

TETRAPHOSPHORUS LIGANDS FOR CATALYTIC HYDROFORMYLATION AND RELATED REACTIONS

Cross Reference to Related Application

[001] This application claims the benefit of priority of Provisional Application No. 60/750,733 filed December 15, 2005, which is incorporated herein by reference.

Field of the Invention

[002] The present invention relates to new phosphorous ligands and their applications in hydroformylation and related reactions. More particularly, the present invention relates to transition metal complexes having chelating tetraphosphorus ligands with multichelating modes. Tetraphosphorus ligands with multichelating modes can enhance coordinating abilities for transition metals such as Rh and Ni, and thus enhance selectivities of catalytic reactions. The transition metal-tetraphosphorus complexes according to the present invention are useful as catalysts in hydroformylation, isomerization-hydroformylation, hydrocarboxylation, hydrocyanation, tandem reactions such as isomerization-formylation, and hydroaminomethylation.

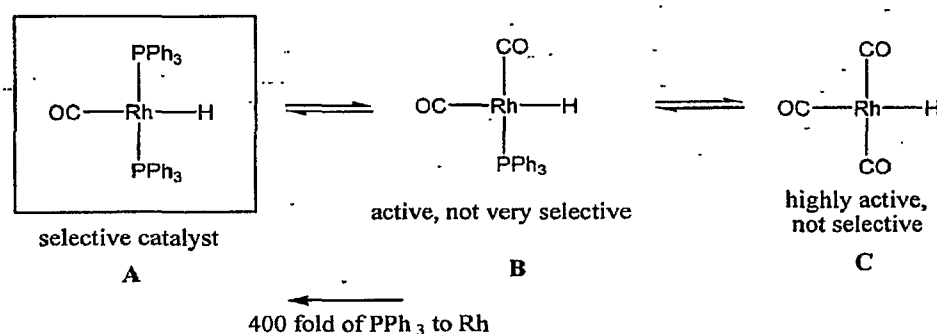
Background of the Invention

[003] Hydroformylation, discovered by Roelen in 1938, has been the largest homogeneous catalytic process in industry. More than 15 billion pounds of aldehydes and alcohols per year have been produced based on Fe, Zn, Mn, Co, Cu, Ag, Ni, Pt, Pd, Rh, Ru and Ir based catalysts. In these processes, achieving high selectivity to linear products is extremely important for commercial application. Despite the extensive investigation by both academic and industrial groups such as BASF, Dow, Shell and Eastman, among others, there still remain fundamental and practical problems regarding selectivity. New concepts for controlling selectivities are very important in catalytic reactions. Highly efficient selective catalysts will allow some bulky chemicals to be produced in an environmentally sound manner under milder conditions.

[004] Cobalt catalysts (e.g., $\text{HCo}(\text{CO})_4$) dominated industrial hydroformylation until rhodium catalysts (e.g., $\text{HRh}(\text{CO})_2(\text{PPh}_3)_3$) were introduced in earlier 1970's. In 2004, it is

estimated that approximately 75% of all hydroformylation processes were based on rhodium triarylphosphine catalysts. Achieving high regioselectivity to linear aldehydes is critical for hydroformylation and related reactions. The resulting aldehydes are converted to alcohols, carboxylic acids or other derivatives, which are used as plasticizers, detergents, surfactants, solvents, lubricants and chemical intermediates.

[005] Scheme 1 below shows the dissociation of a Rh catalyzed hydroformylation catalyst.



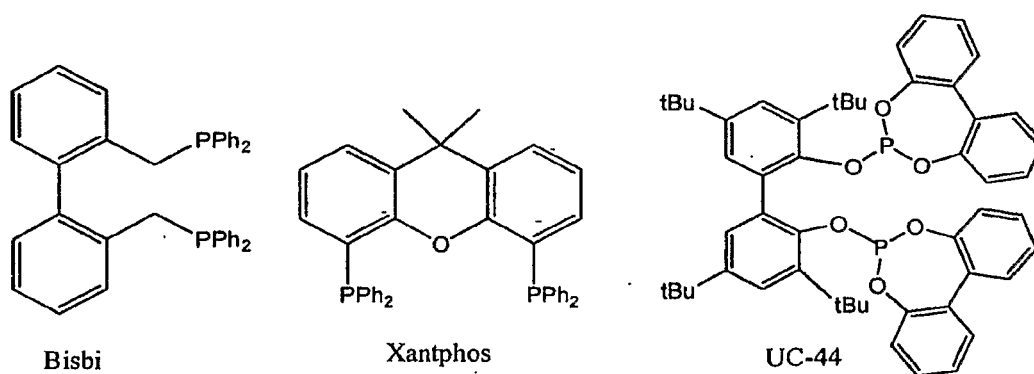
[006] The successful commercialization of $\text{HRh}(\text{CO})(\text{PPh}_3)_2$ technology has been based on the key discovery of Pruett at Union Carbide and Booth at Union oil that the use of rhodium with excess phosphine ligand can lead to forming active, selective hydroformylation catalysts. The need for excess phosphines is due to the facile $\text{Rh}-\text{PPh}_3$ dissociation in the catalytic system as illustrated by Scheme 1. Loss of PPh_3 from $\text{HRh}(\text{CO})(\text{PPh}_3)_2$ results in more active, but less regioselective hydroformylation catalysts B and C. In the commercial process, up to an 820 fold excess of PPh_3 to Rh is used to assure high linear:branch selectivity ratio, i.e., up to 17:1, for the hydroformylation of 1-hexene. Commercial hydroformylation of propylene has been run with a 400 fold excess of PPh_3 to Rh with a linear:branch selectivity ratio of 8-9:1 being achieved.

[007] Rh/PPh_3 catalyzed hydroformylation is the key for making all oxo alcohols. Propylene is the largest single alkene hydroformylated to produce butylaldehyde, which can be hydrogenated to produce butanol, or dimerized by an aldol condensation and then hydrogenated to form 2-ethyl-1-hexanol, the largest single product produced by hydroformylation (over 5 billion lbs a year). 2-ethyl-1-hexanol is usually reacted with

phthalic anhydride to produce dialkyl phthalic esters that are used as plasticizers to keep polyvinyl chloride plastics soft and flexible.

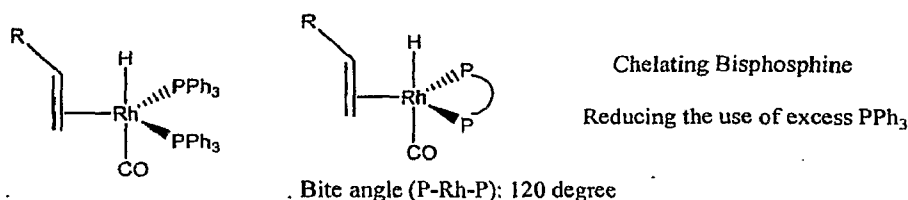
[008] In the hydroformylation process, it is critical to get cheaper feed stocks for starting materials. For example, internal higher alkenes (SHOP alkenes) such as 3-octenes are desirable for converting the alkenes to linear aldehydes. Direct use of raffinate II (a mixture of n-butenes/butanes) and 1-butene and 2-butene mixtures are useful for hydroformylation. For hydroformylation of n-alkenes, it is important to obtain high linear selectivity. Hydroformylation of allylic alcohol and subsequent reduction can lead to 1, 4 butenol. Functionalized internal alkenes can be used as alternative routes to bifunctional building blocks for polymers. Hydroformylation of methyl-3-pentenoate leads to making starting materials for polyamides and polyesters. In the tandem-isomerization and hydroformylation processes, high isomerization rates combined with high selectivity towards terminal aldehydes are desirable with minimized undesirable hydrogenation reactions and minimum isomerization towards conjugated compounds.

[009] To overcome the need of using large excess of phosphines in the hydroformylation processes and achieve high regioselectivity, a new generation of transition metal catalysts were developed using bisphosphine ligands. For example: Bisbi by Eastman Chemical; Xantphos by Prof. Leeuwen (University of Amsterdam), Bernhard Breit, Acc. Chem. Res. 2003, 36, 264-275, Bernhard Breit, Wolfgang Seiche, Synthesis 2001, 1, 1-36); and UC-44 by Union Carbide. These ligands are illustrated below.



By using these ligands, a typical 400 fold excess of PPh_3 has been reduced to a 5 fold excess of chelating phosphines. This new generation of chelating phosphines has led to high linear:branched ratios as well as to higher catalytic activities. For example, a linear to branch

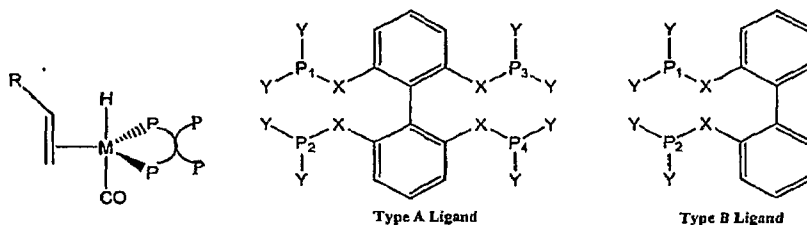
ratio of 70-120:1 for hydroformylation of 1-hexene has been observed. Casey and van Leeuwen proposed that part of regioselectivity in the Rh-catalyzed hydroformylation is due to metal bisphosphine bite angle around 120 degree is formed, i.e., "the Bite angle hypothesis" as illustrated below.



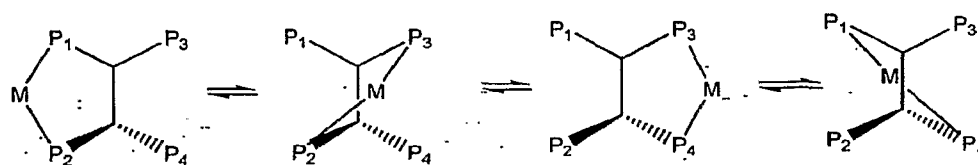
[0010] Despite that a number of chiral bisphosphorus ligands being used as catalysts for hydroformylation and related reactions, the highly selective, active phosphorus ligands for hydroformylation still remain an area of strong research interest. However, because of the dissociation of phosphines from the Rh-CO coordination, is a problem for achieving high regioselectivity, that is high linear to branch ratios of the products produced. Developing families of phosphorus ligands with multi-chelating coordination modes is attractive. The tetraphosphorous ligands of the present invention, because of their coordinating abilities through multi-chelating coordination modes, lead to highly regioselective transition in metal-ligand catalyzed hydroformylation and related reactions to provide high linear to branch ratios than those previously obtained. Also, the symmetric nature of these ligands allows these ligands to be prepared easily.

Summary of the Invention

[0011] In the present invention, we introduce a variety of tetraphosphorus ligands (Type A) with multi-chelating coordination modes as illustrated below to enhance coordination abilities:



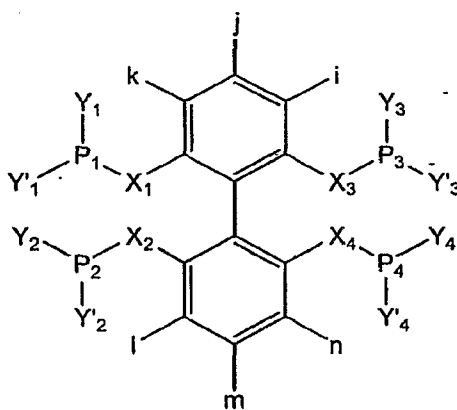
where M is a metal selected from the group consisting of Fe, Zn, Mn, Co, Cu, Ag, Ni, Pt, Pd, Rh, Ru and Ir; X is selected from the group consisting of O, NH, NR and CH₂; Y is selected from the group consisting of Ar, OAr and pyrrole; R is an organic group and Ar is an aryl group. Type A ligand is a tetraphosphorous ligand of the present invention. Type B ligand is a bisphosphorous ligand. As illustrated below, the tetraphosphorous ligand (Type A) has at least four chelating coordination modes to enhance coordination abilities whereas the bisphosphorous ligand (Type B) has a single mode, namely, P₁–M–P₂.



Compared with normal bisphosphorus ligands (Type B), the multi-chelating tetraphosphorous ligands (Type A) of the present invention enhance the coordinating abilities of ligands without major change of electronic properties of ligands.

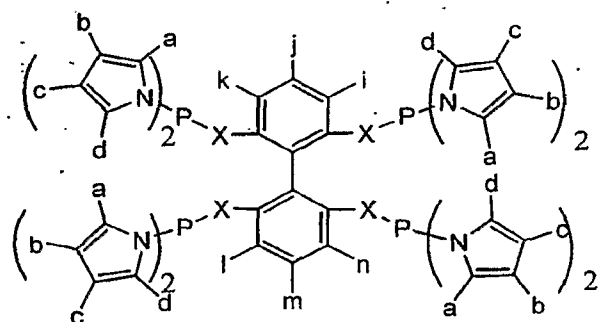
Detailed Description of the Invention

[0012] The present invention is directed to tetraphosphorous ligands having multi-chelating coordination modes to be used as catalysts for hydroformylation and related reactions. The transition metal catalysts prepared using the tetraphosphorous ligands of the present invention are highly active and regioselective. The tetraphosphorous ligands of the present invention have the following generic structure:



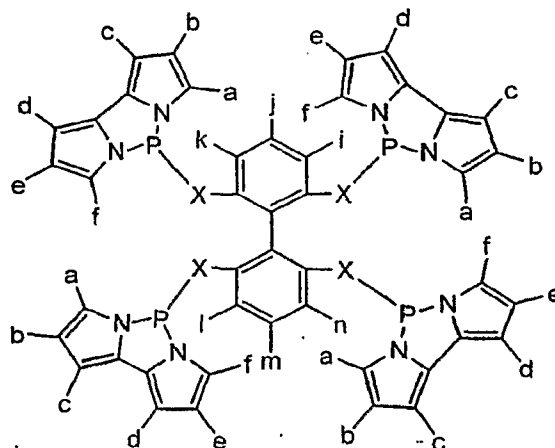
wherein i, j, k, l, m and n are, independently, H, R, Ar, substituted Ar, OR, OAr, COOEt, halide, SO₂R, SO₃H, SO₂NHR, POR₂, POAr₂ or NR₂, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; X₁-X₄ are, independently, R, Ar, OR, OAr, pyrrole or substituted pyrrole, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and Y₁, Y'₁, Y₂, Y'₂, Y₃, Y'₃, Y₄, Y'₄, are, independently, R, Ar, OR, OAr, pyrrole or substituted pyrrole, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl, or where R, Ar, OR, OAr, pyrrole and substituted pyrrole are linked with a carbon to carbon bond, CH₂, NH, NR and O. The substituted groups would include, for example, methyl, ethyl, *t*-butyl and phenyl.

[0013] The following illustrates a first embodiment of the invention:



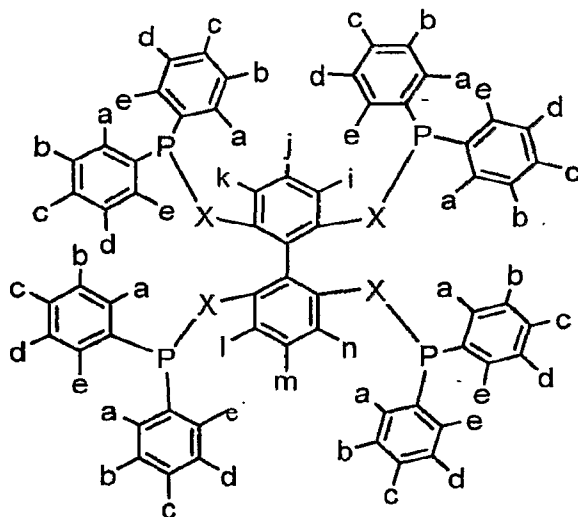
wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a, b, c, d, i, j, k, l, m and n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide or two of a, b, c, d, i, j, k, l, m and n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

[0014] A second embodiment of the invention is illustrated below:



wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl; and Ar is an aryl; and a, b, c, d, e, f, i, j, k, l, m and n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, COOR, SO₃R, SO₃H, POR₂, halide or two of a, b, c, d, e, f, i, j, k, l, m and n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

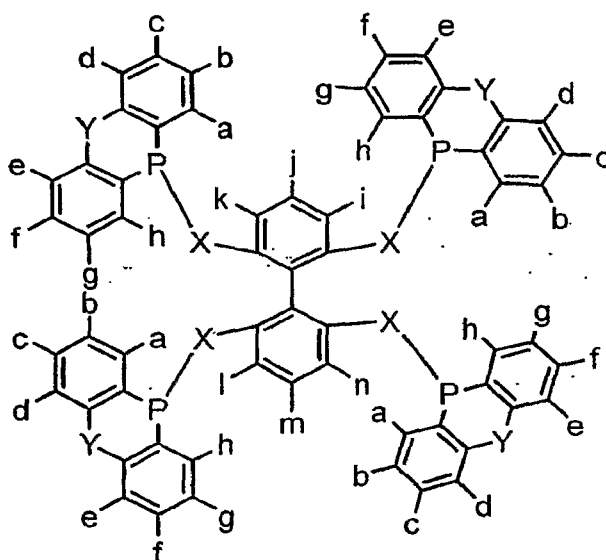
[0015] A third embodiment of the invention is illustrated below:



wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a, b, c, d, e, i, j, k, l, m and n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide, NR₂, or two of a, b, c, d, e, i, j, k, l, m and n can be a cyclic fused ring or an

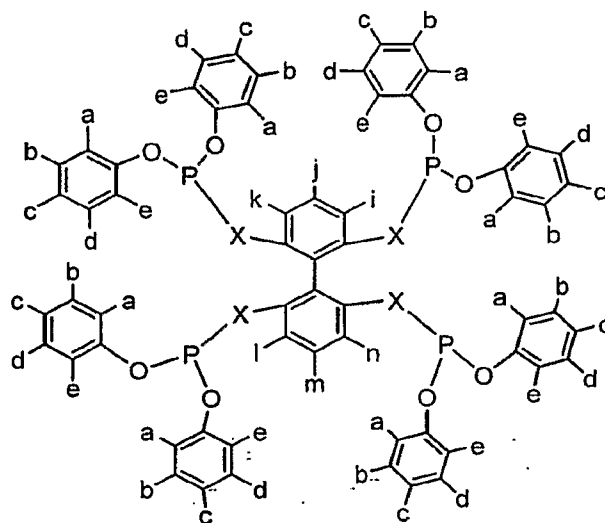
extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

[0016] A fourth embodiment of the invention is illustrated below:



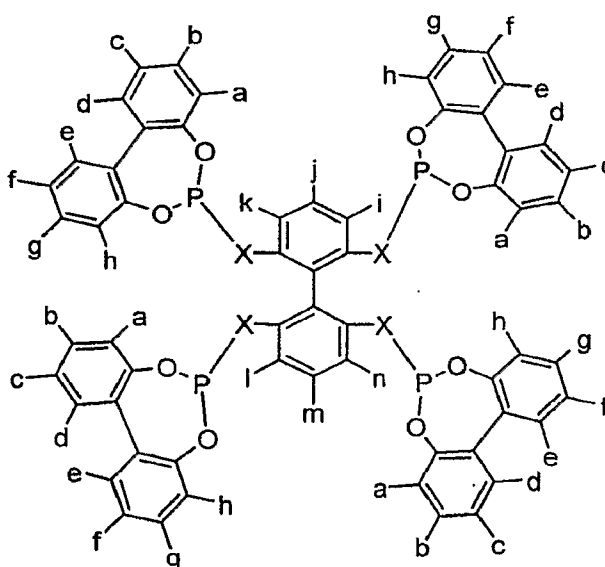
wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; Y is a carbon-carbon bond, O, CH₂, NH or NR, where R is an alkyl, substituted alkyl, aryl or substituted aryl; and a to n are; independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide, NR₂, or two of a to n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

[0017] A fifth embodiment of the invention is illustrated below:



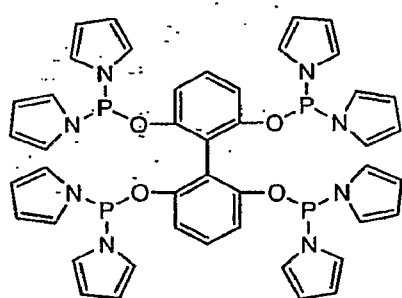
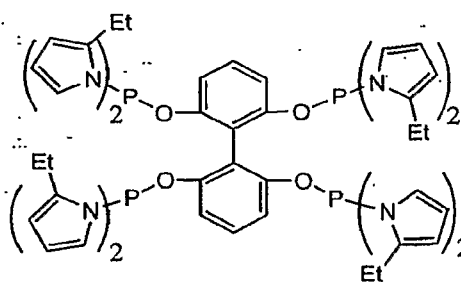
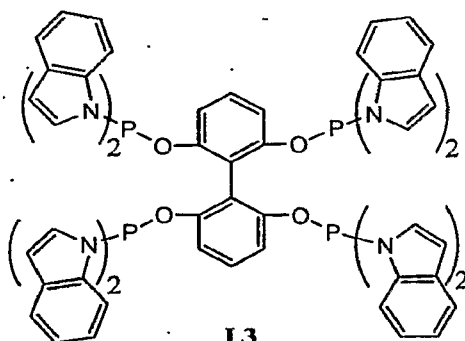
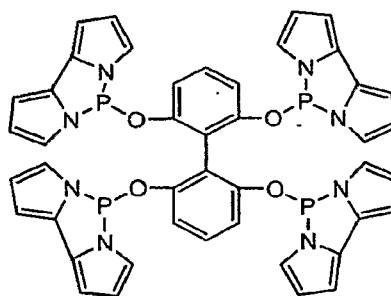
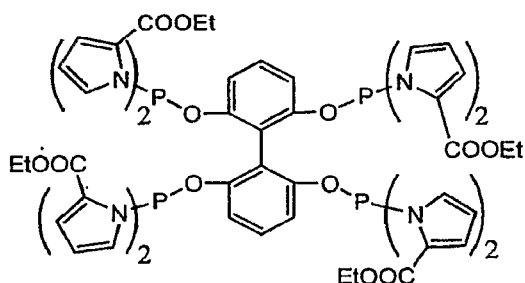
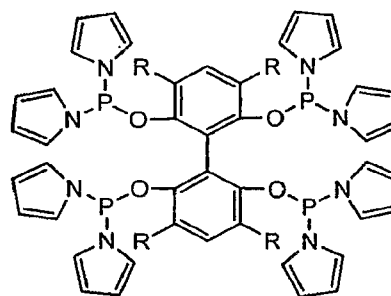
wherein X is Θ , CH_2 , NH , NR , NSO_2R , or NSO_2Ar , where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a, b, c, d, e, i, j, k, l, m and n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR_3 , CF_3 , COOR, SO_3R , SO_3H , POR_2 , halide, NR_2 , or two of a, b, c, d, e, i, j, k, l, m and n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

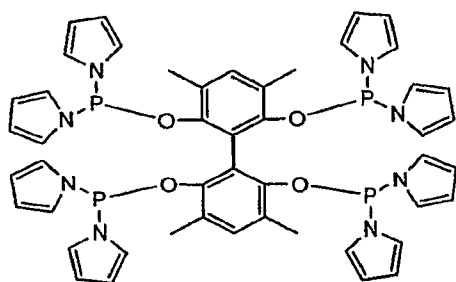
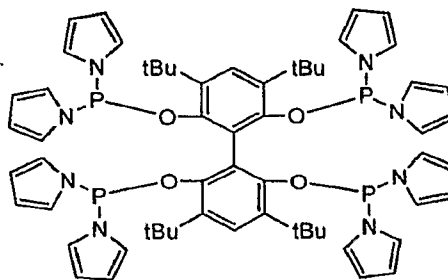
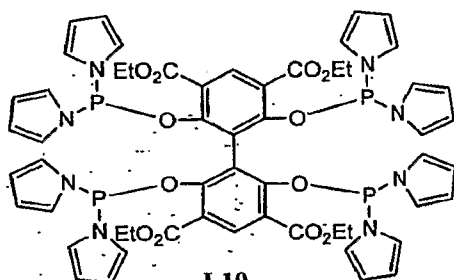
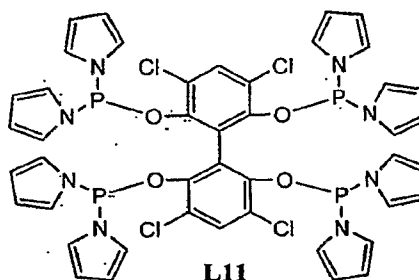
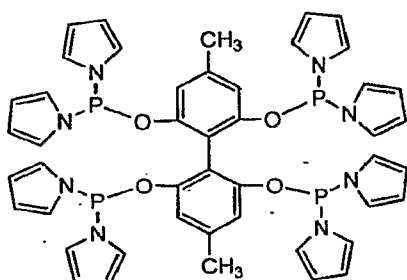
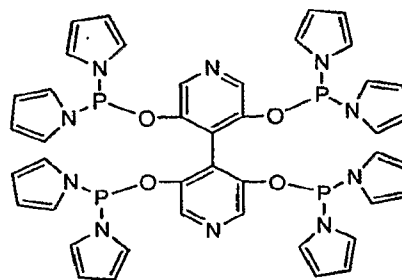
[0018] A sixth embodiment of the invention is illustrated below:

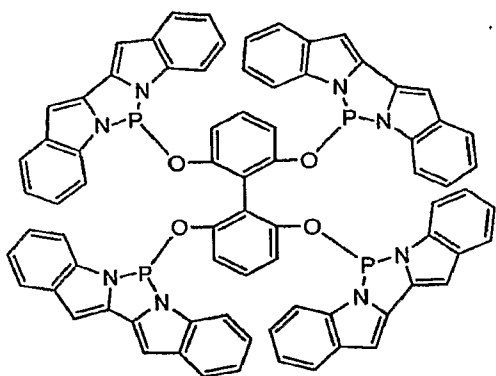
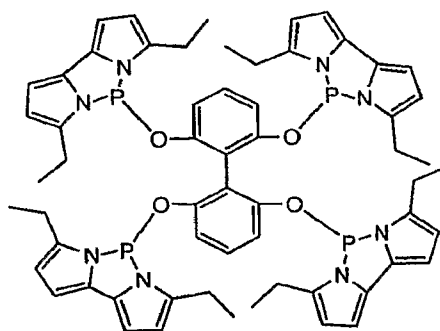
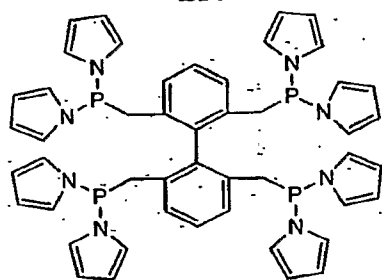
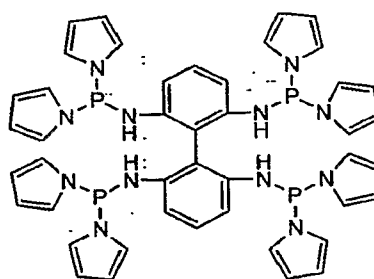
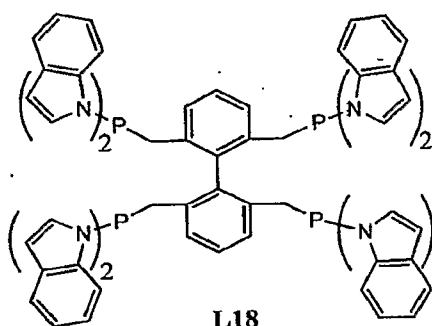
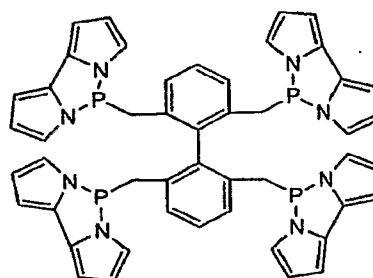


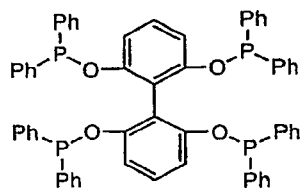
wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a to n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide, NR₂, or two of a to n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl. When d and e are not hydrogen, enantiomers of these ligands can be prepared for asymmetric catalytic reactions.

[0019] Examples of the tetraphosphorus ligands of the present invention (L1 to L91) are illustrated below:

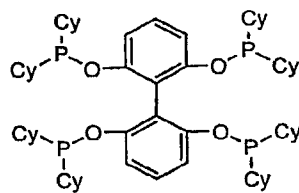
**L1****L2****L3****L4****L5****L6, L7**R = CH₃, tBu

**L8****L9****L10****L11****L12****L13**

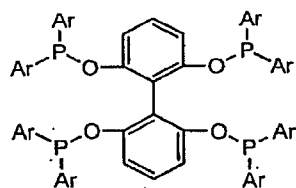
**L14****L15****L16****L17****L18****L19**



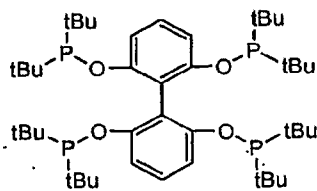
L20



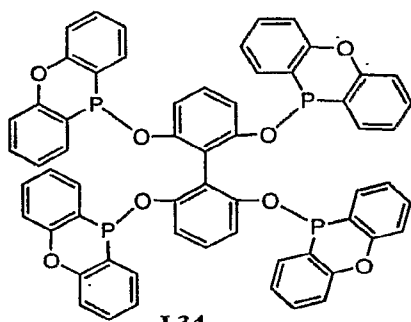
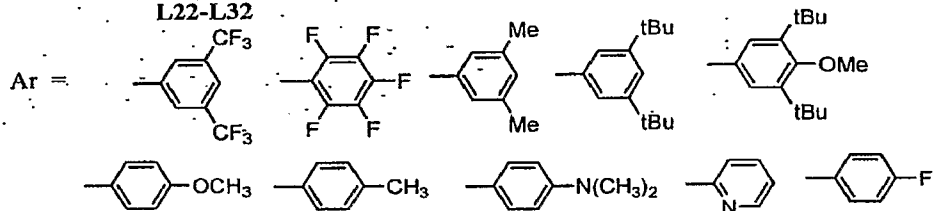
L21



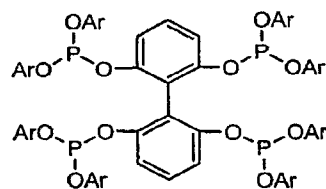
L22-L32



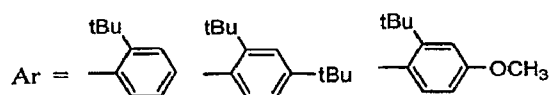
L33

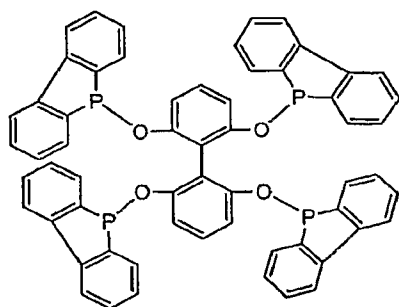
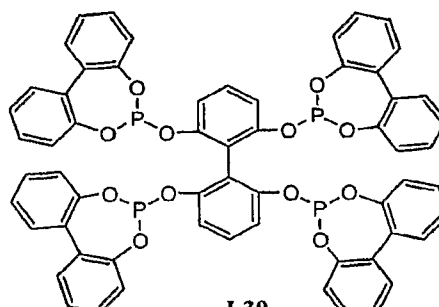
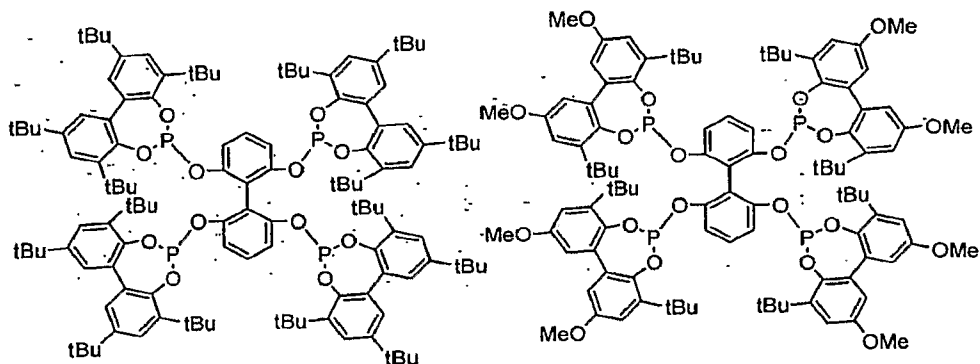
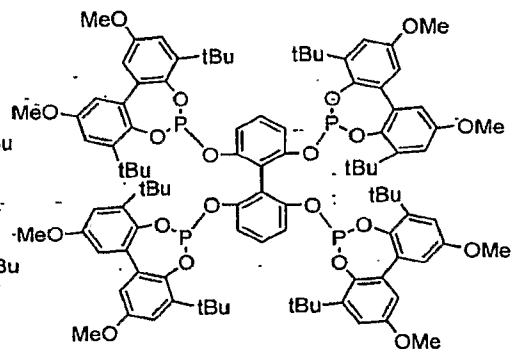
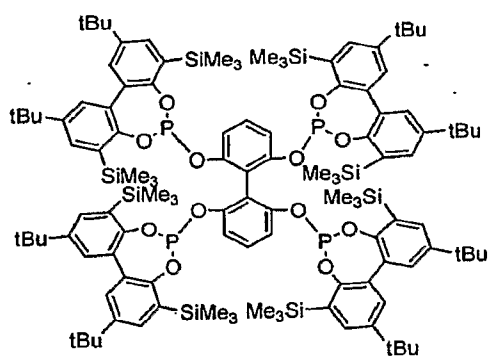
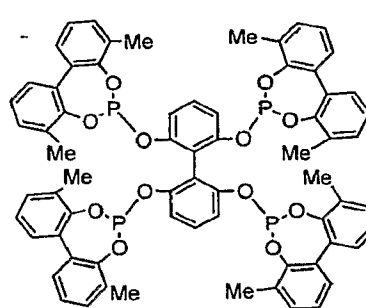


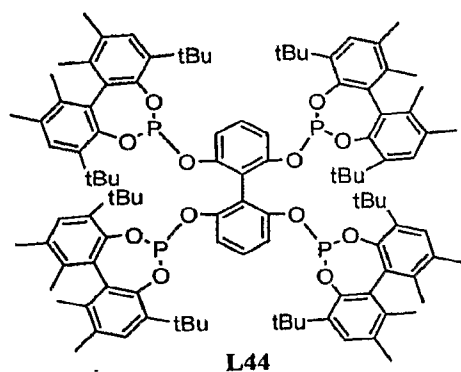
L34



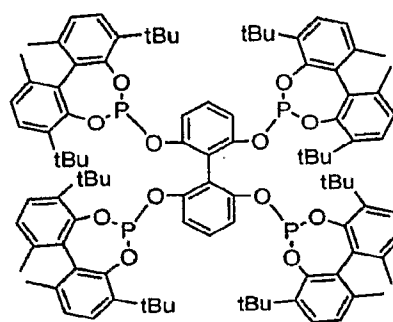
L35-L37



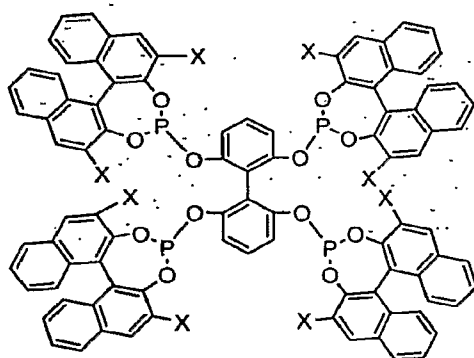
**L38****L39****L40****L41****L42****L43**



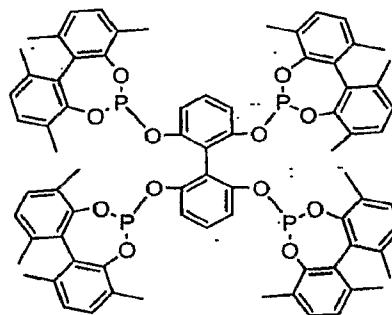
L44



L45

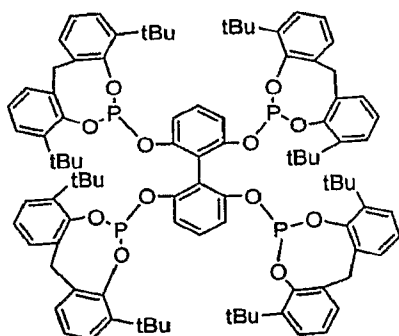


L46-L53

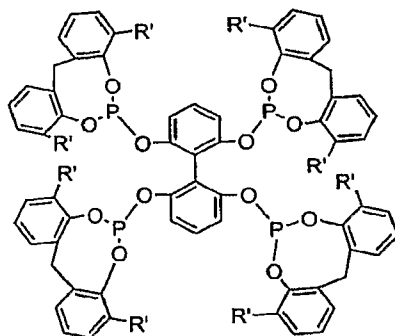


L54

X = H, SiMe₃, Br, I, COOEt, CF₃, Ph, substituted aryl

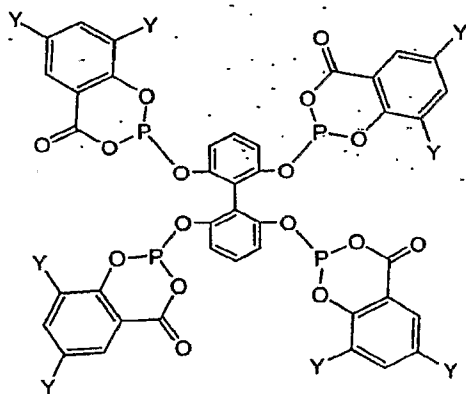


L55



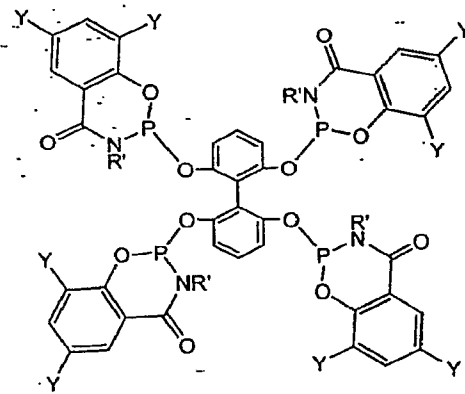
L56-L58

R' = H, alkyl, aryl



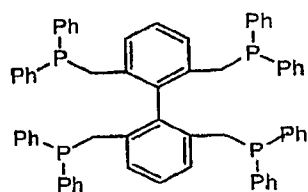
L59-L62

Y = Br, Me, iPr, tBu

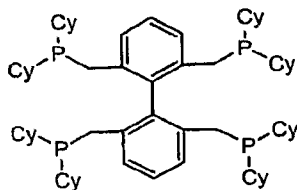


L63-L69

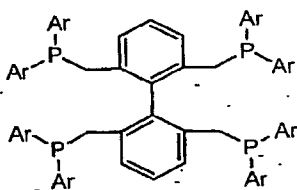
R' = H, alkyl, aryl, Y = Br, Me, iPr, tBu



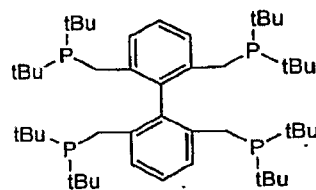
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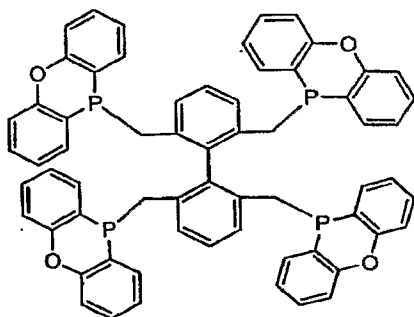
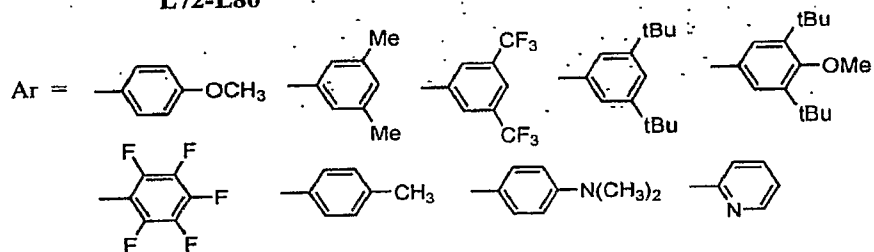
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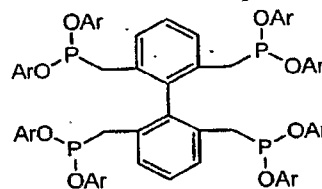
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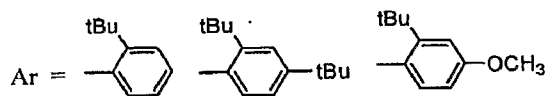
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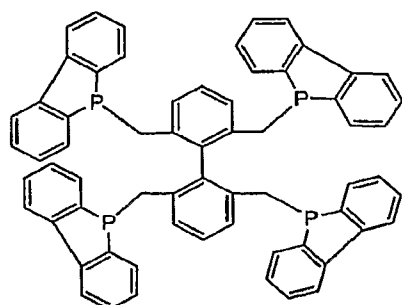


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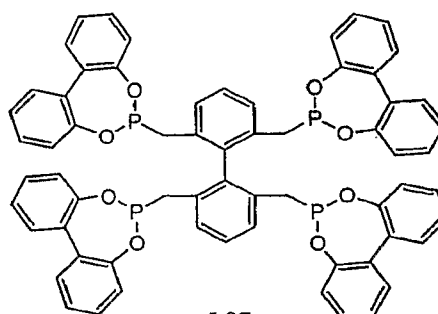


L83-L85

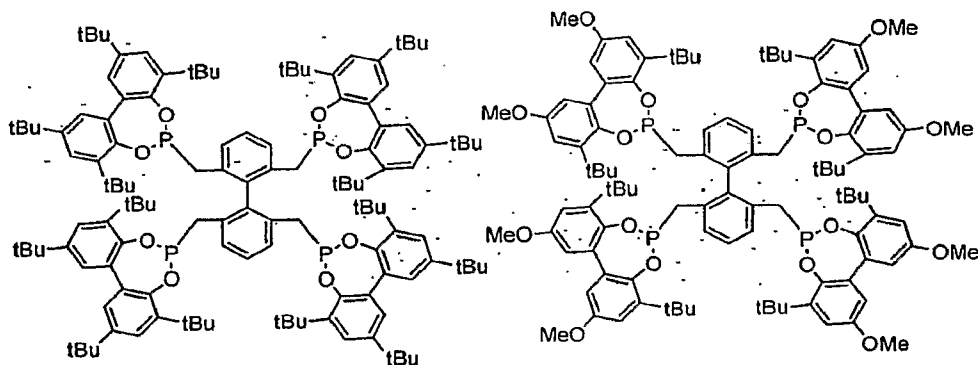




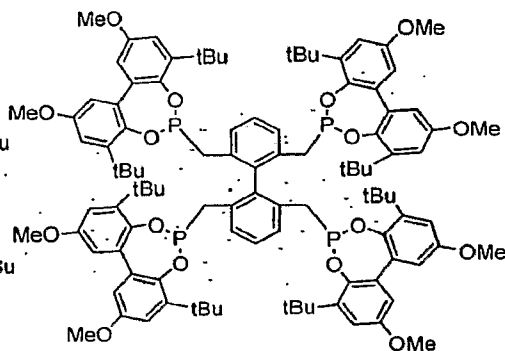
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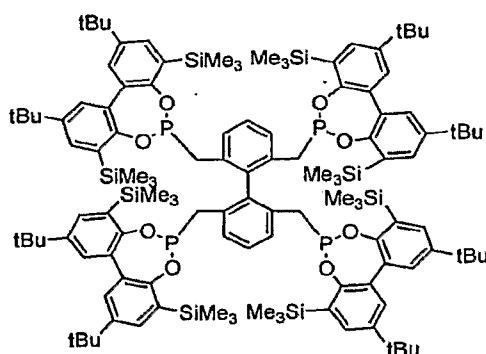
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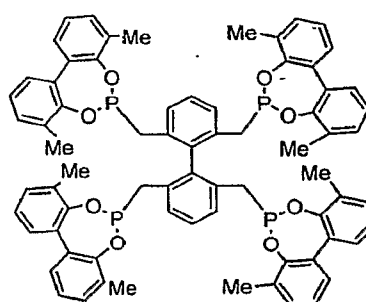
L88



L89



L90



L91

[0020] In a hydroformylation or related reaction, the transition metal-tetraphosphorous ligand complex is prepared by mixing a transition metal salt with the ligand. The transition metal salt is a salt of a transition metal selected from the group consisting of Fe, Zn, Mn, Co, Cu, Ag, Ni, Pt, Pd, Rh, Ru and Ir. Examples of the transition metal salts are FeX_3 , $\text{Fe}(\text{OTf})_3$, $\text{Fe}(\text{OAc})_3$, $\text{Mn}(\text{OAc})_3$, $\text{Mn}(\text{OTf})_3$, MnX_3 , $\text{Zn}(\text{OTf})_2$, $\text{Co}(\text{OAc})_2$, AgX , $\text{Ag}(\text{OTf})$, $\text{Ag}(\text{OTf})_2$, AgOAc , PtCl_2 , H_2PtCl_4 , $\text{Pd}_2(\text{DBA})_3$, $\text{Pd}(\text{OAc})_2$,

$\text{PdCl}_2(\text{RCN})_2$, $\text{Pd}(\text{allyl})\text{Cl}_2$, $\text{Pd}(\text{PR}_3)_4$, $(\text{Rh}(\text{NBD})_2)_2\text{X}$, $(\text{Rh}(\text{NBD})\text{Cl})_2$, $(\text{Rh}(\text{COD})\text{Cl})_2$, $(\text{Rh}(\text{COD})_2)_2\text{X}$, $\text{Rh}(\text{acac})(\text{CO})_2$, $\text{Rh}(\text{ethylene})_2(\text{acac})$, $(\text{Rh}(\text{ethylene})_2\text{Cl})_2$, $\text{RhCl}(\text{PPh}_3)_3$, $\text{Rh}(\text{CO})_2\text{Cl}_2$, $\text{RuH}(\text{CO})_2(\text{PPh}_3)_2$, $\text{Ru}(\text{Ar})\text{X}_2$, $\text{Ru}(\text{Ar})\text{X}_2(\text{PPh}_3)_3$, $\text{Ru}(\text{COD})(\text{COT})$, $\text{Ru}(\text{COD})(\text{COT})\text{X}$, $\text{RuX}_2(\text{cymen})$, $\text{Ru}(\text{COD})_n$, $\text{RuCl}_2(\text{COD})$, $(\text{Ru}(\text{COD})_2)_2\text{X}$, $\text{RuX}_2(\text{PN})$, $\text{RuCl}_2(=\text{CHR})(\text{PR}'_3)_2$, $\text{Ru}(\text{ArH})\text{Cl}_2$, $\text{Ru}(\text{COD})(\text{methallyl})_2$, $(\text{Ir}(\text{NBD})_2\text{Cl})_2$, $(\text{Ir}(\text{NBD})_2)_2\text{X}$, $(\text{Ir}(\text{COD})_2\text{Cl})_2$, $(\text{Ir}(\text{COD})_2)_2\text{X}$, $\text{CuX}(\text{NCCH}_3)_4$, $\text{Cu}(\text{OTf})$, $\text{Cu}(\text{OTf})_2$, $\text{Cu}(\text{Ar})\text{X}$, CuX , $\text{Ni}(\text{acac})_2$, NiX_2 , $(\text{Ni}(\text{allyl})\text{X})_2$, $\text{Ni}(\text{COD})_2$, $\text{MoO}_2(\text{acac})_2$, $\text{Ti}(\text{OiPr})_4$, $\text{VO}(\text{acac})_2$ and MeReO_3 , wherein each R and R' is independently selected from the group consisting of alkyl or aryl; Ar is an aryl group group; X is a counteranion, such as BF_4 , ClO_4 , OTf , SbF_6 , CF_3SO_3 , $\text{B}(\text{C}_6\text{H}_3(\text{CF}_3)_2)_4$, Cl , Br or I ; OTf is OSO_2CF_3 ; DBA is $\text{PhCH}=\text{CHCOCH}=\text{CHPh}$, NDB is norbornadiene; COD is cyclooctadiene and COT is cyclooctotriene. The mixture is placed in an autoclave that is purged with nitrogen and subsequently charged with CO and H_2 .

Synthesis of the Tetrphosphate Ligand

[0021] All reactions and manipulations in the example set forth below were performed in a nitrogen-filled glovebox or using standard Schlenk techniques. THF and toluene were dried and distilled from sodium-benzophenone ketyl under nitrogen. Methylene chloride was distilled from CaH_2 . Methanol was distilled from Mg under nitrogen. Column chromatography was performed using EM silica gel 60 (230–400 mesh). ^1H , ^{13}C and ^{31}P NMR were recorded on Bruker WP-200, AM-300, and AMX-360 spectrometers. Chemical shifts were reported in ppm down field from tetramethylsilane with the solvent resonance as the internal standard. MS spectra were recorded on a KRATOS mass spectrometer MS 9/50 for LR-EI and HR-EI. GC analysis was carried on Helwett-Packard 6890 gas chromatography using chiral capillary columns. HPLC analysis was carried on WatersTM 600 chromatography.

[0022] The following procedure was used to synthesize ligand having the structure **L1**. To a solution of chlorodipyrrolyphosphine (4.4 mmol, 0.87g) in THF (10 mL) was added dropwise triethylamine 1mL and a solution of tetraol (1 mmol, 0.218 g) in THF (5 mL) at room temperature. Tetraol was synthesized according to Lindsten, G.; Wennerstroem, O.; Isaksson, R., *J. Org. Chem.* **1987**, 52, 547-54, and chlorodipyrrolyphosphine was prepared according van der Slot, S. C.; Duran, J.; Luten, J.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *Organometallics* **2002**, 21, 3873-3883. Triethylamine•HCl salts were formed immediately after the addition. The reaction mixture was stirred for 6h at room temperature. The

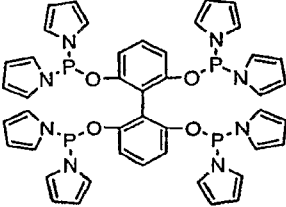
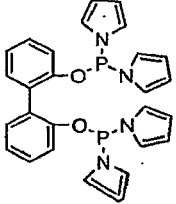
triethylamine•HCl salts were then filtered off and the solvent was removed under vacuum. The crude product was purified by flash chromatography on basic aluminum oxide eluted with hexane/EtOAc/NEt₃ (6:1:0.01) to produce ligand **L1** (0.31 g, 36%) as a air-stable colorless solid. ¹H NMR (300 Hz, CDCl₂) δ 7.23 (t, 2H, *J* = 8.3 Hz), 6.68 (m, 20H), 6.21 (m, 16H); ¹³C NMR (90 Hz, CDCl₂) δ 152.86 (d, *J* = 12.2Hz), 131.0, 121.4(d, *J* = 16.8Hz), 118.1, 115.3(d, *J* = 13.7 Hz), 112.7; ³¹P NMR (146Hz, CDCl₂) δ 107.3. HRMS (ES⁺) calcd. for C₄₄H₃₉N₈O₄P₄ [MH⁺] 867.2045, found 867.2021.

Typical Hydroformylation Process

[0023] To a 2 mL vial with a magnetic stirring bar was charged the tetraphosphorus ligand **L1** prepared in the previous example (3 μmol, 2.6 mg) and Rh(acac)(CO)₂ (1 μmol, 0.1 mL of 10 mM solution in toluene). The mixture was stirred for 5 min. Then 2-octene (10 mmol, 1.56 mL) was added followed by decane (0.01 mL) as internal standard. The reaction mixture was transferred to an autoclave. The autoclave was purged with nitrogen for three times and subsequently charged with CO (5 bar) and H₂ (5 bar). The autoclave was then heated to 100°C (oil bath). After 12h, the autoclave was cooled in icy water and the pressure was carefully released in a well ventilated hood. The reaction mixture was immediately analyzed by GC.

[0024] The remarkable regioselectivities using a multi-chelating tetraphosphorus ligand **L1** for hydroformylation of styrene, 1-octene and 1-hexene are demonstrated in Table 1. Normally, styrene is a difficult substrate for achieving more than 2:1 ratio of linear to branched products when compared to bisphosphorous ligands of the prior art such as xantphos and UC-44. As shown in Table 1, the new tetraphosphorus ligands (Type A) such as **L1** is more selective hydroformylation ligand than the prior art bisphosphorous ligand (Type B). The reaction conditions included 0.1 mol% Rh(CO)₂(acac) and ligand, reaction temperature 80° C for 1 hour at 20 atm of CO and H₂. These results indicate that tetraphosphorus ligands with multi-chelating coordination can be used to increase coordinating abilities of bisphosphine ligands. The regioselectivity with **Type A** is the highest reported to date.

Table 1: Regioselective Hydroformulation of Alkenes

Ligand	Linear vs Branched ratio		
	Styrene	1-octene	1-hexene
 Type A (L1)	5:1	372:1	382:1
 Type B	1.5:1	74:1	81:1

The results of hydroformylation of 2-hexene and 2-octene using the tetraphosphorus ligand (Type A) vs bisphosphorus ligand (Type B) to produce an aldehyde are summarized below in Table 2. In Tables 2 to 11 which follow, "n:i" is the ratio of linear aldehyde to branched aldehyde and "TOF" is turnover frequency (turnover per catalyst per hour). The tetraphosphorus ligands of the present invention produce higher "n:i" ratios than bisphosphorus ligands.

Table 2: Results of Hydroformylation of 2-Hexene and 2-Octene

Substrate	Ligand	Time (h)	Yield of Aldehyde	n:i	Linear Selectivity	TOF (mol.h) ⁻¹
2-hexene	tetraphos	1	17.0%	80.6	98.8%	1.7x10 ³
2-hexene	tetraphos	12	59.9%	56	98.2%	0.50x10 ³
2-hexene	bisphos	1	20.7%	15	93.8%	2.1x10 ³
2-hexene	bisphos	12	68.2%	13.5	93.1%	0.57 x10 ³
2-octene	tetraphos	1	15.1%	51.7	98.1%	1.5 x10 ³
2-octene	tetraphos	12	77.2%	38	97.4%	0.64 x10 ³
2-octene	bisphos	1	23.0%	10.1	91%	2.3 x10 ³
2-octene	bisphos	12	84.3%	5.5	84.6%	0.70 x10 ³

The hydroformylation conditions were S/C = 10000, [Rh] is 0.69 mM (for 2-hexene) and 0.57 mM (for 2-octene), Ligand/Rh ratio is 3:1, reaction temperature is 100°C, CO/H₂ is 5/5 atm, toluene is the solvent, and decane is the internal standard.

[0025] Table 3 below shows the results of hydroformylation of 1-hexene and 1-octene using the tetraphosphorus ligand (Type A) vs bisphosphorus ligand (Type B) to produce an aldehyde by a hydroformylation reaction:

Table 3: Results of Hydroformylation of 1-Hexene and 1-Octene

Substrate	Ligand	Time (h)	Yield of Aldehyde	n:i	Linear Selectivity	TOF (mol.h) ⁻¹	Isomerization
1-hexene	tetraphos	1	67.2%	382	99.7%	6.7x10 ³	18.7%
1-hexene	tetraphos	2	80.4%	380	99.7%	4.0 x10 ³	18.4%
1-hexene	bisphos	1	79.3%	80.8	98.8%	7.9 x10 ³	12.2%
1-hexene	bisphos	2	87.2%	78.1	98.7%	4.4 x10 ³	12.4%
1-octene	tetraphos	1	68.6%	372	99.7%	6.9 x10 ³	15.3%
1-octene	tetraphos	2	83.6%	369	99.7%	4.2 x10 ³	15.1%
1-octene	bisphos	1	83.9%	74.1	98.7%	8.4 x10 ³	10%
1-octene	bisphos	2	88.6%	69.4	98.6%	4.4 x10 ³	10.7%

The reaction conditions: S/C = 10000, Rh concentration is 0.2mM, Ligand/Rh ratio is 3:1, temperature is 80°C, CO/H₂ is 10/10 atm, toluene is the solvent, and decane is the internal standard.

[0026] The hydroformylation reaction is highly dependent on the reaction conditions. Typical reaction conditions are S/C=10000, ligand metal ratio of about 3, transition metal concentration of about 0.2 to 0.7mM, reaction temperature is 100°C, and the reaction time is 12h. To optimize the reaction conditions, the following experiments have been carried out with tetraphosphorus ligand (L1). As evidenced by the "n:i" ratios in Tables 2 and 3, there a substantial and significant improvement in the amount of linear aldehyde produced using a tetraphosphorus ligand of the present invention as opposed to using a bisphosphorus ligand.

Ligand to Metal Ratio

[0027] The hydroformylation was first carried out with different ligand to metal ratios. As shown in Table 4, increasing the ligand metal ratio slightly decreased the reaction rate. On the other hand, the ligand to metal ratio significantly affects the regioselectivity. At

lower ratios, low regioselectivity were observed. A minimum ligand to metal ratio of 2 is essential to achieve high regioselectivity, which allows the tetraphosphorus ligand to be coordinated in a multi-coordination mode. Further increasing the ligand to metal ratio did not significantly improve the regioselectivity.

Table 4. hydroformylation of 2-octene with different ligand metal ratio using ligand L1.

L/Rh ratio	n:i	Linear Selectivity	TOF[h ⁻¹]
1:2	2.92	74.5%	2.1x10 ³
1:1	17.7	94.7%	1.8 x10 ³
2:1	43.4	97.7%	1.5 x10 ³
4:1	46	97.9%	1.5x10 ³

The reaction conditions: substrate is 2-octene, S/C=10000, Rh concentration is 0.57 mM, temperature is 100°C, CO/H₂ is 10/10 atm, reaction time is 1h, toluene is the solvent, and decane is the internal standard. The results in Table 4 show that presence of two of free phosphorus ligands with the tetraphosphorus ligand is important for achieving high regioselectivity (n:i goes from 2.92 to 17.7). Table 5 below shows similar results with 2-hexene as the substrate.

Table 5. Hydroformylation of 2-hexene with different ligand metal ratio using ligand L1.

L/Rh ratio	n:i	Linear Selectivity	TOF[h ⁻¹]
1:2	12.7	92.7%	2.2x10 ³
1:1	42	97.7%	1.9 x10 ³
2:1	68.5	98.6%	1.9 x10 ³
4:1	70.3	98.6%	1.8x10 ³

Reaction conditions: substrate is 2-hexene, S/C=10000, Rh concentration is 0.69mM, reaction temperature is 100°C, CO/H₂ is 10/10 atm, reaction time is 1h, toluene is the solvent, and decane is the internal standard. The results in Table 5 show that presence of two of free phosphorus ligands with the tetraphosphorus ligand is important for achieving high regioselectivity (n:i goes from 12.7 to 42).

Temperature

[0028] The reaction temperature also plays a key role in hydroformylation. As shown in Tables 6 and 7 below, at low temperature, though high regioselectivity was observed, the reaction rate was low. To facilitate the olefin isomerization and hydroformylation, high temperature (100°C) is preferred to achieve high reaction rate as well as acceptable regioselectivity.

Table 6. Hydroformylation of 2-octene at different temperature using a Rh-ligand L1

T °C	n:i	Linear Selectivity	TOF[h ⁻¹]
140	29.5	96.7%	3.7x10 ³
120	30.4	96.8%	3.4 x10 ³
100	46	97.9%	1.6 x10 ³
80	47.7	97.9%	0.77x10 ³
60	53.6	98.2%	0.14x10 ³

Reaction conditions: substrate is 2-octene, S/C=10000, Rh concentration is 0.57mM, Ligand/Rh ratio is 3:1, CO/H₂ is 10/10 atm, reaction time is 1h, toluene is the solvent, and decane is the internal standard.

Table 7. Hydroformylation of 2-hexene at different temperature using Rh-ligand L1

T °C	n:i	Linear Selectivity	TOF[h ⁻¹]
140	24.3	96 %	4.4x10 ³
120	49.5	98%	2.8 x10 ³
100	68.1	98.6%	1.7 x10 ³
80	114	99.1%	0.99x10 ³
60	179	99.4%	0.67x10 ³

Reaction conditions: substrate is 2-hexene, S/C=10000, Rh concentration is 0.69mM, Ligand/Rh ratio is 3:1, CO/H₂ is 10/10 atm, reaction time is 1h, toluene is the solvent, and decane is the internal standard.

Pressure

[0029] The CO/H₂ total pressure also influences the reaction. At high pressure, both reaction rate and regioselectivity were low. Lowering the pressure generally results in higher reaction rate and regioselectivity. Decreasing the CO/H₂ pressure from 10/10 atm to 5/5 atm

did not change the reaction rate very much, but the regioselectivity improved further. The results from the hydroformylation of 2-octene and 2-hexene are shown in Tables 8 and 9.

Table 8. Hydroformylation of 2-octene at different pressure using ligand L1

CO/H ₂ Pressure	n:i	Linear Selectivity	TOF[h ⁻¹]
30/30 atm	24.3	96%	0.31x10 ³
20/20 atm	30	96.8%	0.51 x10 ³
10/10 atm	46	98%	1.6 x10 ³
5/5 atm	51.7	98.1%	1.5x10 ³

Reaction conditions: substrate is 2-octene, S/C=10000, Rh concentration is 0.57mM, Ligand/Rh ratio is 3:1, reaction temperature is 100°C, reaction time is 1h, toluene is the solvent, and decane is the internal standard.

Table 9. Hydroformylation 2-hexene at different pressure using ligand L1

CO/H ₂ Pressure	n:i	Linear Selectivity	TOF[h ⁻¹]
30/30 atm	54.8	98.2%	0.96x10 ³
20/20 atm	58.8	98.3%	1.3 x10 ³
10/10 atm	68.1	98.6%	1.7 x10 ³
5/5 atm	80.6	98.8%	1.7x10 ³

Reaction conditions: substrate is 2-hexene, S/C=10000, Rh concentration is 0.69mM, Ligand/Rh ratio is 3:1, reaction temperature is 100°C, reaction time is 1h, toluene is the solvent, and decane is the internal standard.

Reaction time

[0030] The reaction time also affects the hydroformylation selectivity. As shown in Tables 10 and 11 below, the longer the reaction time, the lower the regioselectivity. Further an increase in the reaction time from 12h to 18h only slightly improved the turnover number (TON), i.e. turnover per catalyst, at the expense of decreased regioselectivity.

Table 10 Hydroformylation of 2-octene at different time using ligand L1

Time (h)	n:i	Linear Selectivity	TON	TOF (h ⁻¹)
1	51.7	98.1%	1.5x10 ³	1.5x10 ³
2	51.3	98.1%	2.8 x10 ³	1.4 x10 ³
6	41.3	97.6%	5.7 x10 ³	0.94x10 ³
12	38	97.4%	7.7x10 ³	0.64x10 ³
18	27.7	96.5%	8.1x10 ³	0.45x10 ³

Reaction conditions: substrate is 2-octene, S/C=10000, Rh concentration is 0.57mM, Ligand/Rh ratio is 3:1, reaction temperature is 100°C, CO/H₂ is 5/5 atm, toluene is the solvent, and decane is the internal standard.

Table 11. Hydroformylation of 2-hexene at different time using ligand L1

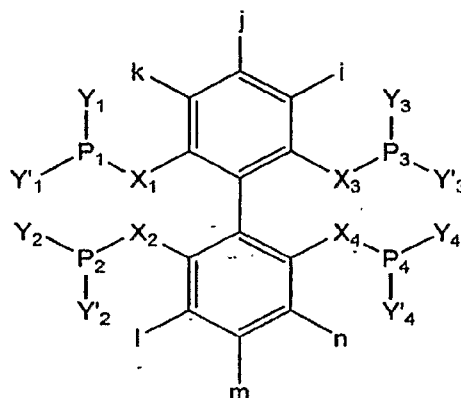
Time (h)	n:i	Linear Selectivity	TON	TOF (h ⁻¹)
1	80.6	98.8%	1.7x10 ³	1.7x10 ³
2	71.9	98.6%	2.4 x10 ³	1.2 x10 ³
6	63	98.4%	5.5 x10 ³	0.92x10 ³
12	56	98.2%	6.0x10 ³	0.5x10 ³
18	51.9	98.1%	6.7x10 ³	0.37x10 ³

Reaction conditions: substrate is 2-hexene, S/C=10000, Rh concentration is 0.69mM, Ligand/Rh ratio is 3:1, reaction temperature is 100°C, CO/H₂ is 5/5 atm, toluene is the solvent, and decane is the internal standard.

[0031] While this invention has been described with reference to several preferred embodiments, it is contemplated that various alterations and modifications thereof will become apparent to those skilled in the art upon a reading of the preceding detailed description. It is therefore intended that the following appended claims be interpreted as including all such alterations and modifications as fall within the true spirit and scope of this invention.

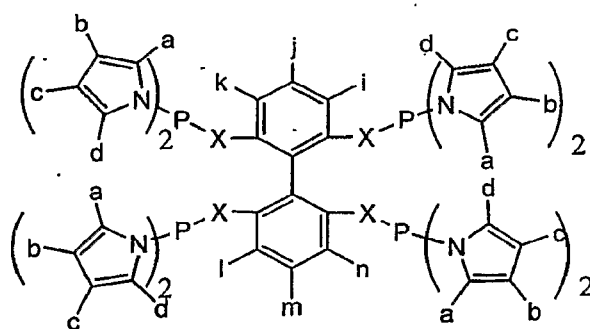
What is claimed is:

1. A phosphorous ligand having the following formula:



wherein i, j, k, l, m and n are, independently, H, R, Ar, substituted Ar, OR, OAr, COOEt, halide, SO₂R, SO₃H, SO₂NHR, POR₂, POAr₂ or NR₂, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; X₁-X₄ are, independently, R, Ar, OR, OAr, pyrrole or substituted pyrrole, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and Y₁, Y'₁, Y₂, Y'₂, Y₃, Y'₃, Y₄, Y'₄, are, independently, R, Ar, OR, OAr, pyrrole or substituted pyrrole, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl, or where R, Ar, OR, OAr, pyrrole and substituted pyrrole are linked with a carbon to carbon bond, CH₂, NH, NR or O.

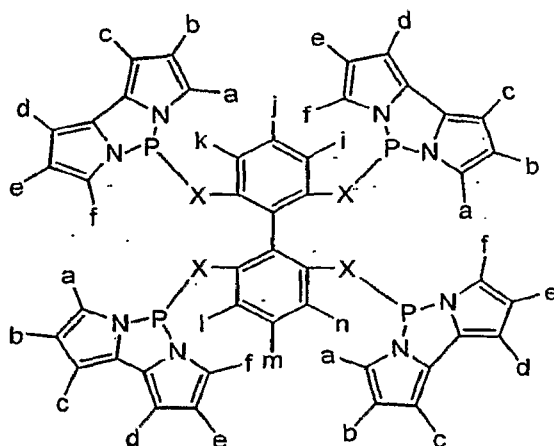
2. The phosphorous ligand according to claim 1, wherein the ligand has the following structure:



wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a, b, c, d, i, j, k, l, m and n are, independently, H,

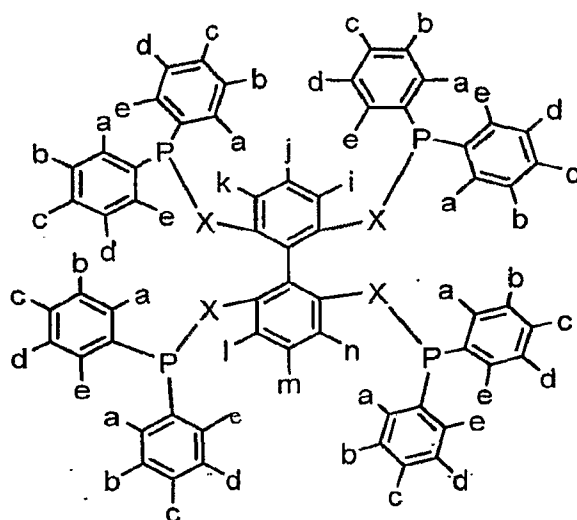
alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide or two of a, b, c, d, i, j, k, l, m and n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

3. The phosphorous ligand according to claim 1, wherein the ligand has the following structure:



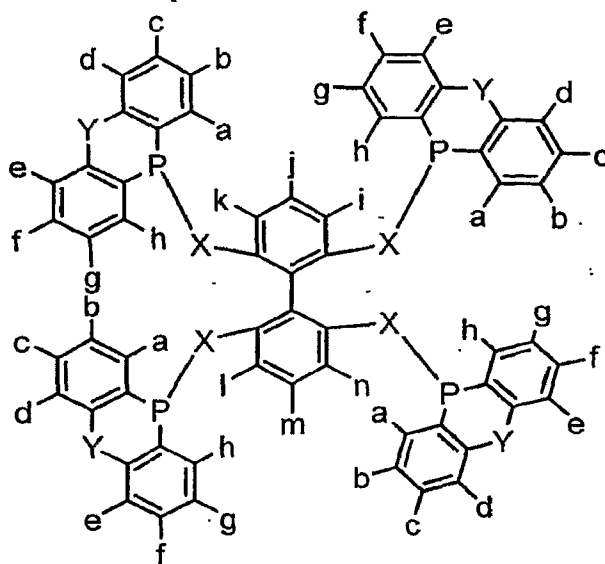
wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a, b, c, d, e, f, i, j, k, l, m and n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, COOR, SO₃R, SO₃H, POR₂, halide or two of a, b, c, d, e, f, i, j, k, l, m and n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

4. The phosphorous ligand according to claim 1, wherein the ligand has the following structure:



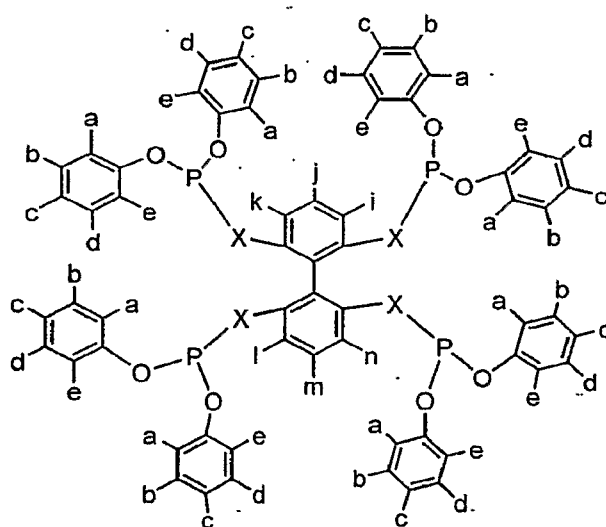
wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl; and Ar is an aryl; and a, b, c, d, e, i, j, k, l, m and n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide, NR₂, or two of a, b, c, d, e, i, j, k, l, m and n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

5. The phosphorous ligand according to claim 1, wherein the ligand has the following structure:



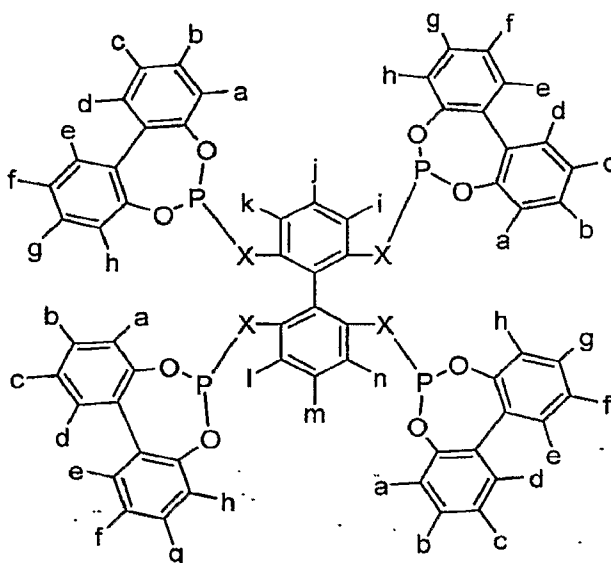
wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; Y is a carbon-carbon bond, O, CH₂, NH or NR, where R is an alkyl, substituted alkyl, aryl or substituted aryl; and a to n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide, NR₂, or two of a to n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

6. The phosphorous ligand according to claim 1, wherein the ligand has the following structure:



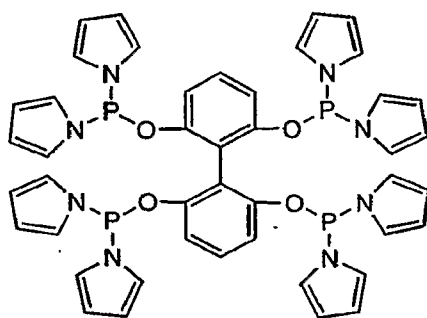
wherein X is O, CH₂, NH, NR, NSO₂R, or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a, b, c, d, e, i, j, k, l, m and n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide, NR₂, or two of a, b, c, d, e, i, j, k, l, m and n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

7. The phosphorous ligand according to claim 1, wherein the ligand has the following structure:



wherein X is O, CH₂, NH, NR, NSO₂R or NSO₂Ar, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl; and a to n are, independently, H, alkyl, aryl, substituted alkyl, substituted aryl, OR, OAr, SiR₃, CF₃, COOR, SO₃R, SO₃H, POR₂, halide, NR₂, or two of a to n can be a cyclic fused ring or an extended aromatic ring, where R is an alkyl, substituted alkyl, aryl or substituted aryl and Ar is an aryl.

8. The phosphorous ligand according to claim 1, wherein the ligand has the following structure:



9. A catalyst comprising a ligand in claims 1 to 8 and a transition metal salt, wherein the metal of said metal salt is selected from the group consisting of: Fe, Zn, Mn, Co, Cu, Ag, Ni, Pt, Pd, Rh, Ru and Ir.

10. The catalyst of claim 9, wherein said transition metal salt is selected from the group consisting of FeX_3 , $\text{Fe}(\text{OTf})_3$, $\text{Fe}(\text{OAc})_3$, $\text{Mn}(\text{OAc})_3$, $\text{Mn}(\text{OTf})_3$, MnX_3 , $\text{Zn}(\text{OTf})_2$, $\text{Co}(\text{OAc})_2$, AgX , $\text{Ag}(\text{OTf})$, $\text{Ag}(\text{OTf})_2$, AgOAc , PtCl_2 , H_2PtCl_4 , $\text{Pd}_2(\text{DBA})_3$, $\text{Pd}(\text{OAc})_2$, $\text{PdCl}_2(\text{RCN})_2$, $(\text{Pd}(\text{allyl})\text{Cl})_2$, $\text{Pd}(\text{PR}_3)_4$, $(\text{Rh}(\text{NBD})_2)\text{X}$, $(\text{Rh}(\text{NBD})\text{Cl})_2$, $(\text{Rh}(\text{COD})\text{Cl})_2$, $(\text{Rh}(\text{COD})_2)\text{X}$, $\text{Rh}(\text{acac})(\text{CO})_2$, $\text{Rh}(\text{ethylene})_2(\text{acac})$, $(\text{Rh}(\text{ethylene})_2\text{Cl})_2$, $\text{RhCl}(\text{PPh}_3)_3$, $\text{Rh}(\text{CO})_2\text{Cl}_2$, $\text{RuH}(\text{CO})_2(\text{PPh}_3)_2$, $\text{Ru}(\text{Ar})\text{X}_2$, $\text{Ru}(\text{Ar})\text{X}_2(\text{PPh}_3)_3$, $\text{Ru}(\text{COD})(\text{COT})$, $\text{Ru}(\text{COD})(\text{COT})\text{X}$, $\text{RuX}_2(\text{cymen})$, $\text{Ru}(\text{COD})_n$, $\text{RuCl}_2(\text{COD})$, $(\text{Ru}(\text{COD})_2)\text{X}$, $\text{RuX}_2(\text{PN})$, $\text{RuCl}_2(=\text{CHR})(\text{PR}'_3)_2$, $\text{Ru}(\text{ArH})\text{Cl}_2$, $\text{Ru}(\text{COD})(\text{methallyl})_2$, $(\text{Ir}(\text{NBD})_2\text{Cl})_2$, $(\text{Ir}(\text{NBD})_2)\text{X}$, $(\text{Ir}(\text{COD})_2\text{Cl})_2$, $(\text{Ir}(\text{COD})_2)\text{X}$, $\text{CuX}(\text{NCCH}_3)_4$, $\text{Cu}(\text{OTf})$, $\text{Cu}(\text{OTf})_2$, $\text{Cu}(\text{Ar})\text{X}$, CuX , $\text{Ni}(\text{acac})_2$, NiX_2 , $(\text{Ni}(\text{allyl})\text{X})_2$, $\text{Ni}(\text{COD})_2$, $\text{MoO}_2(\text{acac})_2$, $\text{Ti}(\text{OiPr})_4$, $\text{VO}(\text{acac})_2$ and MeReO_3 , wherein each R and R' is independently selected from the group consisting of: alkyl or aryl; Ar is an aryl group group; and X is a counteranion, such as BF_4 , ClO_4 , OTf , SbF_6 , CF_3SO_3 , $\text{B}(\text{C}_6\text{H}_3(\text{CF}_3)_2)_4$, Cl, Br or I; OTf is OSO_2CF_3 ; DBA is $\text{PhCH}=\text{CHCOCH}=\text{CHPh}$, NBD is norbornadiene; COD is cyclooctadiene; and COT is cyclooctotriene.

11. The catalyst according to claim 10, wherein the transition metal salt is selected from the group consisting of $(\text{Rh}(\text{COD})\text{Cl})_2$, $(\text{Rh}(\text{COD})_2)\text{X}$, $\text{Rh}(\text{acac})(\text{CO})_2$, and $\text{RuH}(\text{CO})_2(\text{PPh}_3)_2$.

12. A method of using the catalyst of claim 10, wherein the catalyst is the catalyst in a reaction selected from the group consisting of hydroformylation, isomerization-hydroformylation, hydro-carboxylation, hydrocyanation, isomerization-formylation, and hydroaminomethylation reactions of alkenes.

13. The method of claim 12, wherein the reaction is a hydroformylation reaction.

14. A method of using the catalyst in a hydroformylation reaction, the catalyst comprising a ligand of claim 8 and a transition metal salt selected from the group consisting of $(\text{Rh}(\text{COD})\text{Cl})_2$, $(\text{Rh}(\text{COD})_2)\text{X}$, $\text{Rh}(\text{acac})(\text{CO})_2$, and $\text{RuH}(\text{CO})_2(\text{PPh}_3)_2$.