs were calibrated with poly(styrene) standards at 30 °C.

General Procedure for NMR Scale Isomerization Reactions. Under an N_2 atmosphere, a solution of the original amide and catalyst **2** was prepared in the indicated solvent (600 μL) in an NMR tube, and NMR spectra were acquired at 35 °C. At the end of the isomerization reaction (after complete consumption or no further isomerization of amide as judged by the change of the olefinic proton resonance), each reaction was terminated with ethyl vinyl ether (100 μL) and stirred for 30 min. The solvent was evaporated, and the resulting residue was purified by silica chromatography to isolate the isomerized amide.

*i-[4.2.0] Amide **1a′***. Amide **1a** (28 mg, 120 μmol, 20 equiv) and catalyst **2** (5.3 mg, 6 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube for 16 h; during this time, the integral for the olefinic proton decreased to 10% of its original value. The mixture was concentrated, and the product was isolated by chromatography (100:1/CH_2Cl_2:MeOH) to yield 24 mg (80%) of **1a′**. ^{1}H NMR (500 MHz, $CDCl_3$): δ 5.99 (s, 1H, CONH), 4.68 (m, 1H, CH), 3.78 (s, 3H, OCH_3), 2.88 (dd, J = 12.2, 6.7 Hz, 1H, CH_2), 2.73 (ddd, J = 15.4, 7.6, 3.9 Hz, 1H, CH_2), 2.38 (m, 1H, CH), 2.24 (m, 1H, CH_2), 2.10 (m, 2H, CH_2), 1.94 (m, 1H, CH_2), 1.75 (m, 1H, CH_2), 1.45 (dt, J = 18.6, 9.3 Hz, 3H, CH_3), 1.34 (m, 2H, CH_2), 1.16 (m, 1H, CH_2).

*i-[4.2.0] Amide **1b′***. Amide **1b** (67 mg, 300 μmol, 50 equiv) and catalyst **2** (5.3 mg, 6 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube for 8 h. The mixture was concentrated, and the product was isolated by chromatography (100:1/CH_2Cl_2:MeOH) to yield 49 mg (75%) of **1b′**. ^{1}H NMR (500 MHz, $CDCl_3$): δ 5.98 (s, 1H, CONH), 4.11 (d, J = 5.3 Hz, 2H, side chain CH_2), 3.78 (s, 3H, OCH_3), 2.87 (dd, J = 13.4, 2.7 Hz, 1H, CH_2), 2.75 (dt, J = 12.0, 3.8 Hz, 1H, CH_2), 2.37 (m, 1H, CH), 2.23 (m, 1H, CH_2), 2.10 (m, 2H, CH_2), 1.93 (m, 1H, CH_2), 1.75 (m, 1H, CH_2), 1.34 (m, 2H, CH_2), 1.12 (m, 1H, CH_2).

*i-[4.2.0] Amide **1c′***. Amide **1c** (58 mg, 300 μmol, 50 equiv) and catalyst **2** (5.3 mg, 6 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube for 1.5 h, when isomerization was complete. The mixture was concentrated, and the product was isolated by chromatography (100:1/CH_2Cl_2:MeOH) to yield 49 mg (85%) of **1c′**. ^{1}H NMR (500 MHz, $CDCl_3$): δ 5.50 (s, 1H, CONH), 3.21 (m, 2H, side chain CH_2), 2.81 (dd, J = 13.4, 2.7 Hz, 1 Hz, CH_2), 2.65 (dt, J = 12.0, 3.8 Hz, 1H, CH_2), 2.31 (m, 1H, CH), 2.15 (m, 1H, CH_2), 2.04 (m, 2H, CH_2), 1.89 (m, 1H, CH_2), 1.69 (m, 2H, side chain CH_2), 1.51 (m, 2H, CH_2), 1.27 (m, 2H, CH_2), 0.91(t, J = 7.5 Hz, 3H, CH_3). ^{13}C NMR (126 MHz, CD_2Cl_2): δ 164.1 (CONH), 161.7 (=C), 126.7 (=CCONH), 40.4 (side chain CH_2), 37.6 (CH), 33.9 (CH_2), 32.8 (CH_2), 27.1 (CH_2), 26.6 (CH_2), 24.5 (CH_2), 22.9 (side chain CH_2),

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11.3 (CH_3). HRMS (ESI) calcd for $C_{12}H_{19}NO$ $[M + H]^+$ 194.1539; found 194.1535. $\lambda_{max.}$ 224 nm was consistent with the $\lambda_{max.}$ 223 nm previously reported for bicyclo[4,2,0]oct-1(8)-ene-8-carboxyamide.[34]

*i-[4.2.0] Amide **1c**′ with MeOH.* A 0.01 M fresh solution of catalyst **2** in 600 μL of CD_2Cl_2 was divided into two NMR tubes, a 50 μL aliquot of MeOH (in large excess relative to catalyst **2**) was added to one tube, and a 50 μL aliquot of CD_2Cl_2 was added to the second tube; both tubes were stirred for 2 h. Monomer **1c** (10 equiv in 250 μL of CD_2Cl_2) was added to each tube, and the kinetics of isomerization were monitored by ^{1}H NMR spectroscopy.

*i-[4.2.0] Amide **1d**′.* Amide **1d** (23 mg, 120 μmol) and catalyst **2** (5.3 mg, 6 μmol) were mixed in CD_2Cl_2 in an NMR tube; after 20 min, isomerization was complete. The mixture was concentrated, and the product was isolated by chromatography (100:1/CH_2Cl_2:MeOH) to yield 17.5 mg (78%) of **1d**′. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.61 (d, *J* = 7.8 Hz, 2H, Ph), 7.37 (t, *J* = 7.6 Hz, 2H, Ph), 7.20 (s, 1H, CONH), 7.13 (t, *J* = 7.4 Hz, 1H, Ph), 2.98 (dd, *J* = 13.4, 2.7 Hz, 1 Hz, CH_2), 2.84 (dt, *J* = 12.0, 3.8 Hz, 1H, CH_2), 2.49 (m, 1H, CH_2), 2.35 (m, 1H, CH_2), 2.20 (m, 2H, CH_2), 2.00 (m, 1H, CH_2), 1.81 (m, 1H, CH_2), 1.44 (m, 2H, CH_2), 1.21 (m, 1H, CH_2).

*i-[4.2.0] Amide **1e**′.* Amide **1e** (68 mg, 300 μmol, 50 equiv) and catalyst **2** (5.3 mg, 6 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube for 6 h when isomerization was complete. ^{1}H NMR of the crude product **1e**′ (600 MHz, CD_2Cl_2): δ 7.20−7.02 (m, 4H, Ph), 5.64 (s, 1H, CONH), 3.3 (m, 2H, side chain CH_2), 2.85 (m, 1H, CH_2), 2.63 (m, 3H, ring CH_2 and side chain CH_2), 2.33 (m, 4H, ring CH and side chain CH_2), 2.13 (m, 2H, side chain CH_2), 2.03 (m, 1H, CH_2), 1.93 (m, 1H, CH_2), 1.84 (m, 2H, CH_2), 1.76 (m, 1H, CH_2), 1.32 (m, 2H, CH_2), 1.11 (m, 1H, CH_2).

*i-[4.2.0] Amide **1e**′ Monitored with ^{13}C NMR Spectroscopy.* Amide **1e** (19.2 mg, 67 μmol, 1 equiv) and catalyst **2** (60 mg, 67 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube, and the reaction was monitored with ^{13}C NMR spectroscopy at 35 °C.

*i-[4.2.0] Amide **1e**′ with 3-Bromopyridine.* A 0.01 M solution of catalyst **2** in CD_2Cl_2 was divided into two NMR tubes; 3-bromopyridine (50 equiv) was added to one tube. Monomer **1e** (10 equiv) was added to both aliquots ($[\mathbf{2}]_{final}$ = 0.005 M), and the extent of isomerization was evaluated by ^{1}H NMR spectroscopy over 14 h.

*i-[4.2.0] Amide **1e**′ with $Cl_2(H_2IMes)(PCy_3)Ru{=}CHPh$.* A 0.1 M solution of monomer **1e** was divided into two NMR tubes. Catalyst $Cl_2(H_2IMes)(PCy_3)Ru{=}CHPh$ in CD_2Cl_2 was added to one tube ($[\text{catalyst}]_{final}$ = 0.01 M, $[\mathbf{1e}']_{final}$ = 0.05 M), and **2** in CD_2Cl_2 was added to the second tube ($[\mathbf{2}]_{final}$ = 0.01 M). The kinetics of isomerization were monitored by ^{1}H NMR spectroscopy.

*i-[4.2.0] Amide **1e**′ with 1,4-Benzoquinone.* A 0.01 M solution of catalyst **2** in CD_2Cl_2 was divided into two NMR tubes; 1,4-benzoquinone (5 equiv relative to **2**) was added to one tube. Monomer **1e** (10 equiv) was added to both tubes ($[\mathbf{2}]_{final}$ = 0.005 M), and the extent of isomerization was evaluated by ^{1}H NMR spectroscopy over 14 h.

*i-[4.2.0] Amide **1f**′.* Amide **1f** or **1f*** (16 mg, 60 μmol, 10 equiv) and catalyst **2** (5.3 mg, 6 μmol, 1 equiv) were mixed in $CDCl_3$ in an NMR tube for 24 h, at which point the integral for the olefinic proton had decreased to 30% or 10% of its original value, respectively. Partial ^{1}H NMR spectroscopy of the crude **1f**′ (600 MHz, CD_2Cl_2): δ 6.69 (s, 0.1H, =CH), 6.31 (m, 0.1H, CONH), 6.09 (d, *J* = 6.9 Hz, 0.9H, CONH). Partial ^{1}H NMR of the crude **1f***′ (600 MHz, CD_2Cl_2): δ 6.71 (s, 0.2H, =CH), 6.36−6.26 (m, 0.3H, CONH), 6.11 (d, *J* = 6.9 Hz, 0.7H, CONH). (Partial ^{1}H NMR spectroscopic data are reported due to incomplete isomerization and significant upfield overlap of **1f**/**1f*** with the new peaks from **1f**′/**1f***′.)

*Attempted Isomerization of Amide **4**.* Amide **4** (27 mg, 120 μmol, 20 equiv) and catalyst **2** (5.3 mg, 6 μmol) were mixed in CD_2Cl_2 in an NMR tube for 18 h. Only a 2% decrease in the intensity of the olefinic resonance of amide **4** was observed.

General Procedure for NMR Scale AROMP Reactions. All reactivity experiments were performed at least twice, and preparative polymerization experiments were performed three times. Under an N_2 atmosphere, a solution of amide **1** in CD_2Cl_2 (300 μL) was added to the NMR tube. Then 300 μL of catalyst **2** solution was added to the NMR tube. After complete mixing of the solution, NMR spectra were acquired at 35 °C. Cyclohexene **3** was added after the amide was completely converted to its tetrasubstituted isomer as judged by the disappearance of the olefinic proton resonance around 6.7 ppm. This procedure was used for the preparation of polymers with up to 50 **AB** repeats. To ensure narrow dispersities, in the preparation of longer alternating polymers, the isomer **1**′ was isolated and mixed with fresh catalyst **2** in CD_2Cl_2 or $CDCl_3$. Cyclohexene **3** was added after catalyst **2** completely initiated as determined by the disappearance of the Ru alkylidene resonance at 19.1 ppm in the ^{1}H NMR spectrum. When the propagation stopped or the isomerized amide disappeared as judged by a complete upfield shift of the amide N−H resonance from ∼5.4 to ∼6 ppm, the reaction was quenched with ethyl vinyl ether and stirred for 30 min. The solvent was evaporated, and alternating copolymer was purified by step chromatography (100% CH_2Cl_2 to remove contaminants, then 20:1/CH_2Cl_2:MeOH to elute copolymer). The theoretical M_n^{theor} was calculated from the monomer:catalyst feed ratio.

*Poly(**1a**′-alt-**3**)$_{50}$.* Amide **1a**′ (14.2 mg, 60 μmol, 50 equiv), catalyst **2** (1.1 mg, 1.20 μmol, 1 equiv), and **3** (9.8 mg, 120 μmol, 100 equiv) were mixed in $CDCl_3$ in an NMR tube. After 2 h, amide **1a**′ was completely consumed. Flash column chromatography of the crude product yielded poly(**1a**′-*alt*-**3**)$_{50}$ (14.9 mg, 78% yield). ^{1}H NMR (700 MHz, $CDCl_3$): δ 7.45−7.27 (m, 5H, Ph), 6.45−6.08 (m, 77H, =CH and CONH), 5.08 (m, 45H, =CH), 4.63 (m, 45H, CH), 3.77 (m, 142H, CH_3), 2.55 (m, 45H), 2.41 (m, 45H), 2.16−1.95 (m, 320H), 1.64−1.50 (m, 157H), 1.43−1.28 (m, 530H). M_n^{theor} = 15 800. M_n^{GPC} = 12 500. M_w^{GPC} = 15 100. $Đ_M$ = 1.2.

*Poly(**1a**′-alt-**3**)$_{100}$.* Amide **1a**′ (28.5 mg, 120 μmol, 100 equiv), catalyst **2** (1.1 mg, 1.20 μmol, 1 equiv), and **3** (19.6 mg, 240 μmol, 200 equiv) were mixed in $CDCl_3$ in an NMR tube. After 6 h, amide **1a**′ was completely consumed. Flash column chromatography of the crude product yielded poly(**1a**′-*alt*-**3**)$_{100}$ (26.8 mg, 70% yield). ^{1}H NMR (700 MHz, CD_2Cl_2): δ 7.45−7.27 (m, 5H, Ph), 6.50−6.10 (m, 188H, =CH and CONH), 5.08 (m, 105H, =CH), 4.63 (m, 98H, CH), 3.77 (m, 296H, CH_3), 2.55 (m, 104H), 2.38 (m, 105H), 2.16−1.95 (m, 730H), 1.64−1.28 (m, 1560H). ^{13}C NMR (126 MHz, CD_2Cl_2): δ 173.6, 169.2, 141.6, 136.0, 135.8, 120.8, 52.2, 48.1, 43.7, 43.5, 33.1, 30.0, 28.8, 28.4, 28.1, 26.9, 26.5, 23.6, 18.2. M_n^{theor} = 31 900. M_n^{GPC} = 29 100. M_w^{GPC} = 30 700. $Đ_M$ = 1.1.

*Poly(**1b**′-alt-**3**)$_{140}$.* Amide **1b**′ (40.2 mg, 180 μmol, 150 equiv), catalyst **2** (1.1 mg, 1.20 μmol, 1 equiv), and **3** (29.4 mg, 360 μmol, 300 equiv) were mixed in $CDCl_3$ in an NMR tube. After 2.5 h, amide **1b**′ was completely consumed. Flash column chromatography of the crude product yielded poly(**1b**′-*alt*-**3**)$_{140}$ (34.0 mg, 62% yield). ^{1}H NMR (700 MHz, CD_2Cl_2): δ 7.45−7.27 (m, 5H, Ph), 6.64−6.42 (m, 133H, CONH), 6.27 (m, 141H, =CH), 5.10 (m, 146H, =CH), 4.02 (m, 370H, CH_2), 3.76 (m, 420H, CH_3), 2.58 (m, 160H), 2.41 (m, 118H), 2.23−2.01 (m, 1020H), 1.64−1.57 (m, 334H), 1.44−1.30 (m, 1288H). M_n^{theor} = 45 700. M_n^{GPC} = 34 000. M_w^{GPC} = 40 300. $Đ_M$ = 1.2.

*Poly(**1b**′-alt-**3**)$_{260}$.* Amide **1b**′ (40.2 mg, 180 μmol, 300 equiv), catalyst **2** (0.55 mg, 0.60 μmol, 1 equiv), and **3** (29.4 mg, 360 μmol, 600 equiv) were mixed in $CDCl_3$ in an NMR tube. After 3.5 h, 90% of amide **1b**′ was consumed. Flash column chromatography of the crude product yielded poly(**1b**′-*alt*-**3**)$_{260}$ (27.5 mg, 52% yield). ^{1}H NMR (700 MHz, CD_2Cl_2): δ 7.45−7.27 (m, 5H, Ph), 6.63−6.41 (m, 242H, CONH), 6.27 (m, 256H, =CH), 5.10 (m, 267H, =CH), 4.02 (m, 510H, CH_2), 3.76 (m, 769H, CH_3), 2.58 (m, 284H), 2.41 (m, 206H), 2.23−2.01 (m, 2036H), 1.68−1.57 (m, 633H), 1.44−1.30 (m, 2358H). ^{13}C NMR (126 MHz, CD_2Cl_2): δ 170.6, 169.7, 141.6, 136.3, 135.7, 121.0, 60.1, 52.1, 43.4, 41.2, 33.3, 30.0, 28.7, 28.3, 27.9, 26.8, 24.0, 20.6, 14.2. M_n^{theor} = 91 000. M_n^{GPC} = 69 600. M_w^{GPC} = 80 900. $Đ_M$ = 1.2.

*Poly(**1c**′-alt-**3**)$_{10}$.* Amide **1c** (11.6 mg, 60 μmol, 10 equiv) and catalyst **2** (5.3 mg, 6 μmol, 1 equiv) were mixed. Upon completion of isomerization, **3** (9.8 mg, 120 μmol, 20 equiv) was added, and after 1.5 h, amide **1c**′ was completely consumed. Flash column chromatography of the crude product yielded poly(**1c**′-*alt*-**3**)$_{10}$ (12 mg, 72% yield). ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.45−7.21 (m, 5H, Ph), 6.40−5.57 (m,

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20H, =CH and CONH), 5.09 (m, 10H, =CH), 3.31−3.16 (m, 26H, CH_2), 2.68−1.09 (m, 342H), 0.95 (t, J = 7.4 Hz, 38H, CH_3).

*Poly(**1c**′-alt-**3**)$_{50}$*. Amide **1c** (11.6 mg, 60 μmol, 50 equiv) and catalyst **2** (1.1 mg, 1.20 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube. Upon completion of isomerization, **3** (9.8 mg, 120 μmol, 100 equiv) was added, and after 2 h, amide **1c**′ was completely consumed. Flash column chromatography of the crude product yielded poly(**1c**′-*alt*-**3**)$_{50}$ (14 mg, 74% yield). ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.45−7.27 (m, 5H, Ph), 6.40−5.57 (m, 97H, =CH and CONH), 5.09 (m, 49H), 3.24 (m, 105H, CH_2), 2.58 (m, 46H), 2.39 (m, 44H), 2.29−1.90 (m, 363H), 1.80−1.17 (m, 700H), 1.04−0.87 (m, 160H, CH_3). M_n^{theor} = 14 500. M_n^{GPC} = 9400. M_w^{GPC} = 17 000. $Đ_M$ = 1.8.

*Poly(**1c**′-alt-**3**)$_{100}$*. Amide **1c**′ (23.2 mg, 120 μmol, 100 equiv), catalyst **2** (1.1 mg, 1.20 μmol, 1 equiv), and **3** (19.6 mg, 240 μmol, 200 equiv) were mixed in CD_2Cl_2 in an NMR tube. After 2 h, amide **1c**′ was completely consumed. Flash column chromatography of the crude product yielded poly(**1c**′-*alt*-**3**)$_{100}$ (24 mg, 85% yield). ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.45−7.27 (m, 5H, Ph), 6.40−5.57 (m, 186H, =CH and CONH), 5.09 (m, 98H, =CH), 3.24 (m, 199H, CH_2), 2.58 (m, 98H), 2.39 (m, 84H), 2.29−1.90 (m, 697H), 1.75−1.17 (m, 1259H), 1.04−0.87 (m, 311H). M_n^{theor} = 28 100. M_n^{GPC} = 20 500. M_w^{GPC} = 28 400. $Đ_M$ = 1.4.

*Poly(**1c**′-alt-**3**)$_{420}$*. Amide **1c**′ (23.2 mg, 120 μmol, 500 equiv), catalyst **2** (0.22 mg, 0.24 μmol, 1 equiv), and **3** (19.6 mg, 240 μmol, 1000 equiv) were mixed in $CDCl_3$ in an NMR tube. After 6 h, 85% of amide **1c**′ was consumed. Flash column chromatography of the crude product yielded poly(**1c**′-*alt*-**3**)$_{420}$ (13 mg, 46% yield). ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.36 (m, 5H, Ph), 6.44−5.65 (m, 741H, =CH and CONH), 5.22−4.99 (m, 424H, =CH), 3.33−3.13 (m, 871H, CH_2), 2.55 (m, 447H), 2.48−2.33 (m, 390H), 2.33−1.87 (m, 3115H), 1.80−1.15 (m, 6126H), 1.06−0.82 (m, 1522H). ^{13}C NMR (126 MHz, CD_2Cl_2): δ 169.8, 141.8, 136.9, 134.4, 120.8, 43.7, 41.3, 33.1, 30.0, 30.0, 28.8, 28.3, 28.1, 26.9, 23.0, 11.3. M_n^{theor} = 137 700. M_n^{GPC} = 111 600. M_w^{GPC} = 130 900. $Đ_M$ = 1.2.

*Poly(**1d**′-alt-**3**-**D**$_{10}$)$_{10}$*. Amide **1d** (13.7 mg, 60 μmol, 10 equiv) and catalyst **2** (5.3 mg, 6.0 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube. Monomer **3**-**D**$_{10}$ (9.8 mg, 120 μmol, 20 equiv) was added upon completion of isomerization. And after 1 h, amide **1d**′ was completely consumed. Flash column chromatography of the crude product yielded poly(**1d**′-*alt*-**3**-**D**$_{10}$)$_{10}$ (13 mg, 68% yield). ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.89 (s, 10H, CONH), 7.59 (m, 20H, Ph), 7.38−7.26 (m, 20H, Ph), 7.10 (m, 10H, Ph), 3.67 (m, 10H), 2.63 (m, 10H), 2.4 (m, 20H), 2.15 (m, 20H), 2.08 (m, 10H), 1.67−1.23 (m, 203H).

*Poly(**1d**′-alt-**3**)$_{50}$*. Amide **1d** (13.7 mg, 60 μmol, 50 equiv) and catalyst **2** (1.1 mg, 1.20 μmol, 1 equiv) were mixed in CD_2Cl_2 in an NMR tube. Monomer **3** (9.8 mg, 120 μmol, 100 equiv) was added upon completion of isomerization, and after 1 h, amide **1d**′ was completely consumed. Flash column chromatography of the crude product yielded **poly(1d′-*alt*-3)$_{50}$** (14 mg, 76% yield). ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.89 (s, 43H, CONH), 7.59 (m, 118H, Ph), 7.38−7.26 (m, 143H, Ph), 7.10 (m, 65H, Ph), 6.30 (m, 46H, =CH), 5.11 (m, 50H, =CH), 3.67 (m, 39H), 2.77−1.23 (m, 1359H). ^{13}C NMR (126 MHz, CD_2Cl_2): δ 168.7, 142.1, 139.2, 137.7, 136.6, 68.2, 44.3, 33.7, 30.5, 29.2, 28.9, 28.5, 27.4, 27.0, 26.1, 24.1. M_n^{theor} = 15 600. M_n^{GPC} = 10 100. M_w^{GPC} = 16 000. $Đ_M$ = 1.6.

RESULTS AND DISCUSSION

Synthesis of Monomers. Bicyclo[4.2.0] and -[3.2.0] esters were synthesized by a modification of Snider's approach[35] as previously described.[32] Basic hydrolysis provided the carboxylic acids that were coupled to selected amines to yield amides **1a**−**1e** and **4**. Diastereomers **1f** and **1f*** were prepared from the mixture of racemic bicyclo[4.2.0]oct-7-ene-7-carboxylic acid and (*S*)-phenylglycinol, separated, and then individually acylated. Relative stereochemistry was not assigned to the diastereomers.

Attempted ROMP of Bicycloamides: Discovery of Isomerization. We submitted the bicyclo[4.2.0] amides **1** to ROMP conditions with catalyst **2** in $CDCl_3$ and monitored the reactions by ^{1}H NMR. The bicyclic monomers underwent rapid reactions. The olefinic proton signals at ∼6.7 ppm disappeared or nearly disappeared (Figures 1a and 1b) within 15 min to 24 h (Table 1, entries 1−7). However, no polymerization could be detected. In contrast, when amide **4** was stirred with catalyst **2** for 18 h at 25 °C, only a 2% decrease in the intensity of the olefinic resonance was observed.

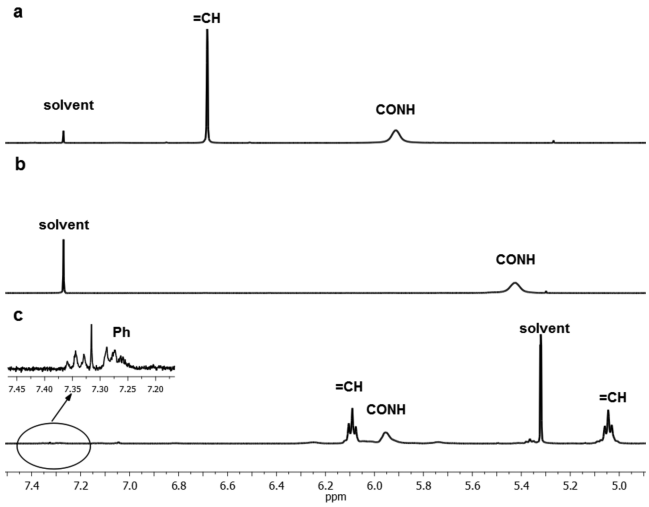

Figure 1. ^{1}H NMR spectra of the alkene and aromatic regions of amide, isomerized amide, and AROMP product. (a) Monomer **1c** in $CDCl_3$. (b) Formation of the tetrasubstituted isomer **1c**′ in the presence of catalyst **2** in $CDCl_3$. (c) Purified alternating copolymer poly(**1c**′-*alt*-**3**)$_{420}$ in CD_2Cl_2. (CD_2Cl_2 was used to avoid overlap with aromatic proton signals and to allow their integration.) The two alkene signals correspond to H1 and H4 of poly(**1c**′-*alt*-**3**)$_{420}$ (see Scheme 1 for structure).

The products derived from monomers **1c** and **1d** were selected for further study. Purification yielded compounds **1c**′ and **1d**′ with molecular masses identical to those of the starting

Table 1. Isomerization of Amides Effected by Catalyst 2

entry	1	[1]:[cat.]	cat./additive	time (h)	% conv[b]
1	**1a**	20:1[a]	**2**	16	90
2	**1b**	50:1[a]	**2**	8	95
3	**1c**	50:1[a]	**2**	1.5	100
4	**1d**	20:1[a]	**2**	0.3	100
5	**1e**	50:1[a]	**2**	6	100
6	**1f**	10:1[a]	**2**	24	70
7	**1f***	10:1[a]	**2**	24	90
8	**1e**	10:1[c]	**2**	14	100
9	**1e**	10:1[c]	**2**/3-Br-pyridine (50 equiv)	14	35
10	**1e**	5:1[a]	**2**	1	100
11	**1e**	5:1[a]	$(Cl)_2(H_2IMes)(PCy_3)Ru$=CHPh	14	5
12	**1e**	10:1[c]	**2**/1,4-benzoquinone (5 equiv)	14	100
13	**1c**	10:1[c]	**2**	1.5	100
14	**1c**	10:1[c]	**2**/8% MeOH	24	65

[a][cat.] = 0.01 M, CD_2Cl_2, 35 °C. [b]% conv was determined by monitoring the monomer alkene resonances in ^{1}H NMR spectra. [c][cat.] = 0.005 M, CD_2Cl_2, 35 °C.

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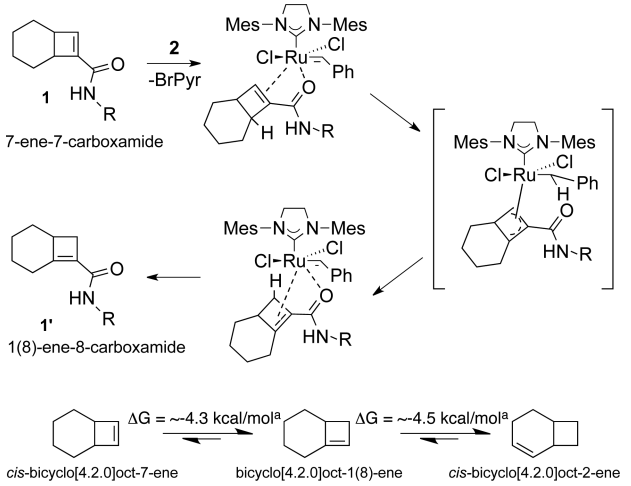
materials. The spectroscopic signatures of **1c′** and **1d′** were distinct from those of **1c** and **1d**, indicating that isomerization had occurred. Relative to the ^{1}H NMR spectra of the starting materials, those of **1c′** and **1d′** contained one more methylene proton signal, one fewer methine signal, and no olefinic proton resonance (Figure 1 and Figure S1). Further spectroscopic characterization of **1c′** by HSQC NMR spectroscopy indicated that it retains the unsaturated bicyclic structure of **1c** but that the double bond had migrated (Scheme 1 and Figures S2 and S3).

Typically, tetra-substituted olefins are not obtained with catalyst **2**.[36−39] However, the isomerization of amide **1** to amide **1′** is less surprising when viewed in the context of the Pd(II)-catalyzed isomerization of the parent system *cis*-bicyclo[4.2.0]-oct-7-ene, analogous to **1**, to the 2-ene, which presumably proceeds through the 1(8)-ene, analogous to **1′** (Scheme 2).

Scheme 2. Proposed π-Allylic Isomerization of Amides 1 to 1′



[a]From the calculations of Curran et al.[40]

Calculations by Curran, Risse, and co-workers suggest that the 1(8)-ene is 3.7−5.0 kcal/mol more stable than the 7-ene.[40] In our system, further isomerization to the *cis*-bicyclo[4.2.0]oct-2-ene-8-carboxamide is unfavorable because in this compound the alkene is not in conjugation with the amide. Results from the Curran group with the [3.2.0] system are also consistent with our observation that the bicyclo[3.2.0] system **4** does not undergo appreciable isomerization. Their calculations show the bond migration from the 6-position to the 1(7)-position is endothermic by more than 9 kcal/mol.[40] As noted above, regioisomer **4′** is not formed upon addition of catalyst **2** to amide **4** is not isomerized by catalyst **2**.

Mechanism of Isomerization. Control experiments support the role of species **2** as the isomerization catalyst. No isomerization was observed upon incubation of **1c** in CH_2Cl_2 at 35 °C for 16 h in the absence of catalyst **2**. Over the course of our experiments, we utilized four different batches of **2**. All four preparations of **2** catalyzed isomerization to the same extent and at the same rate. Furthermore, addition of 50 equiv of 3-bromopyridine to amide **1e** and catalyst **2** reduced the percentage of isomerization 3-fold over a 14 h time period as compared to isomerization in the absence of exogenous 3-bromopyridine ([**2**] = 0.005 M, Table 1, entry 8 vs 9). Likewise, we found that 20 mol % of $(Cl)_2(H_2IMes)(PCy_3)$-Ru=CHPh, for which PCy_3 ligand dissociation is less favored, catalyzed less than 5% isomerization of amide **1e** in 14 h as compared to 100% conversion with 20 mol % catalyst **2** within 1 h (Table 1, entry 10 vs 11). These experiments indicate that coordination of the substrate to the Ru catalyst is required for isomerization.

Cyclobutenes are sensitive to acid-catalyzed decomposition and/or reaction. In order to exclude the possibility that substrates **1** were being converted to isomers **1′** by adventitious acid, we repurified the monomers by passing them through dry basic alumina before subjecting them to catalyst **2**. The isomerization rates and product distributions were unchanged.

Ruthenium catalysts are known to promote olefin isomerization. Previous reports[41−44] have proposed that either a Ru hydride species[45−49] or a π-allyl Ru complex[45,46,50−52] is responsible. The Ru hydride can form upon decomposition that occurs with extended reaction times or extreme reaction conditions.[42,43] The rapid isomerization rates we observe are inconsistent with the formation of a Ru hydride species through decomposition of **2**. Moreover, we never observed Ru hydride resonances at the expected upfield region between 0 and −30 ppm in the ^{1}H NMR spectra of the above reactions. Addition of 1,4-benzoquinone, which has been reported to oxidize Ru hydride species and prevent olefin isomerization,[53] to our amide **1e** did not suppress isomerization. Therefore, a reduced, electron-rich species is unlikely to be responsible for initiation of isomerization (Table 1, entry 8 vs 12).

Alcohols can act as ruthenium reducing agents to enhance Ru hydride formation.[50] However, their coordination with Ru can suppress isomerization that proceeds via a π-allyl mechanism.[51,54,55] Therefore, we tested isomerization of **1c** with and without methanol in the presence of 10 mol % catalyst **2**. The **1c** isomerization reaction containing 8% methanol in CD_2Cl_2 proceeded much more slowly than the reaction without methanol; only 65% isomerization was observed over 24 h as compared to complete isomerization in 1.5 h in the absence of methanol (Table 1, entry 13 vs 14). Our observations are consistent with isomerization via a π-allyl Ru complex formed upon coordination of amide **1** with catalyst **2** (Scheme 2). Evidence in hand does not distinguish between direct formation of this species from amide **1** or its formation by a "ring-walking" mechanism.[40]

The relative rate of isomerization depends on the nature of the amide nitrogen substituent: **1d** > **1c** > **1e** > **1b** > **1a** > **1f**/**1f***. Amides of α-substituted amines and of amines that include an ester in the alkyl chain isomerize slower than primary alkyl or aryl amides.

To investigate further the electronic influence on isomerization, we undertook a control experiment to establish the amount of isomerization with the corresponding methyl bicyclo[4.2.0]oct-7-ene-7-carboxylate. When subjected to catalyst **2** (2 mol %) at 50 °C for 2 days, the ester underwent ROM without isomerization as judged by the disappearance of the catalyst alkylidene proton signal and the remaining signals for the ester starting material. Therefore, the amide moiety assists rapid equilibration of isomers of **1** in the presence of **2**.

The reactivity data taken together with the structure−activity data strongly support a mechanism in which equilibration of regioisomers takes place via initial coordination involving the amide functional group and subsequent formation of a transient Ru π-allyl species (Scheme 2).

Alternating Ring-Opening Metathesis Polymerization of Isomerized Amides. We monitored the isomerization of

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Table 2. Alternating Copolymerization (AROMP) of Bicyclic Amides 1 or 1′ and Cyclohexenes 3 Catalyzed by Catalyst 2[a]

entry	A/B	[A]:[3]:[2]	[2] (M)	time (h)	% conv[b]	$DP_{[AB]}$[c]	M_w^{GPC}[d] (kDa)	M_n^{GPC}[d] (kDa)	$Đ_M$	M_n^{theor}[e] (kDa)
1	**1c**/**3**	10:20:1	0.01	1.5	100	10	nd[f]	nd	nd	nd
2	**1c**/**3**	50:100:1	0.002	2	100	50	17.0	9.4	1.8	14.5
3	**1d**/**3**	50:100:1	0.002	1	100	[g]	16.0	10.1	1.6	15.6
4[h]	**1a′**/**3**	50:100:1	0.002	2	100	50	15.1	12.5	1.2	15.8
5[h]	**1a′**/**3**	100:200:1	0.002	6	100	100	30.7	29.1	1.1	31.9
6[h]	**1b′**/**3**	150:300:1	0.002	2.5	100	140	40.3	34.0	1.2	45.7
7[h]	**1b′**/**3**	300:600:1	0.001	3.5	90	260	80.9	69.6	1.2	91.0
8[i]	**1c′**/**3**	100:200:1	0.002	2	100	100	28.4	20.5	1.4	28.1
9[i]	**1c′**/**3**	500:1000:1	0.0004	6	85	420	130.9	111.6	1.2	137.7

[a]All preparative polymerization experiments were performed three times. Representative molecular weight data are presented from a single polymerization. [b]Conversion was determined by monitoring the disappearance of the amide resonance in **1** or **1′**. [c]Degree of polymerization (DP) was determined for the **AB** repeat by integration of polymer resonances relative to the styrene end group. We estimate the integration error to be within 5%. [d]M_w = weight-average molecular weight; M_n = number-average molecular weight, determined by GPC. [e]Theoretical M_n calculated from the monomer:catalyst feed ratio. [f]Not determined. [g]The DP could not be determined because of spectroscopic overlap and was estimated from the feed ratio of **1d** and catalyst **2**. [h]Isomerized amide was isolated and fresh **2** added before AROMP in $CDCl_3$. [i]Isomerized amide was isolated and fresh **2** added before AROMP in CD_2Cl_2.

amide **1e** to amide **1e′** in the presence of 1 equiv of catalyst **2** by ^{13}C NMR spectroscopy. In addition to the growth of the signals corresponding to the formation of amide **1e′**, remarkably we observed the appearance of new peaks at 322.3 and 178.5 ppm, presumably representing the carbene carbon and the amide carbon respectively in the [Ru]=C(R)CONHR′ species (Figure S4). We also observed a peak at 315.5 ppm, representing a second ruthenium carbene species. On the basis of this experiment, we concluded that ROM occurs upon formation of **1′** despite the tetra-substitution of the alkene monomer. Unlike the ruthenium carbenes from amide-substituted cyclobutenes, previously studied in our laboratory,[27,28] the amide-substituted carbene derived from **1′** does not undergo metathesis with remaining monomer, as noted above.

We reasoned that the amide-substituted carbene derived from **1′** might undergo ring-opening cross-metathesis with cyclohexene **3**, in a reaction analogous, but not identical, to the reaction of Ru enoic carbenes in our previous AROMP work.[22,27,29,32] Indeed, copolymer was rapidly formed upon addition of cyclohexene **3** (Table 2). The copolymerization of monomer **1c′** or **1d′** with **3** yields a 50-**AB**-mer in approximately 2 h. Remarkably, in light of the steric hindrance in the system, this AROMP is faster under similar conditions than that of the less hindered 1-cyclobutene carboxylic methyl ester/cyclohexene AROMP which yields a 50-**AB**-mer in 3 h[22] and that of the corresponding bicyclo[4.2.0]oct-7-ene-7-carboxylic ester which yields a 50-**AB**-mer in 8 h.[32]

^1H NMR spectroscopy of the copolymers displayed two alkene signals consistent with product from AROMP of isomer **1′**. In contrast, AROMP of the original amide **1** would have given copolymer for which the NMR spectrum displayed three alkene signals (Scheme 1).

In order to investigate the possibility of AROMP of the original amide **1c**, we premixed cyclohexene **3** with catalyst **2** before addition of amide. However, no polymer resonances were detected before a significant amount of amide **1c** had isomerized to amide **1c′**. Furthermore, the polymer obtained was identical to poly(**1c′**-*alt*-**3**)$_{10}$ as judged by comparison of the ^1H NMR spectra. Therefore, isomerization of **1c** is faster than ROM and thus faster than ROMP or AROMP of **1c**. Likewise, in the case of amide **1d**, isomerization to amide **1d′** was complete before polymer appeared.

In the cases of **1a**, **1b**, **1e**, and one of the diastereomers of **1f**/**1f***, we obtained mixtures of starting materials and alternating polymers. In these systems, then, the rate of isomerization is slower than or similar to the rate of ROM. Owing to their fast isomerization, amides **1c′** and **1d′** were selected initially for further characterization of their AROMP products.

Analysis of poly(**1d′**-*alt*-**3**)$_{50}$ by ^1H NMR, ^{13}C NMR, APT, and HSQC spectroscopy revealed that the polymer backbone has four alkene carbons and two alkene hydrogens corresponding to C1−C4 and H1 and H4 (Scheme 1 and Figure S5). HSQC spectroscopy confirmed that the amide-substituted olefin is a single stereoisomer; there is a single H1 signal at 6.29 ppm that correlates with C1 at 136 ppm (Figure 2). On the basis of comparison of the H1 alkene chemical shift with model compounds,[27,56] we conclude that the conjugated alkene is of *E*-configuration. A single H4 signal at 5.11 ppm correlates with C4 at 121 ppm. Because of peak broadening in the polymer, we could not determine if the C3−C4 alkene is stereoregular.

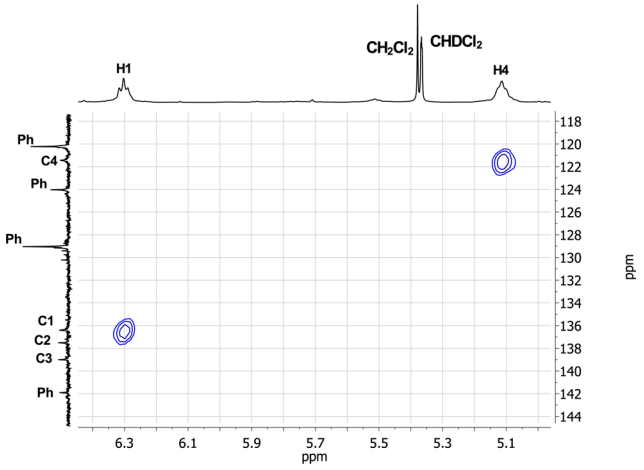

Figure 2. Alkene region of the HSQC spectrum of poly(**1d′**-*alt*-**3**)$_{50}$ in CD_2Cl_2. The polymer backbone has only four alkene carbons and two alkene hydrogens corresponding to C1−C4 and H1 and H4 in Scheme 1. A full spectrum is provided in the Supporting Information (Figure S5).

Integration of the poly(**1′**-*alt*-**3**)$_n$ alkene signals relative to side chain signals demonstrated that an equal incorporation of

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the two monomers had occurred. An **AA** or **BB** dyad would be formed upon backbiting. Additional alkene proton resonances in the 5 ppm region of the ^{1}H NMR spectrum which would indicate formation of **BB** dyad were not observed. In the isomerized amide AROMP product, the **AA** dyad does not possess an alkene proton. Therefore, we inspected the ^{13}C NMR spectra of poly(**1d**′-*alt*-**3**)$_{50}$ and poly(**1c**′-*alt*-**3**)$_{420}$ for the presence of **AA** dyad alkene resonances, specifically, a C3′ resonance between 160 and 145 ppm, and found none (Figure S6). Further evidence for the equal incorporation of monomers **1d**′ and **3** was obtained with experiments with cyclohexene-D_{10}. The ^{1}H NMR spectra of the deuterium-labeled copolymer poly(**1d**′-*alt*-**3-D$_{10}$**)$_{10}$ show a complete loss of the alkene resonances at 6.3 and 5.1 ppm as expected for an alternating **AB** polymer (Figure S7).

We explored the utility of alternating copolymerization by testing the maximal length of alternating copolymer that could be prepared. When cyclohexene **3** was added directly to a completed isomerization reaction of **1c**′ or **1d**′, poly(**1c**′-*alt*-**3**)$_{50}$ or poly(**1d**′-*alt*-**3**)$_{50}$ was obtained (Table 2). However, the dispersities exceeded those expected from the monomer:-catalyst ratio for a ruthenium-catalyzed polymerization, presumably because of loss of catalyst during isomerization. Therefore, in order to facilitate characterization of polymers longer than 100 **AB** dyads, to maximize their purity, and to minimize their dispersity, we isolated amides **1**′ before initiation of the AROMP reaction and added fresh catalyst.

In the case of amides **1a**′ and **1b**′, the AROMP reactions provided maximal lengths of 100 **AB** dyads and 260 **AB** dyads, respectively, with modest $Đ_M$ = 1.1−1.2. Higher monomer feed ratios did not provide longer copolymers. In contrast, when amide **1c**′ was mixed with catalyst **2** in a ratio of 500:1 with 1000 equiv of cyclohexene **3**, we reproducibly obtained alternating copolymer with more than 400 **AB** dyads (Figure 1c) and a modest molecular weight distribution ($Đ_M$ = 1.2). Although the isomerization of **1d** to **1d**′ was facile, the length of the copolymers obtained was limited to 50 **AB** dyads regardless of whether amide **1d**′ or **1d** was used to initiate propagation. Finally, amides **1e**′ and **1f**′ provided only short alternating copolymers that were not characterized further. Overall propagation efficiencies in order are **1c**′ > **1b**′ > **1a**′ > **1d**′ > **1e**′ > **1f**′. Thus, the maximal length of copolymer obtained depends on the degree of steric congestion α to the amide. Moreover, the presence of an aromatic ring in the amide substituent (**1d**′ or **1e**′) significantly reduced propagation efficiency.

CONCLUSIONS

Bicyclo[4.2.0]oct-7-ene-7-carboxamides of primary amines are quantitatively isomerized to bicyclo[4.2.0]oct-1(8)-ene-8-carboxamides in the presence of catalyst **2**. Moreover, reaction of compound **1d** to give **1d**′, which is complete within 15 min, is by far the fastest ruthenium-catalyzed olefin isomerization reported to date. This isomerization of an internal olefin in a bicyclic system provides a facile approach to synthesize tetra-substituted bicyclo[4.2.0]oct-1(8)-ene-8-carboxamides.

Remarkably, bicyclic tetra-substituted α,β-unsaturated amides are excellent AROMP substrates for the preparation of long, alternating copolymers. Isomerized unsaturated amides **1a**′, **1b**′, **1c**′, and **1d**′ undergo alternating ROMP with cyclohexene 1.5−4 times more rapidly than previously studied 1-cyclobutenecarboxylic acid esters or bicyclo[4.2.0]oct-7-ene-7-carboxylic esters. The isomerized amide AROMP reaction is compatible with a variety of amides that provide functional group handles. This facile sequence, isomerization followed by alternating ring-opening cross-metathesis of **A** and ring-opening cross-metathesis of **B**, provides an efficient entry to well-controlled architectures, enables the production of linear, soluble, and impressively long (greater than 100 and up to 400 **AB** units) alternating polymers with superior monomer economics, and unlocks the prospect of employing functionalized alternating and sequence-specific copolymers in multiple applications.

ASSOCIATED CONTENT

Supporting Information

Experimental methods to prepare amides **1** and 56 figures (Figures S1−S56) with additional experimental data and spectra. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.macromol.5b01058.

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Notes

The authors declare no competing financial interest.

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