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BIS-PHENYL-PHENOXY POLYOLEFIN CATALYSTS HAVING TWO METHYLENETRIALKYLSILICON LIGANDS ON THE METAL FOR IMPROVED SOLUBILITY

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Patent Application Serial Number 62/565,771, filed September 29, 2017, which is incorporated by reference in its entirety

TECHNICAL FIELD

[0002] Embodiments of the present disclosure generally relate to olefin polymerization catalyst systems and processes and, more specifically to bis-phenyl-phenoxy polyolefin procatalyst having two methylenetrialkylsilicon ligands on the metal for improved solubility in non-aromatic hydrocarbons.

BACKGROUND

[0003] Olefin-based polymers such as polyethylene, ethylene-based polymer, polypropylene, and propylene-based polymer are produced via various catalyst systems. Selection of such catalyst systems used in the polymerization process of the olefin-based polymers is an important factor contributing to the characteristics and properties of such olefin-based polymers.

[0004] Polyethylene and polypropylene are manufactured for a wide variety of articles. The polyethylene and polypropylene polymerization process can be varied in a number of respects to produce a wide variety of resultant polyethylene resins having different physical properties that render the various resins suitable for use in different applications. The ethylene monomers and, optionally, one or more co-monomers are present in liquid diluents (such as solvents), such as an alkane or isoalkane, for example isobutene. Hydrogen may also be added to the reactor. The catalyst systems for producing polyethylene may typically

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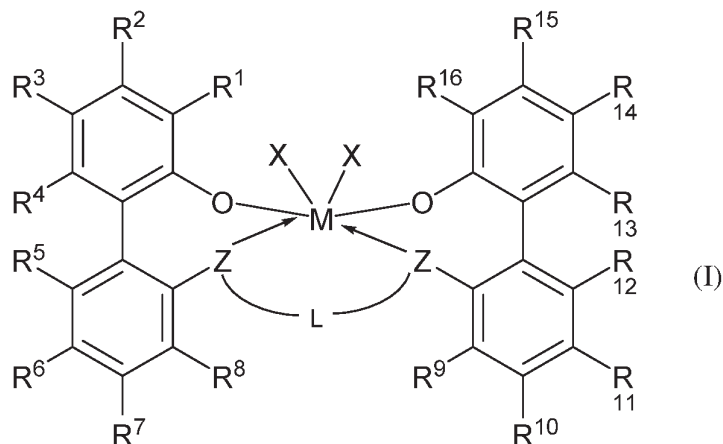
comprise a chromium-based catalyst system, a Ziegler–Natta catalyst system, and/or a molecular (either metallocene or non-metallocene (molecular)) catalyst system. The reactants in the diluent and the catalyst system are circulated at an elevated polymerization temperature around the reactor, thereby producing polyethylene homopolymer or copolymer. Either periodically or continuously, part of the reaction mixture, including the polyethylene product dissolved in the diluent, together with unreacted ethylene and one or more optional co-monomers, is removed from the reactor. The reaction mixture, when removed from the reactor, may be processed to remove the polyethylene product from the diluent and the unreacted reactants, with the diluent and unreacted reactants typically being recycled back into the reactor. Alternatively, the reaction mixture may be sent to a second reactor, serially connected to the first reactor, where a second polyethylene fraction may be produced. Despite the research efforts in developing catalyst systems suitable for olefin polymerization, such as polyethylene or polypropylene polymerization, there is still a need to increase the efficiencies of catalyst systems that are capable of producing polymer with high molecular weights and a narrow molecular weight distribution.

SUMMARY

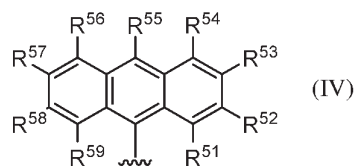
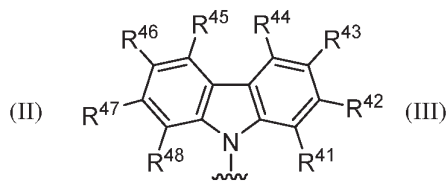
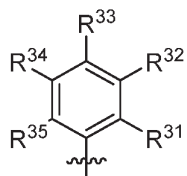
[0005] Molecular catalyst systems are not easily solubilized in apolar solvents. Since ethylene and other olefins are polymerized in apolar solvents, a large amount of solvent (or an undesirable solvent, i.e. toluene) is used in order to dissolve a small amount of catalyst. As a result there is an ongoing need to solubilize a catalyst system with a lesser amount of solvent, while maintaining catalyst efficiency, reactivity, and the ability to produce polymers with a high or low molecular weight.

[0006] According to some embodiments, a catalyst system may include a metal–ligand complex according to formula (I):

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[0007] In formula (I), M is a metal chosen from titanium, zirconium, or hafnium, the metal being in a formal oxidation state of +2, +3, or +4. Each X is selected from the group consisting of $-(CH_2)SiR^X_3$, where each R^X is independently a (C_1-C_{30}) hydrocarbyl and at least one R^X is (C_2-C_{30}) hydrocarbyl, where any two R^X or all three R^X are optionally covalently linked; each Z is independently chosen from $-O-$, $-S-$, $-N(R^N)-$, or $-P(R^P)-$; R^1 and R^{16} are independently selected from the group consisting of $-H$, (C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $-N=C(R^C)_2$, $R^C C(O)O-$, $R^C OC(O)-$, $R^C C(O)N(R)-$, $(R^C)_2NC(O)-$, halogen, radicals having formula (II), radicals having formula (III), and radicals having formula (IV):

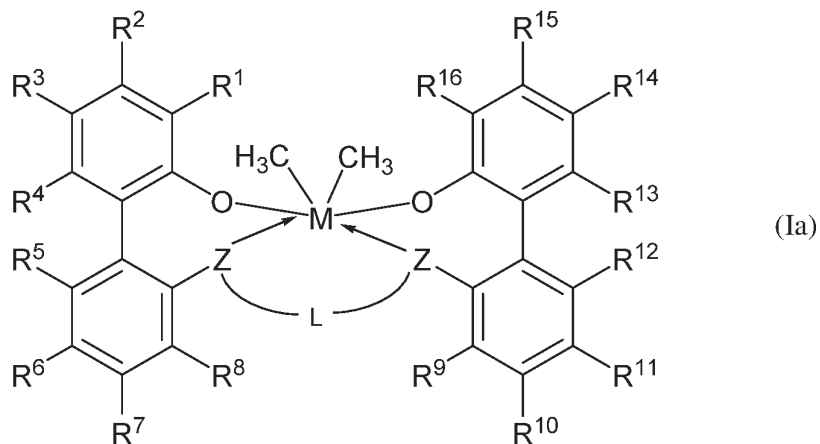


[0008] In formulas (II), (III), and (IV), each of R^{31-35} , R^{41-48} , and R^{51-59} is independently chosen from $-H$, (C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$,

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$-\text{P}(\text{R}^{\text{P}})_2$, $-\text{N}(\text{R}^{\text{N}})_2$, $-\text{OR}^{\text{C}}$, $-\text{SR}^{\text{C}}$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $\text{R}^{\text{C}}\text{S}(\text{O})-$, $\text{R}^{\text{C}}\text{S}(\text{O})_2-$, $(\text{R}^{\text{C}})_2\text{C}=\text{N}-$, $\text{R}^{\text{C}}\text{C}(\text{O})\text{O}-$, $\text{R}^{\text{C}}\text{OC}(\text{O})-$, $\text{R}^{\text{C}}\text{C}(\text{O})\text{N}(\text{R}^{\text{N}})-$, $(\text{R}^{\text{C}})_2\text{NC}(\text{O})-$, or halogen, provided at least one of R^1 or R^{16} is a radical having formula (II), a radical having formula (III), or a radical having formula (IV).

[0009] In formula (I), each of R^{2-4} , R^{5-8} , R^{9-12} , and R^{13-15} is independently selected from $-\text{H}$, $(\text{C}_1-\text{C}_{40})$ hydrocarbyl, $(\text{C}_1-\text{C}_{40})$ heterohydrocarbyl, $-\text{Si}(\text{R}^{\text{C}})_3$, $-\text{Ge}(\text{R}^{\text{C}})_3$, $-\text{P}(\text{R}^{\text{P}})_2$, $-\text{N}(\text{R}^{\text{N}})_2-\text{OR}^{\text{C}}$, $-\text{SR}^{\text{C}}$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $\text{R}^{\text{C}}\text{S}(\text{O})-$, $\text{R}^{\text{C}}\text{S}(\text{O})_2-$, $(\text{R}^{\text{C}})_2\text{C}=\text{N}-$, $\text{R}^{\text{C}}\text{C}(\text{O})\text{O}-$, $\text{R}^{\text{C}}\text{OC}(\text{O})-$, $\text{R}^{\text{C}}\text{C}(\text{O})\text{N}(\text{R})-$, $(\text{R}^{\text{C}})_2\text{NC}(\text{O})-$, and halogen. L is $(\text{C}_2-\text{C}_{40})$ hydrocarbylene or $(\text{C}_2-\text{C}_{40})$ heterohydrocarbylene; and each R^{C} , R^{P} , and R^{N} in formula (I) is independently a $(\text{C}_1-\text{C}_{30})$ hydrocarbyl, $(\text{C}_1-\text{C}_{30})$ heterohydrocarbyl, or $-\text{H}$. The metal-ligand complex according to formula (I) has a solubility greater than the solubility of a comparative complex having a structure according to formula (Ia):



[0010] In formula (Ia), M , each Z , each R^{1-16} , each R^{31-35} , each R^{41-48} , each R^{51-59} , L , each R^{C} , each R^{P} , and each R^{N} all are identical to corresponding groups of the metal-ligand complex according to formula (I).

DETAILED DESCRIPTION

[0011] Specific embodiments of catalyst systems will now be described. It should be understood that the catalyst systems of this disclosure may be embodied in different forms

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and should not be construed as limited to the specific embodiments set forth in this disclosure. Rather, embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the subject matter to those skilled in the art.

[0012] Common abbreviations are listed below:

[0013] **R, Z, M, X and n**: as defined above; **Me** : methyl; **Et** : ethyl; **Ph** : phenyl; **Bn**: benzyl; **i-Pr** : *iso*-propyl; **t-Bu** : *tert*-butyl; **THF** : tetrahydrofuran; **Et₂O** : diethyl ether; **CH₂Cl₂** : dichloromethane; **C₆D₆** : deuterated benzene or benzene-*d*6 ; **CDCl₃** : deuterated chloroform; **Na₂SO₄** : sodium sulfate; **MgSO₄** : magnesium sulfate; **HCl** : hydrogen chloride; ***n*-BuLi**: butyllithium; **HfCl₄** : hafnium(IV) chloride; **HfBn₄** : hafnium(IV) tetrabenzyl; **ZrCl₄** : zirconium(IV) chloride; **ZrBn₄** : zirconium(IV) tetrabenzyl; **ZrBn₂Cl₂(OEt₂)** : zirconium (IV) dibenzyl dichloride mono-diethyletherate; **HfBn₂Cl₂(OEt₂)** : hafnium (IV) dibenzyl dichloride mono-diethyletherate; **N₂** : nitrogen gas; **PhMe**: toluene; **PPR** : parallel polymerization reactor; **MAO** : methylaluminoxane; **MMAO** : modified methylaluminoxane; **NMR** : nuclear magnetic resonance; **mmol** : millimoles; **mL** : milliliters; **M** : molar; **min or mins**: minutes; **h** or **hrs** : hours; **d**: days; **rpm**: revolution per minute; **STP** : standard pressure and temperature.

[0014] The term “independently selected” is used herein to indicate that the R groups, such as, R¹, R², R³, R⁴, and R⁵, can be identical or different (e.g., R¹, R², R³, R⁴, and R⁵ may all be substituted alkyls or R¹ and R² may be a substituted alkyl and R³ may be an aryl, etc.) A chemical name associated with an R group is intended to convey the chemical structure that is recognized in the art as corresponding to that of the chemical name. Thus, chemical names are intended to supplement and illustrate, not preclude, the structural definitions known to those of skill in the art.

[0015] The term “procatalyst” refers to a compound that has catalytic activity when combined with an activator. The term “activator” refers to a compound that chemically reacts with a procatalyst in a manner that converts the procatalyst to a catalytically active catalyst. As used herein, the terms “co-catalyst” and “activator” are interchangeable terms.

[0016] When used to describe certain carbon atom-containing chemical groups, a parenthetical expression having the form “(C_x–C_y)” means that the unsubstituted form of the chemical group has from x carbon atoms to y carbon atoms, inclusive of x and y. For example, a (C₁–C₅₀)alkyl is an alkyl group having from 1 to 50 carbon atoms in its unsubstituted form. In some embodiments and general structures, certain chemical groups may be substituted by one or more substituents such as R^S. An R^S substituted chemical group defined using the “(C_x–C_y)” parenthetical may contain more than y carbon atoms depending on the identity of any groups R^S. For example, a “(C₁–C₅₀)alkyl substituted with exactly one group R^S, where R^S is phenyl (–C₆H₅)” may contain from 7 to 56 carbon atoms. Thus, in general when a chemical group defined using the “(C_x–C_y)” parenthetical is substituted by one or more carbon atom-containing substituents R^S, the minimum and maximum total number of carbon atoms of the chemical group is determined by adding to both x and y the combined sum of the number of carbon atoms from all of the carbon atom-containing substituents R^S.

[0017] The term “substitution” means that at least one hydrogen atom (–H) bonded to a carbon atom or heteroatom of a corresponding unsubstituted compound or functional group is replaced by a substituent (e.g. R^S). The term “persubstitution” means that every hydrogen atom (H) bonded to a carbon atom or heteroatom of a corresponding unsubstituted compound or functional group is replaced by a substituent (e.g., R^S). The term “polysubstitution” means that at least two, but fewer than all, hydrogen atoms bonded to carbon atoms or heteroatoms of a corresponding unsubstituted compound or functional group are replaced by a substituent. The term “–H” means a hydrogen or hydrogen radical that is covalently bonded to another atom. “Hydrogen” and “–H” are interchangeable, and unless clearly specified have identical meanings.

[0018] The term “(C₁–C₅₀)hydrocarbyl” means a hydrocarbon radical of from 1 to 50 carbon atoms and the term “(C₁–C₅₀)hydrocarbylene” means a hydrocarbon diradical of from 1 to 50 carbon atoms, in which each hydrocarbon radical and each hydrocarbon diradical is aromatic or non-aromatic, saturated or unsaturated, straight chain or branched chain, cyclic

(having three carbons or more, and including mono- and poly-cyclic, fused and non-fused polycyclic, and bicyclic) or acyclic, and substituted by one or more R^S or unsubstituted.

[0019] In this disclosure, a (C_1-C_{50}) hydrocarbonyl may be an unsubstituted or substituted (C_1-C_{50}) alkyl, (C_3-C_{50}) cycloalkyl, (C_3-C_{20}) cycloalkyl- (C_1-C_{20}) alkylene, (C_6-C_{40}) aryl, or (C_6-C_{20}) aryl- (C_1-C_{20}) alkylene (such as benzyl $(-CH_2-C_6H_5)$).

[0020] The terms “ (C_1-C_{50}) alkyl” and “ (C_1-C_{18}) alkyl” mean a saturated straight or branched hydrocarbon radical of from 1 to 50 carbon atoms and a saturated straight or branched hydrocarbon radical of from 1 to 18 carbon atoms, respectively, that is unsubstituted or substituted by one or more R^S . Examples of unsubstituted (C_1-C_{50}) alkyl are unsubstituted (C_1-C_{20}) alkyl; unsubstituted (C_1-C_{10}) alkyl; unsubstituted (C_1-C_5) alkyl; methyl; ethyl; 1-propyl; 2-propyl; 1-butyl; 2-butyl; 2-methylpropyl; 1,1-dimethylethyl; 1-pentyl; 1-hexyl; 1-heptyl; 1-nonyl; and 1-decyl. Examples of substituted (C_1-C_{40}) alkyl are substituted (C_1-C_{20}) alkyl, substituted (C_1-C_{10}) alkyl, trifluoromethyl, and $[C_{45}]$ alkyl. The term “ $[C_{45}]$ alkyl” means there is a maximum of 45 carbon atoms in the radical, including substituents, and is, for example, a $(C_{27}-C_{40})$ alkyl substituted by one R^S , which is a (C_1-C_5) alkyl, respectively. Each (C_1-C_5) alkyl may be methyl, trifluoromethyl, ethyl, 1-propyl, 1-methylethyl, or 1,1-dimethylethyl.

[0021] The term “ (C_6-C_{50}) aryl” means an unsubstituted or substituted (by one or more R^S) mono-, bi- or tricyclic aromatic hydrocarbon radical of from 6 to 40 carbon atoms, of which at least from 6 to 14 of the carbon atoms are aromatic ring carbon atoms. A monocyclic aromatic hydrocarbon radical includes one aromatic ring; a bicyclic aromatic hydrocarbon radical has two rings; and a tricyclic aromatic hydrocarbon radical has three rings. When the bicyclic or tricyclic aromatic hydrocarbon radical is present, at least one of the rings of the radical is aromatic. The other ring or rings of the aromatic radical may be independently fused or non-fused and aromatic or non-aromatic. Examples of unsubstituted (C_6-C_{50}) aryl include: unsubstituted (C_6-C_{20}) aryl, unsubstituted (C_6-C_{18}) aryl; 2- (C_1-C_5) alkyl-phenyl; phenyl; fluorenyl; tetrahydrofluorenyl; indacenyl; hexahydroindacenyl; indenyl; dihydroindenyl; naphthyl; tetrahydronaphthyl; and phenanthrene. Examples of substituted

(C₆–C₄₀)aryl include: substituted (C₁–C₂₀)aryl; substituted (C₆–C₁₈)aryl; 2,4-bis([C₂₀]alkyl)-phenyl; polyfluorophenyl; pentafluorophenyl; and fluoren-9-one-1-yl.

[0022] The term “(C₃–C₅₀)cycloalkyl” means a saturated cyclic hydrocarbon radical of from 3 to 50 carbon atoms that is unsubstituted or substituted by one or more R^S. Other cycloalkyl groups (e.g., (C_x–C_y)cycloalkyl) are defined in an analogous manner as having from x to y carbon atoms and being either unsubstituted or substituted with one or more R^S. Examples of unsubstituted (C₃–C₄₀)cycloalkyl are unsubstituted (C₃–C₂₀)cycloalkyl, unsubstituted (C₃–C₁₀)cycloalkyl, cyclopropyl, cyclobutyl, cyclopentyl, cyclohexyl, cycloheptyl, cyclooctyl, cyclononyl, and cyclodecyl. Examples of substituted (C₃–C₄₀)cycloalkyl are substituted (C₃–C₂₀)cycloalkyl, substituted (C₃–C₁₀)cycloalkyl, cyclopentanone-2-yl, and 1-fluorocyclohexyl.

[0023] Examples of (C₁–C₅₀)hydrocarbylene include unsubstituted or substituted (C₆–C₅₀)arylene, (C₃–C₅₀)cycloalkylene, and (C₁–C₅₀)alkylene (e.g., (C₁–C₂₀)alkylene). The diradicals may be on the same carbon atom (e.g., –CH₂–) or on adjacent carbon atoms (i.e., 1,2-diradicals), or are spaced apart by one, two, or more than two intervening carbon atoms (e.g., 1,3-diradicals, 1,4-diradicals, etc.). Some diradicals include 1,2-, 1,3-, 1,4-, or an α,ω -diradical, and others a 1,2-diradical. The α,ω -diradical is a diradical that has maximum carbon backbone spacing between the radical carbons. Some examples of (C₂–C₂₀)alkylene α,ω -diradicals include ethan-1,2-diyl (i.e. –CH₂CH₂–), propan-1,3-diyl (i.e. –CH₂CH₂CH₂–), 2-methylpropan-1,3-diyl (i.e. –CH₂CH(CH₃)CH₂–). Some examples of (C₆–C₅₀)arylene α,ω -diradicals include phenyl-1,4-diyl, naphthalen-2,6-diyl, or naphthalen-3,7-diyl.

[0024] The term “(C₁–C₅₀)alkylene” means a saturated straight chain or branched chain diradical (i.e., the radicals are not on ring atoms) of from 1 to 50 carbon atoms that is unsubstituted or substituted by one or more R^S. Examples of unsubstituted (C₁–C₅₀)alkylene are unsubstituted (C₁–C₂₀)alkylene, including unsubstituted –CH₂CH₂–, –(CH₂)₃–, –(CH₂)₄–, –(CH₂)₅–, –(CH₂)₆–, –(CH₂)₇–, –(CH₂)₈–, –CH₂C*HCH₃, and –(CH₂)₄C*(H)(CH₃), in which “C*” denotes a carbon atom from which a hydrogen atom is removed to form a secondary or tertiary alkyl radical. Examples of substituted (C₁–C₅₀)alkylene are substituted

(C₁–C₂₀)alkylene, –CF₂–, –C(O)–, and –(CH₂)₁₄C(CH₃)₂(CH₂)₅– (i.e., a 6,6-dimethyl substituted normal-1,20-eicosylene). Since as mentioned previously two R^S may be taken together to form a (C₁–C₁₈)alkylene, examples of substituted (C₁–C₅₀)alkylene also include 1,2-bis(methylene)cyclopentane, 1,2- bis(methylene)cyclohexane, 2,3-bis(methylene)-7,7-dimethyl-bicyclo[2.2.1]heptane, and 2,3- bis (methylene)bicyclo [2.2.2] octane.

[0025] The term “(C₃–C₅₀)cycloalkylene” means a cyclic diradical (i.e., the radicals are on ring atoms) of from 3 to 50 carbon atoms that is unsubstituted or substituted by one or more R^S.

[0026] The term “heteroatom,” refers to an atom other than hydrogen or carbon. Examples of groups containing one or more than one heteroatom include O, S, S(O), S(O)₂, Si(R^C)₂, P(R^P), N(R^N), –N=C(R^C)₂, –Ge(R^C)₂–, or –Si(R^C)–, where each R^C and each R^P is unsubstituted (C₁–C₁₈)hydrocarbyl or –H, and where each R^N is unsubstituted (C₁–C₁₈)hydrocarbyl. The term “heterohydrocarbon” refers to a molecule or molecular framework in which one or more carbon atoms of a hydrocarbon are replaced with a heteroatom. The term “(C₁–C₅₀)heterohydrocarbyl” means a heterohydrocarbon radical of from 1 to 50 carbon atoms, and the term “(C₁–C₅₀)heterohydrocarbylene” means a heterohydrocarbon diradical of from 1 to 50 carbon atoms. The heterohydrocarbon of the (C₁–C₅₀)heterohydrocarbyl or the (C₁–C₅₀)heterohydrocarbylene has one or more heteroatoms. The radical of the heterohydrocarbyl may be on a carbon atom or a heteroatom. The two radicals of the heterohydrocarbylene may be on a single carbon atom or on a single heteroatom. Additionally, one of the two radicals of the diradical may be on a carbon atom and the other radical may be on a different carbon atom; one of the two radicals may be on a carbon atom and the other on a heteroatom; or one of the two radicals may be on a heteroatom and the ofther radical on a different heteroatom. Each (C₁–C₅₀)heterohydrocarbyl and (C₁–C₅₀)heterohydrocarbylene may be unsubstituted or substituted (by one or more R^S), aromatic or non-aromatic, saturated or unsaturated, straight chain or branched chain, cyclic (including mono- and poly-cyclic, fused and non-fused polycyclic), or acyclic.

[0027] The (C_1-C_{50}) heterohydrocarbyl may be unsubstituted or substituted. Non-limiting examples of the (C_1-C_{50}) heterohydrocarbyl include (C_1-C_{50}) heteroalkyl, (C_1-C_{50}) hydrocarbyl-O-, (C_1-C_{50}) hydrocarbyl-S-, (C_1-C_{50}) hydrocarbyl-S(O)-, (C_1-C_{50}) hydrocarbyl-S(O)₂-, (C_1-C_{50}) hydrocarbyl-Si(R^C)₂-, (C_1-C_{50}) hydrocarbyl-N(R^N)-, (C_1-C_{50}) hydrocarbyl-P(R^P)-, (C_2-C_{50}) heterocycloalkyl, (C_2-C_{19}) heterocycloalkyl- (C_1-C_{20}) alkylene, (C_3-C_{20}) cycloalkyl- (C_1-C_{19}) heteroalkylene, (C_2-C_{19}) heterocycloalkyl- (C_1-C_{20}) heteroalkylene, (C_1-C_{50}) heteroaryl, (C_1-C_{19}) heteroaryl- (C_1-C_{20}) alkylene, (C_6-C_{20}) aryl- (C_1-C_{19}) heteroalkylene, or (C_1-C_{19}) heteroaryl- (C_1-C_{20}) heteroalkylene.

[0028] The term “ (C_4-C_{50}) heteroaryl” means an unsubstituted or substituted (by one or more R^S) mono-, bi-, or tricyclic heteroaromatic hydrocarbon radical of from 4 to 50 total carbon atoms and from 1 to 10 heteroatoms. A monocyclic heteroaromatic hydrocarbon radical includes one heteroaromatic ring; a bicyclic heteroaromatic hydrocarbon radical has two rings; and a tricyclic heteroaromatic hydrocarbon radical has three rings. When the bicyclic or tricyclic heteroaromatic hydrocarbon radical is present, at least one of the rings in the radical is heteroaromatic. The other ring or rings of the heteroaromatic radical may be independently fused or non-fused and aromatic or non-aromatic. Other heteroaryl groups (e.g., (C_x-C_y) heteroaryl generally, such as (C_4-C_{12}) heteroaryl) are defined in an analogous manner as having from x to y carbon atoms (such as 4 to 12 carbon atoms) and being unsubstituted or substituted by one or more than one R^S. The monocyclic heteroaromatic hydrocarbon radical is a 5-membered ring or a 6-membered ring. The 5-membered ring monocyclic heteroaromatic hydrocarbon radical has 5 minus h carbon atoms, where h is the number of heteroatoms and may be 1, 2, or 3; and each heteroatom may be O, S, N, or P.

[0029] Examples of 5-membered ring heteroaromatic hydrocarbon radicals include pyrrol-1-yl; pyrrol-2-yl; furan-3-yl; thiophen-2-yl; pyrazol-1-yl; isoxazol-2-yl; isothiazol-5-yl; imidazol-2-yl; oxazol-4-yl; thiazol-2-yl; 1,2,4-triazol-1-yl; 1,3,4-oxadiazol-2-yl; 1,3,4-thiadiazol-2-yl; tetrazol-1-yl; tetrazol-2-yl; and tetrazol-5-yl. The 6-membered ring monocyclic heteroaromatic hydrocarbon radical has 6 minus h carbon atoms, where h is the number of heteroatoms and may be 1 or 2 and the heteroatoms may be N or P.

[0030] Examples of 6-membered ring heteroaromatic hydrocarbon radicals include pyridine-2-yl; pyrimidin-2-yl; and pyrazin-2-yl. The bicyclic heteroaromatic hydrocarbon radical can be a fused 5,6- or 6,6-ring system. Examples of the fused 5,6-ring system bicyclic heteroaromatic hydrocarbon radical are indol-1-yl; and benzimidazole-1-yl. Examples of the fused 6,6-ring system bicyclic heteroaromatic hydrocarbon radical are quinolin-2-yl; and isoquinolin-1-yl. The tricyclic heteroaromatic hydrocarbon radical can be a fused 5,6,5-; 5,6,6-; 6,5,6-; or 6,6,6-ring system. An example of the fused 5,6,5-ring system is 1,7-dihydropyrrolo[3,2-f]indol-1-yl. An example of the fused 5,6,6-ring system is 1H-benzo[f]indol-1-yl. An example of the fused 6,5,6-ring system is 9H-carbazol-9-yl. An example of the fused 6,5,6- ring system is 9H-carbazol-9-yl. An example of the fused 6,6,6-ring system is acrydin-9-yl.

[0031] The term “(C₁–C₅₀)heteroalkyl” means a saturated straight or branched chain radical containing one to fifty carbon atoms and one or more heteroatom. The term “(C₁–C₅₀)heteroalkylene” means a saturated straight or branched chain diradical containing from 1 to 50 carbon atoms and one or more than one heteroatoms. The heteroatoms of the heteroalkyls or the heteroalkylenes may include Si(R^C)₃, Ge(R^C)₃, Si(R^C)₂, Ge(R^C)₂, P(R^P)₂, P(R^P), N(R^N)₂, N(R^N), N, O, OR^C, S, SR^C, S(O), and S(O)₂, wherein each of the heteroalkyl and heteroalkylene groups are unsubstituted or are substituted by one or more R^S.

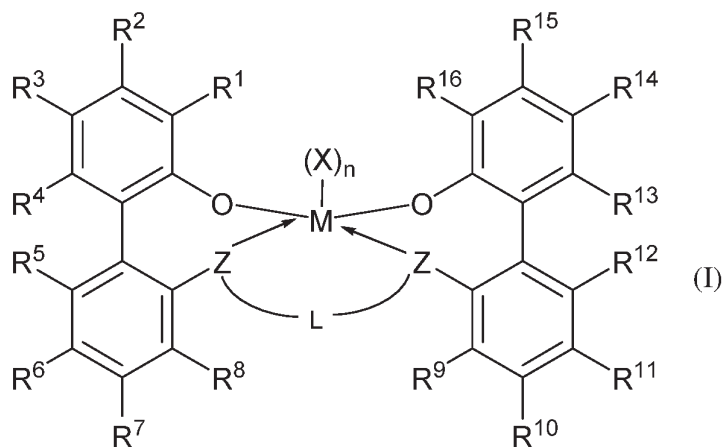
[0032] Examples of unsubstituted (C₂–C₄₀)heterocycloalkyl include unsubstituted (C₂–C₂₀)heterocycloalkyl, unsubstituted (C₂–C₁₀)heterocycloalkyl, aziridin-1-yl, oxetan-2-yl, tetrahydrofuran-3-yl, pyrrolidin-1-yl, tetrahydrothiophen-S,S-dioxide-2-yl, morpholin-4-yl, 1,4- dioxan-2-yl, hexahydroazepin-4-yl, 3-oxa-cyclooctyl, 5-thio-cyclononyl, and 2-aza-cyclodecyl.

[0033] The term “halogen atom” or “halogen” means the radical of a fluorine atom (F), chlorine atom (Cl), bromine atom (Br), or iodine atom (I). The term “halide” means anionic form of the halogen atom: fluoride (F[−]), chloride (Cl[−]), bromide (Br[−]), or iodide (I[−]).

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[0034] The term “saturated” means lacking carbon–carbon double bonds, carbon–carbon triple bonds, and (in heteroatom-containing groups) carbon–nitrogen, carbon–phosphorous, and carbon–silicon double bonds. Where a saturated chemical group is substituted by one or more substituents R^S , one or more double and/or triple bonds optionally may be present in substituents R^S . The term “unsaturated” means containing one or more carbon–carbon double bonds or carbon–carbon triple bonds, or (in heteroatom-containing groups) one or more carbon–nitrogen double bonds, carbon–phosphorous double bonds, or carbon–silicon double bonds, not including double bonds that may be present in substituents R^S , if any, or in aromatic rings or heteroaromatic rings, if any.

[0035] Embodiments of this disclosure include catalyst systems that include a metal–ligand complex according to formula (I):

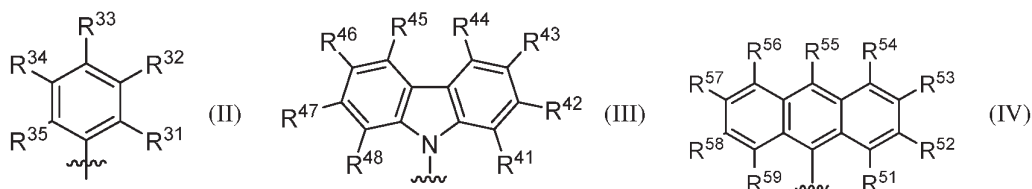


[0036] In formula (I), M is a metal chosen from titanium, zirconium, or hafnium, the metal being in a formal oxidation state of +2, +3, or +4. Each X is selected from the group consisting of $-(CH_2)SiR^X_3$, where each R^X is independently a (C_1-C_{30}) hydrocarbyl or a (C_1-C_{30}) heterohydrocarbyl and at least one R^X is (C_2-C_{30}) hydrocarbyl, where any two R^X or all three R^X are optionally covalently linked. The metal–ligand complex has 6 or fewer metal–ligand bonds and can be overall charge-neutral or may have a positive-charge

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associated with the metal center. Each Z is independently chosen from $-O-$, $-S-$, $-N(R^N)-$, or $-P(R^P)-$; selected from oxygen or sulfur.

[0037] In embodiments, the catalyst system may include a metal–ligand complex according to formula (I), in which each of R^1 and R^{16} is independently selected from the group consisting of $-H$, (C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $-N=C(R^C)_2$, $R^CC(O)O-$, $R^COC(O)-$, $R^CC(O)N(R)-$, $(R^C)_2NC(O)-$, halogen, radicals having formula (II), radicals having formula (III), and radicals having formula (IV):

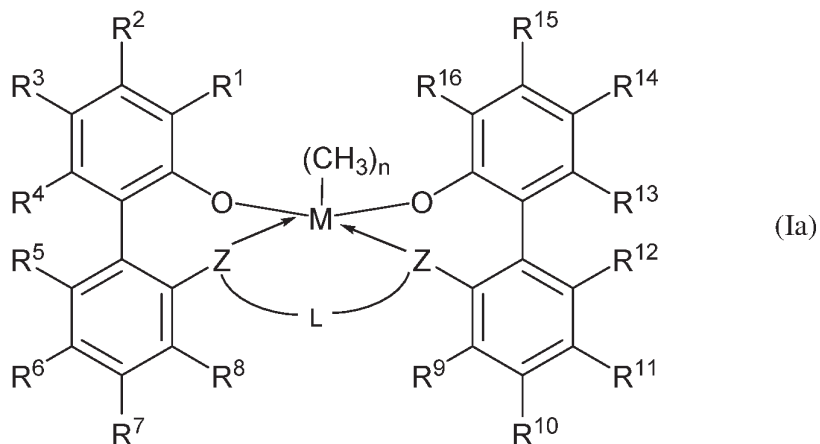


[0038] In formula (II), (III), and (IV), each of R^{31-35} , R^{41-48} , and R^{51-59} is independently chosen from $-H$, (C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $(R^C)_2C=N-$, $R^CC(O)O-$, $R^COC(O)-$, $R^CC(O)N(R^N)-$, $(R^C)_2NC(O)-$, or halogen, provided that at least one of R^1 or R^{16} is a radical having formula (II), a radical having formula (III), or a radical having formula (IV).

[0039] In formula (I), each of R^{2-4} , R^{5-8} , R^{9-12} , and R^{13-15} is independently selected from $-H$, (C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $(R^C)_2C=N-$, $R^CC(O)O-$, $R^COC(O)-$, $R^CC(O)N(R)-$, $(R^C)_2NC(O)-$, and halogen. In one or more embodiments, L is (C_2-C_{40}) hydrocarbylene or (C_2-C_{40}) heterohydrocarbylene; and each R^C , R^P , and R^N in formula (I) is independently a (C_1-C_{30}) hydrocarbyl, (C_1-C_{30}) heterohydrocarbyl, or $-H$.

[0040] In embodiments, the metal–ligand complex according to formula (I) has a solubility greater than the solubility of a corresponding comparative complex having a structure according to formula (Ia):

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[0041] In formula (Ia), M, n, each Z, each R^{1-16} , each R^{31-35} , each R^{41-48} , each R^{51-59} , L, each R^C , each R^P , and each R^N all are identical to corresponding groups of the metal–ligand complex according to formula (I). Thus, the corresponding comparative complex differs from the metal–ligand complex according to formula (I) in that all groups X of the metal–ligand complex according to formula (I) are replaced with methyl groups.

[0042] The metal–ligand complex of formula (I) and the corresponding comparative complex of formula (Ia) both have a weight percent (wt.%) solubility in various solvents. In general, as used herein, weight percent (wt.%) solubility of a solute in a solution is the weight of the solute divided by the weight of the solution, multiplied by 100. Solubility measurements of individual metal–ligand complexes are conducted as follows: The solute (procatalyst) is added to a solvent such as methylcyclohexane (MCH) or Isopar-ETM, such that the amount of solute added is greater than the amount that will dissolve in that amount of solvent. The resulting suspension is stirred for an hour and then allowed to sit overnight. After sitting overnight (approximately 16 hours), the suspension is filtered through a 0.2- μ m PTFE syringe filter into a tared vial. The amount of solution in the tared vial is weighed, and the solvent is removed under reduced pressure. The weight of the residual solid is measured after all solvent is removed. The wt.% solubility is determined by dividing the weight of the residual solid by the weight of solution in the tared vial and multiplying by 100.

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[0043] In one or more embodiments, the metal–ligand complex according to formula (I) has a weight percent (wt.%) solubility from 1.5 wt.% to 50 wt.% in methylcyclohexane (MCH) at ambient temperature and pressure. All individual values and subranges encompassed by “from 1.5 wt.% to 50 wt.%” are disclosed herein as separate embodiments. For example, in some embodiments, the solubility of the metal–ligand complex according to formula (I) is from 2.5 wt.% to 15 wt.%, from 1.5 wt.% to 10 wt.%, or from 3.0 wt.% to 15 wt.% in MCH, and in other embodiments, the solubility is greater than 20 wt.% in MCH at standard temperature and pressure (STP) (temperature of 22.5 ± 2.5 °C and a pressure of approximately 1 atmosphere).

[0044] In one or more embodiments, the metal–ligand complex according to formula (I) has a wt.% solubility from 1.5 wt.% to 50 wt.% in Isopar-ETM at ambient temperature and pressure. All individual values and subranges encompassed by “from 1.5 wt.% to 50 wt.%” are disclosed herein as separate embodiments. For example, in some embodiments, the metal–ligand complex according to formula (I) has a wt.% solubility from 2.5 wt.% to 15 wt.%, from 2.5 wt.% to 10 wt.%, or from 3.0 wt.% to 15 wt.% in Isopar-ETM, and in other embodiments, the wt.% solubility is greater than 20 wt.% in Isopar-ETM at STP.

[0045] The metal–ligand complex of formula (I) in MCH at STP has a wt.% solubility of W, as measured by the procedure previously described. The corresponding metal–ligand complex of formula (Ia) in MCH at STP has a wt.% solubility in MCH at STP of Y, as measured by the same procedure as the corresponding metal–ligand complex of formula (I). A wt.% solubility ratio (SR) is defined as W divided by Y (W/Y). For example, Complex A, a metal–ligand complex of formula (I), has a wt.% solubility of 10 wt.% in MCH at STP, as measured by the procedure in the preceding paragraphs. Complex B, the corresponding metal–ligand complex of formula (Ia), has a wt.% solubility of 2 wt.% in MCH at STP, as measured by the same procedure as Complex A. Thus, Complex A has a SR of 5.

[0046] In one or more embodiments of this disclosure, the SR of the metal–ligand complex of formula (I) is at least 1.5, at least 2, or at least 3. In some embodiments, the SR is from 1.5 to 50, from 2 to 50, from 2 to 10, from 3 to 15, or from 1.5 to 100. All individual

values and subranges encompassed by “from 2 to 100” are disclosed herein as separate embodiments.

[0047] Industrial-scale polymerization processes typically involve large volumes of procatalyst solutions in non-aromatic hydrocarbon solvents. When procatalyst solubility is low in non-aromatic hydrocarbons, very dilute solutions must be used. This necessitates larger volumes of solvent to transport the procatalyst. Increasing procatalyst solubility, can therefor lead to a greener process, as smaller solvent volumes could be used. Dilute solutions can also lead to process disruptions. In some cases, the procatalyst is so insoluble in non-aromatic hydrocarbons that even dilute solutions cannot be used, and undesirable aromatic hydrocarbon solvents are required.

[0048] In some embodiments, any or all of the chemical groups (e.g., L, R^{1-16} , R^{31-35} , R^{41-48} , R^{51-59}) of the metal–ligand complex of formula (I) may be unsubstituted. In other embodiments, none, any, or all of the chemical groups, L, R^{1-16} , R^{31-35} , R^{41-48} , R^{51-59} , of the metal–ligand complex of formula (I) may be substituted with one or more than one R^S . When two or more than two R^S are bonded to a same chemical group of the metal–ligand complex of formula (I), the individual R^S of the chemical group may be bonded to the same carbon atom or heteroatom or to different carbon atoms or heteroatoms. In some embodiments, none, any, or all of the chemical groups L, R^{1-16} , R^{31-35} , R^{41-48} , R^{51-59} may be persubstituted with R^S . In the chemical groups that are persubstituted with R^S , the individual R^S may all be the same or may be independently chosen.

[0049] In one or more embodiments, each X is independently $-(CH_2)SiR^X_3$, in which each R^X is independently a (C_1-C_{30}) alkyl or a (C_1-C_{30}) heteroalkyl and at least one R^X is (C_2-C_{30}) alkyl. In some embodiments, when one of R^X is a (C_1-C_{30}) heteroalkyl, the hetero atom is silica. In some embodiments, R^X is methyl, ethyl, propyl, 2-propyl, butyl, 1,1-dimethylethyl (or *tert*-butyl), pentyl, hexyl, heptyl, n-octyl, *tert*-octyl, or nonyl.

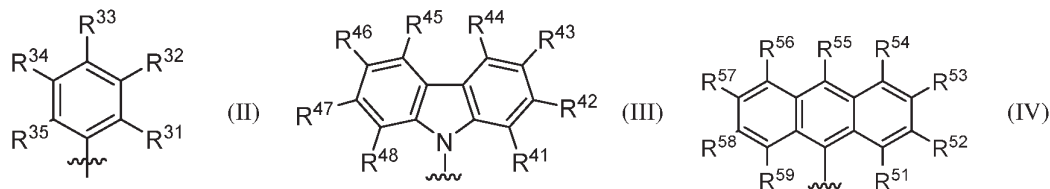
[0050] In one or more embodiments X is $-(CH_2)Si(CH_3)_2(CH_2CH_3)$; $-(CH_2)Si(CH_3)(CH_2CH_3)_2$, $-(CH_2)Si(CH_2CH_3)_3$, $-(CH_2)Si(CH_3)_2(n\text{-butyl})$, $-(CH_2)Si(CH_3)_2(n\text{-hexyl})$, $-(CH_2)Si(CH_3)(n\text{-Oct})R^X$, $-(CH_2)Si(n\text{-Oct})R^X_2$,

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$-(\text{CH}_2)\text{Si}(\text{CH}_3)_2(2\text{-ethylhexyl})$, $-(\text{CH}_2)\text{Si}(\text{CH}_3)_2(\text{dodecyl})$, $-\text{CH}_2\text{Si}(\text{CH}_3)_2\text{CH}_2\text{Si}(\text{CH}_3)_3$ (also referred to herein as $-\text{CH}_2\text{Si}(\text{CH}_3)_2\text{CH}_2\text{TMS}$). Optionally, in some embodiments, the metal–ligand complex according to formula (I), exactly two R^{X} are covalently linked or exactly three R^{X} are covalently linked.

[0051] In one or more embodiments, L is chosen from $(\text{C}_2\text{--C}_{12})$ alkylene, $(\text{C}_2\text{--C}_{12})$ heteroalkylene, $(\text{C}_6\text{--C}_{50})$ arylene, $(\text{C}_5\text{--C}_{50})$ heteroarylene, $(-\text{CH}_2\text{Si}(\text{R}^{\text{C}})_2\text{CH}_2-)$, $(-\text{CH}_2\text{CH}_2\text{Si}(\text{R}^{\text{C}})_2\text{CH}_2\text{CH}_2-)$, $(-\text{CH}_2\text{CH}_2\text{Ge}(\text{R}^{\text{C}})_2\text{CH}_2\text{CH}_2-)$, or $(-\text{CH}_2\text{Ge}(\text{R}^{\text{C}})_2\text{CH}_2-)$, in which R^{C} is $(\text{C}_1\text{--C}_{30})$ hydrocarbyl. In some embodiments, L is $-(\text{CH}_2)_x-$, in which subscript x is from 2 to 5. In other embodiments, subscript x, of $-(\text{CH}_2)_x-$, is 3 or 4. In some embodiments, L is 1,3-bis(methylene)cyclohexane or 1,2-bis(2-ylloethyl)cyclohexane.

[0052] In some embodiments, in the metal–ligand complex of formula (I), either one of R^1 or R^{16} , or both R^1 and R^{16} , are chosen from radicals having formula (II), formula (III), or formula (IV):



[0053] When present in the metal–ligand complex of formula (I) as part of a radical having formula (II), formula (III), or formula (IV), the groups R^{31-35} , R^{41-48} , and R^{51-59} of the metal–ligand complex of formula (I) are each independently chosen from $(\text{C}_1\text{--C}_{40})$ hydrocarbyl, $(\text{C}_1\text{--C}_{40})$ heterohydrocarbyl, $\text{Si}(\text{R}^{\text{C}})_3$, $\text{P}(\text{R}^{\text{P}})_2$, $\text{N}(\text{R}^{\text{N}})_2$, OR^{C} , SR^{C} , NO_2 , CN , CF_3 , $\text{R}^{\text{C}}\text{S}(\text{O})-$, $\text{R}^{\text{C}}\text{S}(\text{O})_2-$, $(\text{R}^{\text{C}})_2\text{C}=\text{N}-$, $\text{R}^{\text{C}}\text{C}(\text{O})\text{O}-$, $\text{R}^{\text{C}}\text{OC}(\text{O})-$, $\text{R}^{\text{C}}\text{C}(\text{O})\text{N}(\text{R}^{\text{N}})-$, $(\text{R}^{\text{N}})_2\text{NC}(\text{O})-$, halogen, hydrogen ($-\text{H}$), or combinations thereof. Independently each R^{C} , R^{P} , and R^{N} are unsubstituted $(\text{C}_1\text{--C}_{18})$ hydrocarbyl, $(\text{C}_1\text{--C}_{30})$ heterohydrocarbyl, or $-\text{H}$.

[0054] The groups R^1 and R^{16} in the metal–ligand complex of formula (I) are chosen independently of one another. For example, R^1 may be chosen from a radical having formula (II), (III), or (IV) and R^{16} may be a (C_1-C_{40}) hydrocarbyl; or R^1 may be chosen from a radical having formula (II), (III), or (IV) and R^{16} may be chosen from a radical having formula (II), (III), or (IV) the same as or different from that of R^1 . Both R^1 and R^{16} may be radicals having formula (II), for which the groups R^{31-35} are the same or different in R^1 and R^{16} . In other examples, both R^1 and R^{16} may be radicals having formula (III), for which the groups R^{41-48} are the same or different in R^1 and R^{16} ; or both R^1 and R^{16} may be radicals having formula (IV), for which the groups R^{51-59} are the same or different in R^1 and R^{16} .

[0055] In some embodiments, at least one of R^1 and R^{16} is a radical having formula (II), where R^{32} and R^{34} are *tert*-butyl.

[0056] In some embodiments, when at least one of R^1 or R^{16} is a radical having formula (III), one of or both of R^{43} and R^{46} is *tert*-butyl and each of R^{41-42} , R^{44-45} , and R^{47-48} are $-H$. In other embodiments, one of or both of R^{42} and R^{47} is *tert*-butyl and R^{41} , R^{43-46} , and R^{48} are $-H$. In some embodiments, both R^{42} and R^{47} are $-H$.

[0057] In one or more embodiments, R^3 and R^{14} are (C_1-C_{12}) alkyl. In some embodiments, R^3 and R^{14} are *tert*-octyl, *n*-octyl, methyl, ethyl, propyl, 2-propyl, butyl, 1,1-dimethylethyl (or *tert*-butyl). In one or more embodiments, R^6 and R^{11} are halogen. In some embodiments, R^3 and R^{14} are methyl; and R^6 and R^{11} are halogen.

[0058] In some embodiments of the metal–ligand complex of formula (I), when R^{5-7} are fluorine, not more than one of R^{10-12} is fluorine. In other embodiments, when R^{10-12} are fluorine, not more than one of R^{5-7} is fluorine. In other embodiments, fewer than four of R^{5-7} and R^{10-12} are fluorine. In one or more embodiments, R^7 , R^8 , R^9 , and R^{10} are $-H$. In some embodiments, R^7 and R^{10} are halogen. In some embodiments, two of R^{5-7} are fluorine and two of R^{10-12} are fluorine.

[0059] The M in the metal–ligand complex of formula (I) may be a transition metal such as titanium (Ti), zirconium (Zr), or hafnium (Hf), and the transition metal may have a formal oxidation state of +2, +3, or +4.

[0060] The metal M in the metal–ligand complex of formula (I) may be derived from a metal precursor that is subsequently subjected to a single-step or multi-step synthesis to prepare the metal–ligand complex. Suitable metal precursors may be monomeric (one metal center), dimeric (two metal centers), or may have a plurality of metal centers greater than two, such as 3, 4, 5, or more than 5 metal centers. Specific examples of suitable hafnium and zirconium precursors, for example, include, but are not limited to HfCl_4 , HfMe_4 , $\text{Hf}(\text{CH}_2\text{Ph})_4$, $\text{Hf}(\text{CH}_2\text{CMe}_3)_4$, $\text{Hf}(\text{CH}_2\text{SiMe}_3)_4$, $\text{Hf}(\text{CH}_2\text{Ph})_3\text{Cl}$, $\text{Hf}(\text{CH}_2\text{CMe}_3)_3\text{Cl}$, $\text{Hf}(\text{CH}_2\text{SiMe}_3)_3\text{Cl}$, $\text{Hf}(\text{CH}_2\text{Ph})_2\text{Cl}_2$, $\text{Hf}(\text{CH}_2\text{CMe}_3)_2\text{Cl}_2$, $\text{Hf}(\text{CH}_2\text{SiMe}_3)_2\text{Cl}_2$, $\text{Hf}(\text{NMe}_2)_4$, $\text{Hf}(\text{NEt}_2)_4$, and $\text{Hf}(\text{N}(\text{SiMe}_3)_2)_2\text{Cl}_2$; ZrCl_4 , ZrMe_4 , $\text{Zr}(\text{CH}_2\text{Ph})_4$, $\text{Zr}(\text{CH}_2\text{CMe}_3)_4$, $\text{Zr}(\text{CH}_2\text{SiMe}_3)_4$, $\text{Zr}(\text{CH}_2\text{Ph})_3\text{Cl}$, $\text{Zr}(\text{CH}_2\text{CMe}_3)_3\text{Cl}$, $\text{Zr}(\text{CH}_2\text{SiMe}_3)_3\text{Cl}$, $\text{Zr}(\text{CH}_2\text{Ph})_2\text{Cl}_2$, $\text{Zr}(\text{CH}_2\text{CMe}_3)_2\text{Cl}_2$, $\text{Zr}(\text{CH}_2\text{SiMe}_3)_2\text{Cl}_2$, $\text{Zr}(\text{NMe}_2)_4$, $\text{Zr}(\text{NEt}_2)_4$, $\text{Zr}(\text{NMe}_2)_2\text{Cl}_2$, $\text{Zr}(\text{NEt}_2)_2\text{Cl}_2$, $\text{Zr}(\text{N}(\text{SiMe}_3)_2)_2\text{Cl}_2$, TiBn_4 , TiCl_4 and $\text{Ti}(\text{CH}_2\text{Ph})_4$. Lewis base adducts of these examples are also suitable as metal precursors, for example, ethers, amines, thioethers, and phosphines are suitable as Lewis bases. Specific examples include $\text{HfCl}_4(\text{THF})_2$, $\text{HfCl}_4(\text{SMe}_2)_2$ and $\text{Hf}(\text{CH}_2\text{Ph})_2\text{Cl}_2(\text{OEt}_2)$. Activated metal precursors may be ionic or zwitterionic compounds, such as $(\text{M}(\text{CH}_2\text{Ph})_3^+)(\text{B}(\text{C}_6\text{F}_5)_4^-)$ or $(\text{M}(\text{CH}_2\text{Ph})_3^+)(\text{PhCH}_2\text{B}(\text{C}_6\text{F}_5)_3^-)$ where M is defined above as being Hf or Zr.

[0061] In the metal–ligand complex of formula (I), each Z independently is O, S, $\text{N}(\text{C}_1\text{--C}_{40})\text{hydrocarbyl}$, or $\text{P}(\text{C}_1\text{--C}_{40})\text{hydrocarbyl}$. In some embodiments, each Z is different. For example, one Z is O and the other Z is NCH_3 . In some embodiments, one Z is O and one Z is S. In another embodiment, one Z is S and one Z is $\text{N}(\text{C}_1\text{--C}_{40})\text{hydrocarbyl}$, (for example, NCH_3). In a further embodiment, each Z is the same. In yet another embodiment, each Z is O. In another embodiment, each Z is S.

Cocatalyst Component

[0062] The catalyst system comprising a metal–ligand complex of formula (I) may be rendered catalytically active by any technique known in the art for activating metal-based catalysts of olefin polymerization reactions. For example, the procatalyst according to a metal–ligand complex of formula (I) may be rendered catalytically active by contacting the complex to, or combining the complex with, an activating co-catalyst. Additionally, the metal–ligand complex according for formula (I) includes both a procatalyst form, which is neutral, and a catalytic form, which may be positively charged due to the loss of a monoanionic ligand, such a benzyl or phenyl. Suitable activating co-catalysts for use herein include alkyl aluminums; polymeric or oligomeric alumoxanes (also known as aluminoxanes); neutral Lewis acids; and non-polymeric, non-coordinating, ion-forming compounds (including the use of such compounds under oxidizing conditions). A suitable activating technique is bulk electrolysis. Combinations of one or more of the foregoing activating co-catalysts and techniques are also contemplated. The term “alkyl aluminum” means a monoalkyl aluminum dihydride or monoalkylaluminum dihalide, a dialkyl aluminum hydride or dialkyl aluminum halide, or a trialkylaluminum. Examples of polymeric or oligomeric alumoxanes include methylalumoxane, triisobutylaluminum-modified methylalumoxane, and isobutylalumoxane.

[0063] Lewis acid activating co-catalysts include Group 13 metal compounds containing (C₁–C₂₀)hydrocarbyl substituents as described herein. In some embodiments, Group 13 metal compounds are tri((C₁–C₂₀)hydrocarbyl)-substituted-aluminum or tri((C₁–C₂₀)hydrocarbyl)-boron compounds. In other embodiments, Group 13 metal compounds are tri(hydrocarbyl)-substituted-aluminum, tri((C₁–C₂₀)hydrocarbyl)-boron compounds, tri((C₁–C₁₀)alkyl)aluminum, tri((C₆–C₁₈)aryl)boron compounds, and halogenated (including perhalogenated) derivatives thereof. In further embodiments, Group 13 metal compounds are tris(fluoro-substituted phenyl)boranes, tris(pentafluorophenyl)borane. In some embodiments, the activating co-catalyst is a tris((C₁–C₂₀)hydrocarbyl borate (e.g. trityl tetrafluoroborate) or a tri((C₁–C₂₀)hydrocarbyl)ammonium tetra((C₁–C₂₀)hydrocarbyl)borane (e.g. bis(octadecyl)methylammonium tetrakis(pentafluorophenyl)borane). As used herein, the term

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“ammonium” means a nitrogen cation that is a $((C_1-C_{20})hydrocarbyl)_4N^+$, a $((C_1-C_{20})hydrocarbyl)_3N(H)^+$, a $((C_1-C_{20})hydrocarbyl)_2N(H)_2^+$, $(C_1-C_{20})hydrocarbylN(H)_3^+$, or $N(H)_4^+$, wherein each $(C_1-C_{20})hydrocarbyl$, when two or more are present, may be the same or different.

[0064] Combinations of neutral Lewis acid activating co-catalysts include mixtures comprising a combination of a tri((C_1-C_4) alkyl)aluminum and a halogenated tri((C_6-C_{18}) aryl)boron compound, especially a tris(pentafluorophenyl)borane. Other embodiments are combinations of such neutral Lewis acid mixtures with a polymeric or oligomeric alumoxane, and combinations of a single neutral Lewis acid, especially tris(pentafluorophenyl)borane with a polymeric or oligomeric alumoxane. Ratios of numbers of moles of (metal–ligand complex): (tris(pentafluoro-phenyl)borane): (alumoxane) [e.g., (Group 4 metal–ligand complex) : (tris(pentafluoro-phenyl)borane): (alumoxane)] are from 1:1:1 to 1:10:30, in other embodiments, from 1:1:1.5 to 1:5:10.

[0065] The catalyst system that includes the metal–ligand complex of formula (I) may be activated to form an active catalyst composition by combination with one or more cocatalysts, for example, a cation forming cocatalyst, a strong Lewis acid, or combinations thereof. Suitable activating co-catalysts include polymeric or oligomeric aluminoxanes, especially methyl aluminoxane, as well as inert, compatible, noncoordinating, ion forming compounds. Exemplary suitable co-catalysts include, but are not limited to modified methyl aluminoxane (MMAO), bis(hydrogenated tallow alkyl)methyl, tetrakis(pentafluorophenyl)borate(1–) amine, and combinations thereof.

[0066] In some embodiments, more than one of the foregoing activating co-catalysts may be used in combination with each other. A specific example of a co-catalyst combination is a mixture of a tri((C_1-C_4) hydrocarbyl)aluminum, tri((C_1-C_4) hydrocarbyl)borane, or an ammonium borate with an oligomeric or polymeric alumoxane compound. The ratio of total number of moles of one or more metal–ligand complexes of formula (I) to total number of moles of one or more of the activating co-catalysts is from 1:10,000 to 100:1. In some embodiments, the ratio is at least 1:5000, in some other embodiments, at least 1: 1000; and

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10:1 or less, and in some other embodiments, 1:1 or less. When an alumoxane alone is used as the activating co-catalyst, preferably the number of moles of the alumoxane that are employed is at least 100 times the number of moles of the metal–ligand complex of formula (I). When tris(pentafluorophenyl)borane alone is used as the activating co-catalyst, in some other embodiments, the number of moles of the tris(pentafluorophenyl)borane that are employed to the total number of moles of one or more metal–ligand complexes of formula (I) from 0.5: 1 to 10:1, from 1:1 to 6:1, or from 1:1 to 5:1. The remaining activating co-catalysts are generally employed in approximately mole quantities equal to the total mole quantities of one or more metal–ligand complexes of formula (I).

[0067] In some embodiments, when more than one of the foregoing co-catalysts is used in combination with a second co-catalyst, one of the co-catalysts may function as a scavenger. The purpose of the scavenger is to react with any water or other impurities present in the system that would otherwise react with the catalyst leading to reduced efficiency.

Polyolefins

[0068] The catalytic systems described in the preceding paragraphs are utilized in the polymerization of olefins, primarily ethylene and propylene. In some embodiments, there is only a single type of olefin or α -olefin in the polymerization scheme, creating a homopolymer. However, additional α -olefins may be incorporated into the polymerization procedure. The additional α -olefin co-monomers typically have no more than 20 carbon atoms. For example, the α -olefin co-monomers may have 3 to 10 carbon atoms or 3 to 8 carbon atoms. Exemplary α -olefin co-monomers include, but are not limited to, propylene, 1-butene, 1-pentene, 1-hexene, 1-heptene, 1-octene, 1-nonene, 1-decene, and 4-methyl-1-pentene. For example, the one or more α -olefin co-monomers may be selected from the group consisting of propylene, 1-butene, 1-hexene, and 1-octene; or in the alternative, from the group consisting of 1-hexene and 1-octene.

[0069] The ethylene-based polymers, for example homopolymers and/or interpolymers (including copolymers) of ethylene and optionally one or more co-monomers such as α -olefins, may comprise from at least 50 mole percent (mol%) monomer units derived from ethylene. All individual values and subranges encompassed by “from at least 50 mole percent” are disclosed herein as separate embodiments; for example, the ethylene based polymers, homopolymers and/or interpolymers (including copolymers) of ethylene and optionally one or more co-monomers such as α -olefins may comprise at least 60 mole percent monomer units derived from ethylene; at least 70 mole percent monomer units derived from ethylene; at least 80 mole percent monomer units derived from ethylene; or from 50 to 100 mole percent monomer units derived from ethylene; or from 80 to 100 mole percent monomer units derived from ethylene.

[0070] In some embodiments, the ethylene-based polymers may comprise at least 90 mole percent units derived from ethylene. All individual values and subranges from at least 90 mole percent are included herein and disclosed herein as separate embodiments. For example, the ethylene-based polymers may comprise at least 93 mole percent units derived from ethylene; at least 96 mole percent units; at least 97 mole percent units derived from ethylene; or in the alternative, from 90 to 100 mole percent units derived from ethylene; from 90 to 99.5 mole percent units derived from ethylene; or from 97 to 99.5 mole percent units derived from ethylene.

[0071] In some embodiments of the ethylene-based polymer, the amount of additional α -olefin is less than 50 mole percent (mol%); other embodiments include at least 1 mol% to 25 mol%; and in further embodiments the amount of additional α -olefin includes at least 5 mol% to 103 mol%. In some embodiments, the additional α -olefin is 1-octene.

[0072] Any conventional polymerization processes may be employed to produce the ethylene-based polymers. Such conventional polymerization processes include, but are not limited to, solution polymerization processes, gas phase polymerization processes, slurry phase polymerization processes, and combinations thereof using one or more conventional

reactors such as loop reactors, isothermal reactors, fluidized bed gas phase reactors, stirred tank reactors, batch reactors in parallel, series, or any combinations thereof, for example.

[0073] In one embodiment, the ethylene-based polymer may be produced via solution polymerization in a dual reactor system, for example a dual loop reactor system, wherein ethylene and, optionally, one or more α -olefins are polymerized in the presence of the catalyst system, as described herein, and optionally one or more co-catalysts. In another embodiment, the ethylene-based polymer may be produced via solution polymerization in a dual reactor system, for example a dual loop reactor system, wherein ethylene and optionally one or more α -olefins are polymerized in the presence of the catalyst system in this disclosure, and as described herein, and optionally one or more other catalysts. The catalyst system, as described herein, can be used in the first reactor, or second reactor, optionally in combination with one or more other catalysts. In one embodiment, the ethylene-based polymer may be produced via solution polymerization in a dual reactor system, for example a dual loop reactor system, wherein ethylene and optionally one or more α -olefins are polymerized in the presence of the catalyst system, as described herein, in both reactors.

[0074] In another embodiment, the ethylene-based polymer may be produced via solution polymerization in a single reactor system, for example a single loop reactor system, in which ethylene and optionally one or more α -olefins are polymerized in the presence of the catalyst system, as described within this disclosure, and optionally one or more cocatalysts, as described in the preceding paragraphs.

[0075] The ethylene-based polymers may further comprise one or more additives. Such additives include, but are not limited to, antistatic agents, color enhancers, dyes, lubricants, pigments, primary antioxidants, secondary antioxidants, processing aids, UV stabilizers, and combinations thereof. The ethylene-based polymers may contain any amounts of additives. The ethylene-based polymers may comprise from about 0 to about 10 percent by the combined weight of such additives, based on the weight of the ethylene-based polymers and the one or more additives. The ethylene-based polymers may further comprise fillers, which may include, but are not limited to, organic or inorganic fillers. The ethylene-based polymers

may contain from about 0 to about 20 weight percent fillers such as, for example, calcium carbonate, talc, or $\text{Mg}(\text{OH})_2$, based on the combined weight of the ethylene-based polymers and all additives or fillers. The ethylene-based polymers may further be blended with one or more polymers to form a blend.

[0076] In some embodiments, a polymerization process for producing an ethylene-based polymer may include polymerizing ethylene and at least one additional α -olefin in the presence of a catalyst system, wherein the catalyst system incorporates at least one metal–ligand complex of formula (I). The polymer resulting from such a catalyst system that incorporates the metal–ligand complex of formula (I) may have a density according to ASTM D792 (incorporated herein by reference in its entirety) from 0.850 g/cm^3 to 0.950 g/cm^3 , from 0.880 g/cm^3 to 0.920 g/cm^3 , from 0.880 g/cm^3 to 0.910 g/cm^3 , or from 0.880 g/cm^3 to 0.900 g/cm^3 , for example.

[0077] In another embodiment, the polymer resulting from the catalyst system that includes the metal–ligand complex of formula (I) has a melt flow ratio (I_{10}/I_2) from 5 to 15, in which melt index I_2 is measured according to ASTM D1238 (incorporated herein by reference in its entirety) at 190°C and 2.16 kg load, and melt index I_{10} is measured according to ASTM D1238 at 190°C and 10 kg load. In other embodiments the melt flow ratio (I_{10}/I_2) is from 5 to 10, and in others, the melt flow ratio is from 5 to 9.

[0078] In some embodiments, the polymer resulting from the catalyst system that includes the metal–ligand complex of formula (I) has a molecular-weight distribution (MWD) from 1.5 to 25, where MWD is defined as M_w/M_n with M_w being a weight-average molecular weight and M_n being a number-average molecular weight. In other embodiments, the polymers resulting from the catalyst system have a MWD from 1.5 to 6. Another embodiment includes a MWD from 1.5 to 3; and other embodiments include MWD from 2 to 2.5.

[0079] Embodiments of the catalyst systems described in this disclosure yield unique polymer properties as a result of the high molecular weights of the polymers formed and the amount of the co-monomers incorporated into the polymers.

[0080] All solvents and reagents are obtained from commercial sources and used as received unless otherwise noted. Anhydrous toluene, hexanes, tetrahydrofuran, and diethyl ether are purified *via* passage through activated alumina and, in some cases, Q-5 reactant. Solvents used for experiments performed in a nitrogen-filled glovebox are further dried by storage over activated 4Å molecular sieves. Glassware for moisture-sensitive reactions is dried in an oven overnight prior to use. NMR spectra are recorded on Varian 400-MR and VNMR5-500 spectrometers. ¹H NMR data are reported as follows: chemical shift (multiplicity (br = broad, s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, sex = sextet, sept = septet and m = multiplet), integration, and assignment). Chemical shifts for ¹H NMR data are reported in ppm downfield from internal tetramethylsilane (TMS, δ scale) using residual protons in the deuterated solvent as references. ¹³C NMR data are determined with ¹H decoupling, and the chemical shifts are reported downfield from tetramethylsilane (TMS, δ scale) in ppm versus the using residual carbons in the deuterated solvent as references.

SymRAD HT-GPC Analysis

[0081] The molecular weight data is determined by analysis on a hybrid Robot-Assisted Dilution High-Temperature Gel Permeation Chromatographer (Sym-RAD-GPC) built by Symyx/Dow. The polymer samples are dissolved by heating for 120 minutes at 160°C in 1,2,4-trichlorobenzene (TCB) at a concentration of 10 mg/mL stabilized by 300 parts per million (ppm) of butylated hydroxyl toluene (BHT). Each sample was diluted to 1 mg/mL immediately before the injection of a 250 µL aliquot of the sample. The GPC is equipped with two Polymer Labs PLgel 10 µm MIXED-B columns (300 x 10 mm) at a flow rate of 2.0 mL/minute at 160°C. Sample detection is performed using a PolyChar IR4 detector in concentration mode. A conventional calibration of narrow polystyrene (PS) standards is utilized with apparent units adjusted to homo-polyethylene (PE) using known Mark-Houwink coefficients for PS and PE in TCB at this temperature.

1-Octene Incorporation IR Analysis

[0082] The running of samples for the HT-GPC analysis precedes the IR analysis. For the IR analysis, a 48-well HT silicon wafer is utilized for deposition and analysis of 1-octene incorporation of samples. For the analysis, the samples are heated to 160 °C for less than or equal to 210 minutes; the samples are reheated to remove magnetic GPC stir bars and are shaken with glass-rod stir bars on a J-KEM Scientific heated robotic shaker. Samples are deposited while being heated using a Tecan MiniPrep 75 deposition station, and the 1,2,4-trichlorobenzene is evaporated off the deposited wells of the wafer at 160°C under nitrogen purge. The analysis of 1-octene is performed on the HT silicon wafer using a NEXUS 670 E.S.P. FT-IR.

Batch Reactor Polymerization Procedure

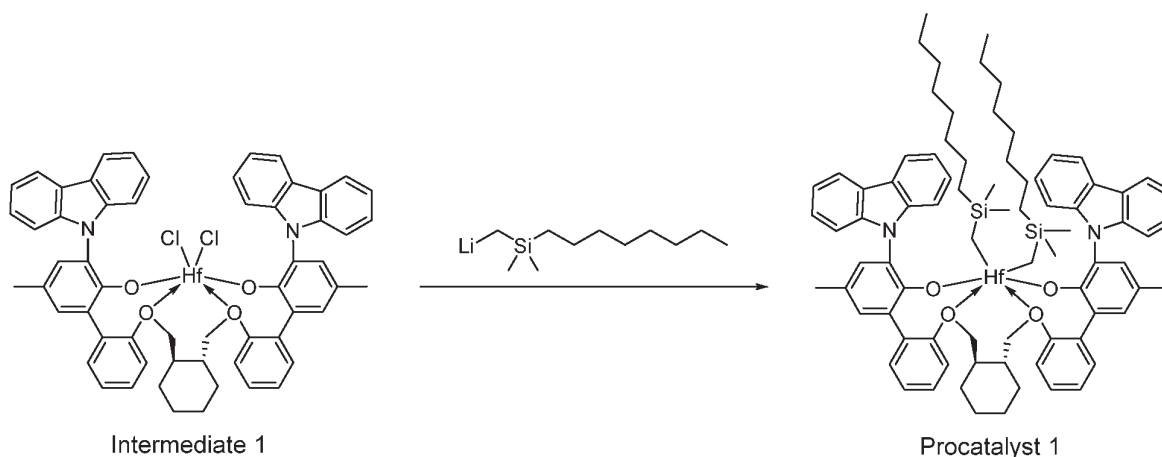
[0083] The batch reactor polymerization reactions are conducted in a one gallon (3.79 L), stirred autoclave reactor that is charged with ca. 1.35 kg of Isopar™ E mixed alkanes solvent and 1-octene (250 g). The reactor is then heated to the desired temperature and charged with hydrogen (if desired), followed by an amount of ethylene to bring the total pressure to ca. 450 psig (2.95 MPa). The ethylene feed was passed through an additional purification column prior to entering the reactor. The catalyst composition was prepared in a drybox, under inert atmosphere, by mixing the desired pro-catalyst and a cocatalyst (a mixture of 1.2 equiv of tetrakis(pentafluorophenyl)borate(1-) amine, and 50 equiv of triisobutylaluminum modified alumoxane (MMAO-3A)), with additional solvent, to give a total volume of about 17 mL. The activated catalyst mixture was then quick-injected into the reactor. The reactor pressure and temperature were kept constant, by feeding ethylene during the polymerization, and cooling the reactor as needed. After 10 minutes, the ethylene feed was shut off, and the solution transferred into a nitrogen-purged resin kettle. The polymer was thoroughly dried in a vacuum oven, and the reactor was thoroughly rinsed with hot Isopar™ E between polymerization runs.

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EXAMPLES

[0084] Example 1 comprises synthetic procedures for intermediates of procatalysts, for reagents used to make procatalysts, and for isolated procatalysts themselves. One or more features of the present disclosure are illustrated in view of the examples as follows:

[0085] Example 1 – Synthesis of Procatalyst 1



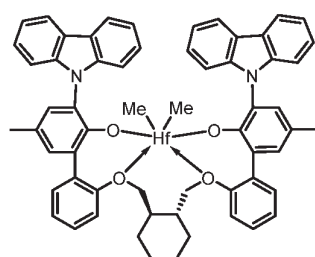
[0086] A solution of Intermediate 1 (2.271 g, 1.84 mmol) in a mixture of benzene (40 mL) and toluene (40 mL) was chilled in a glovebox freezer (−35 °C). A 14 mL solution of dimethyloctylsilylmethyl lithium in hexane (0.13 M, 1.84 mmol) was added to the solution and the reaction mixture was stirred over the weekend at ambient temperature to give a clear colorless solution. At this time the solution was cooled in the glovebox freezer, additional dimethyloctylsilylmethyl lithium (5.26 mL, 0.69 mmol) was added, and the reaction mixture was stirred overnight at 60 °C. Thrice more the reaction mixture was cooled in the glovebox freezer, more dimethyloctylsilylmethyl lithium (4.5 mL, 0.59 mmol; 2.8 mL, 0.36 mmol; 2.2 mL, 0.29 mmol) was added, and the reaction mixture was stirred overnight. The reaction mixture was filtered and the volatiles were removed under reduced pressure. The residue was extracted with warm (50 °C) hexanes, the extract was filtered, and the volatiles were removed under reduced pressure. The residue was extracted a second time with warm (50 °C) hexanes, the extract was filtered from a small amount of insoluble material, and the volatiles were

removed under reduced pressure to give the product as a slightly sticky beige solid. This reaction provided a yield of 2.13 g, 83.6% yield.

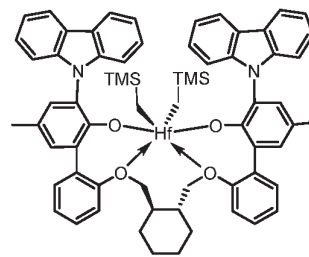
[0087] ^1H NMR (400 MHz, Benzene- d_6) δ 8.37 – 8.26 (m, 1.5H), 8.17 (ddt, J = 7.8, 6.8, 1.3 Hz, 1.7H), 8.14 – 7.82 (m, 3.5H), 7.69 – 7.17 (m, 13.3H), 7.13 – 6.64 (m, 10.4H), 4.93 (dd, J = 8.3, 1.2 Hz, 0.9H), 4.68 (dd, J = 8.2, 1.2 Hz, 0.8H), 4.19 (dd, J = 12.4, 8.6 Hz, 1.3H), 3.85 (d, J = 11.0 Hz, 1.1H), 3.76 (d, J = 10.8 Hz, 0.7H), 3.38 (d, J = 12.4 Hz, 1.3H), 3.19 (d, J = 10.9 Hz, 1.1H), 2.21 – 2.00 (m, 6H), 1.85 – 0.33 (m, 73H), 0.32 - 0.25 (m, 4.6H), 0.22 – 0.04 (m, 5.4H), 0.02 (s, 1H), 0.00 – -0.13 (m, 2.3H), -0.15 (d, J = 2.5 Hz, 2.6H), -0.33 (s, 1.3H), -0.38 (s, 1.6H), -1.70 (dd, J = 372.3, 13.0 Hz, 1.7H), -1.73 (dd, J = 272.4, 13.1 Hz, 1.8H).

[0088] Procatalyst 1, Comparative Procatalyst C1, and Comparative Procatalyst C2 were individually reacted using the polymerization conditions in a single reactor system, as previously described. Properties for the resulting polymers are reported in Table 2. Comparative Procatalyst C1 has a structure according to formula (Ia). When compared to Comparative Procatalyst C1 and Comparative Procatalyst C2, a significant increase in weight percent solubility was observed for the Procatalyst 1, which is a metal–ligand complex according to formula (I).

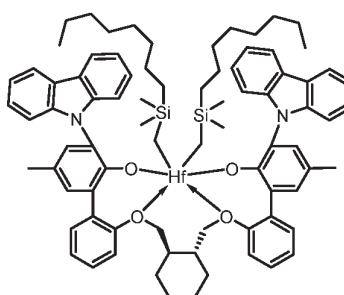
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Comparative C1



Comparative C2



Procatalyst 1

Table 1: Solubility Data at 25 °C

Procatalyst	Solubility (wt.%)	Solubility Ratio	Solvent
Comparative C1	1.5	N/A	Methylcyclohexane
Comparative C2	1.1	N/A	Isopar™ E
Procatalyst 1	> 10 wt.%	≥6.67	Methylcyclohexane

Table 2: Batch Reactor Screening of Procatalyst 1 and Comparative C1

Catalyst	T (°C)	H ₂ ** (mmol)	Efficiency* (MM g/g)	M _w (kg/mol)	M _w /M _n	T _m (°C)	Density (g/cm ³)
Comparative C1	160	0	1.82	1,055	2.6	89	0.8909
Comparative C2	160	0	1.07	1,076	2.5	90	0.8933
Comparative C2	190	0	0.24	519	2.3	91	0.8949
Comparative C2	190	0	0.15	494	2.3	91	0.8936

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*Efficiency is defined in units of 10^6 grams polymer per gram of active metal (Hf or Zr).

**H₂ (mol %) is defined as: the mole fraction of hydrogen, relative to ethylene, fed into the reactor.

Table 3: Batch Reactor Screening of Procatalyst 1 and Comparative C1

Catalyst	T (°C)	**H ₂ (mmol)	*Efficiency (MM g/g)	<i>M_w</i> (kg/mol)	<i>M_w/M_n</i>	<i>T_m</i> (°C)	Density (g/cm ³)
Comparative C1	160	0	1.01	1,038	3.0	88	0.8901
Procatalyst 1	160	0	0.09	1,080	2.9	89	0.8915
Procatalyst 1	160	40	0.10	486	2.3	89	0.8929
Comparative C1	190	0	0.22	495	2.3	90	0.8923
Procatalyst 1	190	0	0.01	548	2.5	91	0.8951
Procatalyst 1	190	40	0.02	313	2.4	92	0.8964

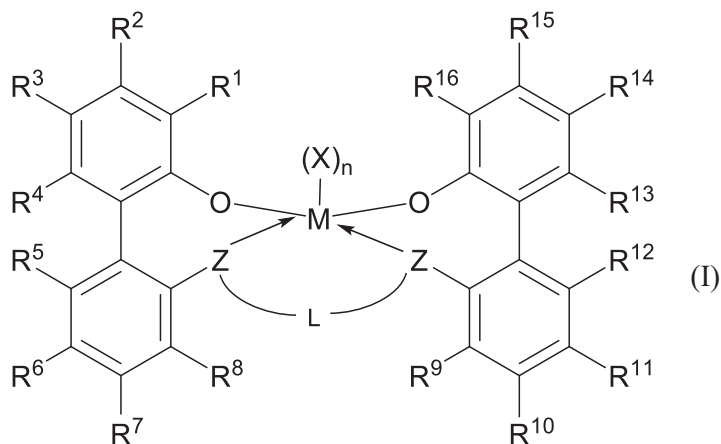
*Efficiency is defined in units of 10^6 grams polymer per gram of active metal (Hf or Zr).

**H₂ (mol %) is defined as: the mole fraction of hydrogen, relative to ethylene, fed into the reactor.

[0089] Batch reactor conditions for Table 3: 1.47 kg of Isopar™ E; 100 grams of octene; 105 grams of ethylene were added at 160 °C or 88 grams of ethylene were added at 190 °C; RIBS : catalyst ratio was approximately 1.2; Procatalyst: activator ratio was 1:1.2; activator was [HNMe(C₁₈H₃₇)₂][B(C₆F₅)₄]; MMAO-3A was used as an impurity scavenger at a MMAO-3A:procatalyst mole ratio of approximately 50; total pressure was initially 410 psig.

CLAIMS

1. A catalyst system comprising a metal–ligand complex according to formula (I):



where:

M is a metal chosen from titanium, zirconium, or hafnium, the metal being in a formal oxidation state of +2, +3, or +4;

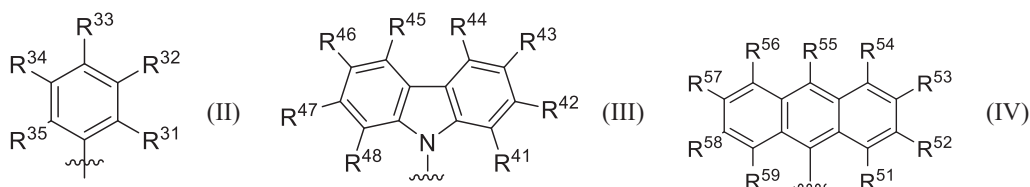
each X is selected from the group consisting of $-(CH_2)SiR^X_3$, each R^X is independently a (C_1-C_{30}) hydrocarbyl or a (C_1-C_{30}) heterohydrocarbyl, and at least one R^X is (C_2-C_{30}) hydrocarbyl, and any two R^X or all three R^X are optionally covalently linked;

n is 1 or 2;

each Z is independently chosen from $-O-$, $-S-$, $-N(R^N)-$, or $-P(R^P)-$;

R^1 and R^{16} are independently selected from the group consisting of $-H$,

(C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $-N=C(R^C)_2$, $R^CC(O)O-$, $R^COC(O)-$, $R^CC(O)N(R)-$, $(R^C)_2NC(O)-$, halogen, radicals having formula (II), radicals having formula (III), and radicals having formula (IV):



where each of R³¹-R³⁵, R⁴¹-R⁴⁸, and R⁵¹-R⁵⁹ is independently chosen from -H, (C₁-C₄₀)hydrocarbyl, (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^P)₂, -N(R^N)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, R^CS(O)-, R^CS(O)₂-, (R^C)₂C=N-, R^CC(O)O-, R^COC(O)-, R^CC(O)N(R^N)-, (R^C)₂NC(O)-, or halogen,

provided that at least one of R¹ or R¹⁶ is a radical having formula (II), a radical having formula (III), or a radical having formula (IV);

each of R²-R⁴, R⁵-R⁸, R⁹-R¹², and R¹³-R¹⁵ is independently selected from -H,

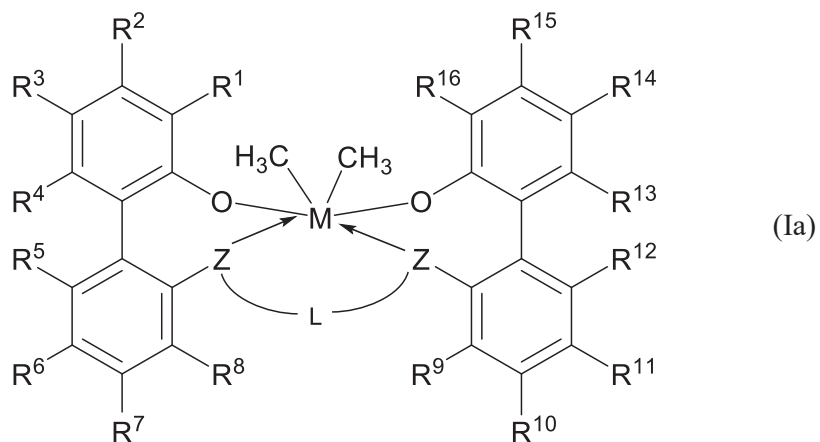
(C₁-C₄₀)hydrocarbyl, (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^P)₂, -N(R^N)₂-OR^C, -SR^C, -NO₂, -CN, -CF₃, R^CS(O)-, R^CS(O)₂-, (R^C)₂C=N-, R^CC(O)O-, R^COC(O)-, R^CC(O)N(R)-, (R^C)₂NC(O)-, and halogen, ;

L is (C₂-C₄₀)hydrocarbylene or (C₂-C₄₀)heterohydrocarbylene; and

each R^C, R^P, and R^N in formula (I) is independently a (C₁-C₃₀)hydrocarbyl,

(C₁-C₃₀)heterohydrocarbyl, or -H,

wherein the metal-ligand complex according to formula (I) has a wt.% solubility ratio W/Y of at least 1.5, wherein W is the wt. % solubility of the metal-ligand complex of formula (I) in methycyclohexane (MCH) at standard temperature and pressure (STP); wherein Y is the wt. % of a corresponding comparative metal-ligand complex of formula (Ia) in MCH at STP; and wherein the corresponding comparative complex has a structure according to formula (Ia):



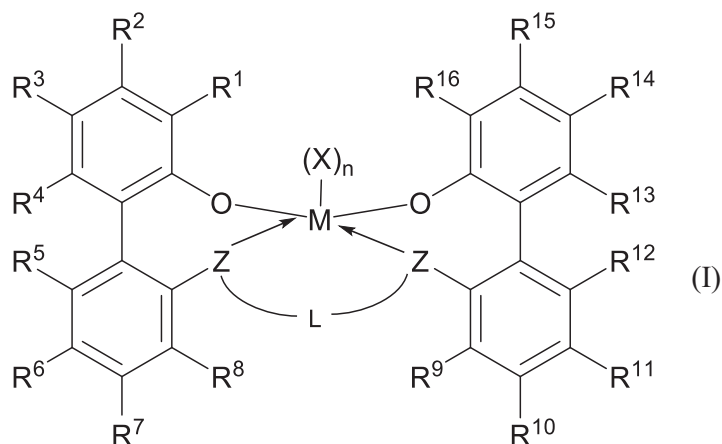
in which M, each Z, each R¹-R¹⁶, and L all are identical to corresponding groups of the metal-ligand complex according to formula (I).

2. The catalyst system according to claim 1, wherein:
M is zirconium or hafnium;
each X is $-(CH_2)Si(CH_2CH_3)_3$; and
each Z is oxygen.

3. The catalyst system according to claim 1, wherein:
M is zirconium or hafnium;
each X is selected from the group consisting of $-(CH_2)Si(CH_3)(n-Oct)R^X$; and
each Z is oxygen

4. The catalyst system according to claim 1, wherein exactly two R^X are covalently linked or exactly three R^X are covalently linked.

5. A catalyst system comprising a metal-ligand complex according to formula (I):



where:

M is a metal chosen from titanium, zirconium, or hafnium, the metal being in a formal oxidation state of +2, +3, or +4;

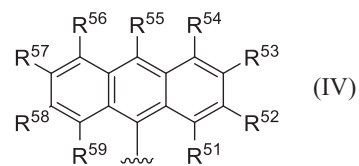
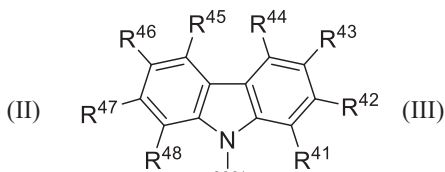
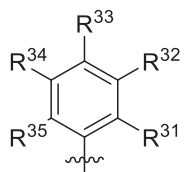
each X is selected from the group consisting of $-(CH_2)Si(n-Oct)R^X_2$, wherein each R^X is independently a (C_1-C_{30}) hydrocarbyl or a (C_1-C_{30}) heterohydrocarbyl, and any two R^X are optionally covalently linked;

n is 1 or 2;

each Z is $-O-$;

R^1 and R^{16} are independently selected from the group consisting of $-H$,

(C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $-N=C(R^C)_2$, $R^CC(O)O-$, $R^COC(O)-$, $R^CC(O)N(R)-$, $(R^C)_2NC(O)-$, halogen, radicals having formula (II), radicals having formula (III), and radicals having formula (IV):



where each of R^{31} - R^{35} , R^{41} - R^{48} , and R^{51} - R^{59} is independently chosen from $-H$, (C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $(R^C)_2C=N-$, $R^CC(O)O-$, $R^COC(O)-$, $R^CC(O)N(R^N)-$, $(R^C)_2NC(O)-$, or halogen,

provided that at least one of R^1 or R^{16} is a radical having formula (II), a radical having formula (III), or a radical having formula (IV);

each of R^2 - R^4 , R^5 - R^8 , R^9 - R^{12} , and R^{13} - R^{15} is independently selected from $-H$,

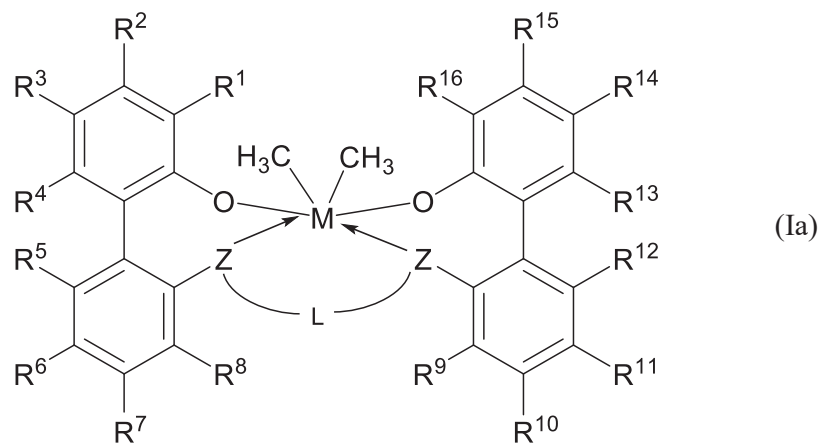
(C_1-C_{40}) hydrocarbyl, (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^P)_2$, $-N(R^N)_2-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $R^CS(O)-$, $R^CS(O)_2-$, $(R^C)_2C=N-$, $R^CC(O)O-$, $R^COC(O)-$, $R^CC(O)N(R)-$, $(R^C)_2NC(O)-$, and halogen, ;

L is (C_2-C_{40}) hydrocarbylene or (C_2-C_{40}) heterohydrocarbylene; and

each R^C , R^P , and R^N in formula (I) is independently a (C_1-C_{30}) hydrocarbyl,

(C_1-C_{30}) heterohydrocarbyl, or $-H$,

wherein the metal-ligand complex according to formula (I) has a wt.% solubility ratio W/Y of at least 1.5, wherein W is the wt. % solubility of the metal-ligand complex of formula (I) in methylcyclohexane (MCH) at standard temperature and pressure (STP); wherein Y is the wt. % of a corresponding comparative metal-ligand complex of formula (Ia) in MCH at STP; and wherein the corresponding comparative complex has a structure according to formula (Ia):



in which M , each Z , each R^1 - R^{16} , and L all are identical to corresponding groups of the metal-ligand complex according to formula (I).