Chiral N,N′- and N,O-Bidentate Anionic Ligands. Preparation, Metal Complexation, and Evaluation in the Asymmetric Aziridination of Olefins

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The chiral ligands 1-phenyl-2-[(4*S*)-phenyl-4,5-dihydrooxazol-2-yl]propen-2-ol (**1a**) and [1-phenyl-2-((4*S*)-phenyl-4,5-dihydrooxazol-2-yl)vinyl]-*p*-tolylamine (**2a**) were prepared, together with some structural analogues (**1b**−**e**, **2b**) in two steps from optically pure phenylglycinol or phenylalaninol. Transition-metal−ligand complexes were isolated from the ligand **1a** and Cu(II), Pd(II), and Co(II). The copper complexes of **1a** and **2a** were found to be highly active catalysts for the asymmetric aziridination of styrene, giving the corresponding *N*-tosylaziridine in excellent yields and with enantiomeric excess in the range of 15−34%.

Introduction

The development of ligands for metal-mediated asymmetric synthesis continues to be an active area of investigation.[1] Despite intense research and enormous progress in the design of chiral catalysts, it remains difficult to predict whether a particular metal−ligand complex will constitute an efficient catalyst or not. One approach, which in many cases has been shown to be successful, is to put the ligand center of chirality close to the chelating metal atom and thereby induce stereoselection via molecular recognition of the substrate. Electronic properties are another important feature to consider in ligand design. Today, *neutral* ligands with C_2 symmetry are one of the most widely used in asymmetric synthesis. A famous example is the bis(oxazoline) family developed by Masamune[2], Pfaltz,[3] and others.[4,5] In some applications of asymmetric catalysis, neutral *unsymmetric* ligands, for example oxazoline−phosphines, have proven to be superior.[6,7] The most commonly used *anionic* ligands include alkoxy or phenoxy moieties, such as Jacobsen's Mn(salen) catalyst for epoxidation of olefins.[8] *Unsymmetric* examples are the aryl−oxazolines,[9] which have been utilized in, for example, the Mg-catalyzed Diels−Alder reaction[9d,10] and the Baeyer−Villiger oxidation.[11] There are also a few examples of ligands based on the acetylacetonate (acac) unit, which probably is one of the simplest, yet one of the most versatile, anionic ligands for a variety of transition and main-group metals. The most well-known structures in this class are the C_2-symmetric semicorrins introduced by Pfaltz.[12] Unsymmetric acac-type ligands are rare but potentially very useful, as unsymmetric complexes offer a possibility to stereocontrol induced by electronic effects.[13]

One reaction under investigation in our laboratories is the metal-catalyzed aziridination of olefins.[14] Most catalysts employed for the asymmetric version of the aziridination reaction contain neutral ligands of bisimine type.[15,16] A general disadvantage of these systems is that the activity of the catalyst is decreased by the presence of the chiral ligand, and adequate reactivity is limited to a relatively small set of styrene derivatives.[17] Another drawback of neutral ligands is their weak coordination to copper, which makes them sensitive to more strongly coordinating species. Furthermore,

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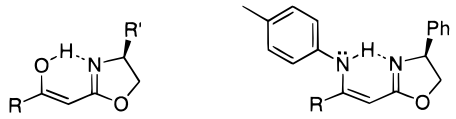
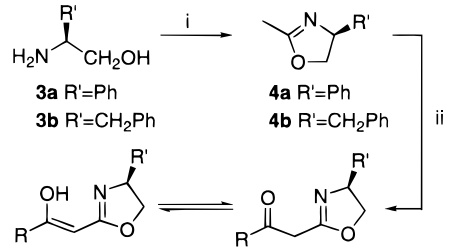
Chart 1



1a) R=Ph ; R'=Ph
1b) R=Ph ; R'=CH_2Ph
1c) R=CH_3 ; R'=Ph
1d) R=CF_3 ; R'=Ph
1e) R=*t*-Bu ; R'=Ph

2a) R=Ph
2b) R=CF_3

Scheme 1[a]



3a R'=Ph
3b R'=CH_2Ph

4a R'=Ph
4b R'=CH_2Ph

1a-e

[a] Legend: (i) 1.1 equiv of methyl orthoacetate, 1,2-dichloroethane (96−98%) or 1.1 equiv of acetimidoethyl ether hydrochloride, CH_2Cl_2 (93%); (ii) 2.2 equiv of LDA, THF, −78 °C, then 1.1 equiv of acid chloride (31−70%).[21]

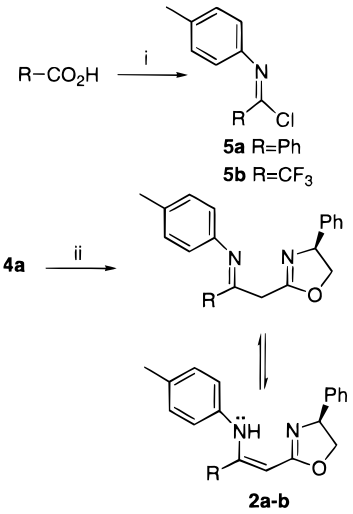
to stabilize the complex, a counterion is needed. This results in a copper complex where the chiral ligand and the counterion occupy three of the available coordination sites. According to the literature, the existence of multiple open coordination sites seems to be crucial for the aziridination reaction.[18]

Considering the disadvantages of the neutral ligands, we were interested in investigating anionic analogues in the aziridination reaction. An anionic ligand would coordinate more strongly to the copper, and without the need for a counterion in the complex, the number of free coordinating sites will increase. The anionic ligands we have developed are of N,O- and N,N′-bidentate type (Chart 1).[19]

Results and Discussion

Ligand Preparation. The synthetic routes for **1** and **2** are straightforward two-step sequences which involve preparation of the desired oxazoline and its connection to the appropriate carbonyl derivative (Schemes 1 and 2).[20] Commercially available, optically pure amino alcohols are used as starting material, giving the possibility to easily modify the chiral unit of the ligand. The amino alcohol is first reacted with either methyl orthoacetate or acetimidoethyl ether hydrochloride to give the 2-methyl-4,5-dihydrooxazole in high yield. After deprotonation with LDA and addition to either an acyl or imidoyl chloride the final ligand is furnished. The

Scheme 2[a]



5a R=Ph
5b R=CF_3

2a-b

[a] Legend: (i) Ph_3P, Et_3N, CCl_4, *p*-toluidine (70−71%); (ii) 2.2 equiv of LDA, THF, −78 °C, then 1.1 equiv of imidoyl chloride **5a**,**b** (40−56%).[21]

imidoyl chlorides are made from the corresponding carboxylic acid and amine using triphenylphosphine, triethylamine, and tetrachloromethane as reagents. The synthetic scheme allows for numerous structural variations not only at the chiral center but also at the carbonyl-derived part of the ligand, since a great variety of both acyl and imidoyl chlorides are readily available.

Complex Formation. With the aim of testing **1** and **2** in catalytic asymmetric synthesis we prepared three different transition-metal complexes (**6**−**8**) from Cu(II), Co(II), Pd(II), and ligand **1a**. The copper complex was formed from copper(II) acetate and 2 equiv of ligand in methanol. The Pd complex was prepared in a similar way using palladium acetate and acetic acid as solvent. To form the cobalt complex, $CoCl_2 \cdot 6H_2O$ was used together with NaOH in ethanol. All attempts to isolate metal complexes of ligands **1d**,**e** and **2a**,**b** failed. In the case of ligands **1e** and **2a**, this is most likely due to steric interactions between the bulky substituents.[22] The complex formation of **1d** and **2b** could be inhibited by the strongly electron withdrawing CF_3 group on the carbonyl carbon.

The complex formation of ligand **1a** with $Pd(OAc)_2$ and $[Cu(CH_3CN)_4]ClO_4$ was studied by ^1H NMR, involving addition of different amounts of metal salt to an acetic acid-d_4 solution of the ligand. The results are presented in Figure 1. On addition of $Pd(OAc)_2$, a new set of signals formed. After addition of 0.5 equiv of metal salt, the signals from the free ligand disappeared, indicating the formation of a 1:2 complex between Pd(II) and ligand. With $[Cu(CH_3CN)_4]ClO_4$, no shift of the oxazoline proton signals was observed. Identical behavior was observed with different copper salts as well as different solvents (methanol, acetonitrile) in the presence of base. The lack of complex formation between Cu-

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(21) According to NMR studies, X-ray crystallography, and ab initio molecular orbital calculations of similar compounds,[20] the enol form of **1** and **2** with a stabilizing intramolecular hydrogen bond between the OH moiety (NH moiety for compound **2**) and the N atom in the oxazoline ring appears to be the major tautomer. In some cases, the keto form is also present as a minor tautomer (see NMR data in the Experimental Section).

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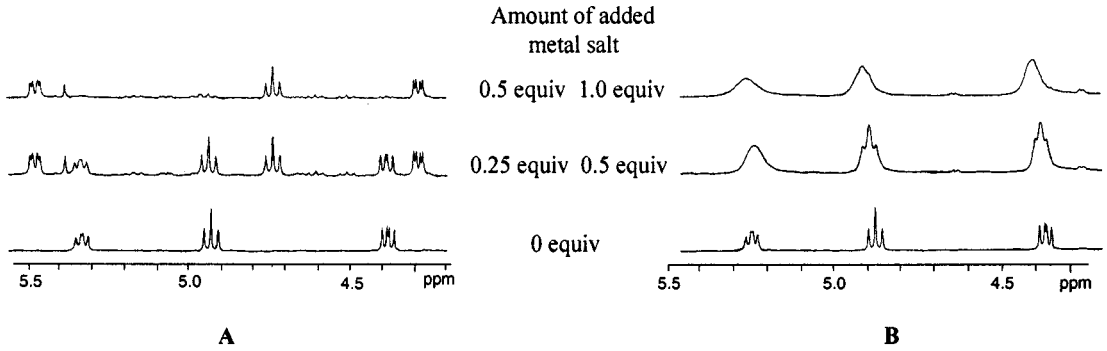


Figure 1. ^{1}H NMR study of the complex formation of ligand **1a** and (a, left) $Pd(OAc)_2$ and (b, right) $[Cu(CH_3CN)_4]ClO_4$ in acetic acid-d_4.

(I) and **1a** indicates that preparation of the complex in situ is not possible.

Complex Structure. To determine the structure of the catalyst precursor, we performed an X-ray analysis of the copper complex **6**. Unfortunately, we failed in solving the complete X-ray structure, probably due to insufficient crystal quality. From the results obtained it was possible to determine the geometry closest to copper to be slightly distorted tetragonal pyramidal. These results are in agreement with X-ray structures of similar complexes.[23]

To further analyze the structure of the precursor, ab initio calculations were performed on the copper complex **6**.[24] By first optimizing the structure closest to copper (exclusion of the four phenyl substituents) we obtained a complex with the ligands coordinated in a square-planar fashion to the metal. Optimizing the complete complex resulted in a tetrahedral coordination of the two bidentate ligands (Figure 2). These results indicate that the coordination geometry at copper is strongly influenced by steric factors. The difference between the results from the X-ray crystallography and the calculations are most probably caused by crystal-packing effects.

Applications. The prepared Cu(II) complex of ligand **1a** was tested as a catalyst precursor in the aziridination of styrene according to Evans' procedure,[15] using [(*p*-tolylsulfonyl)imino)]phenyliodinane (PhI=NTs) as the nitrene source. The result was a very fast reaction with excellent yield and an enantioselectivity of 34% ee (Table 1, entry 1). When the reaction was performed using in situ generated complexes from Cu(I) or Cu(II) triflate,[25] racemic mixtures were obtained (entry 2). These findings are in agreement with the observation made in the ^{1}H NMR study; i.e., Cu complexation does not occur in situ under the studied conditions. With the ligand **2a**, all attempts to isolate the complex failed. The reaction with in situ formed complex[25] proceeded with quantitative yield and 15% ee (entry 3).

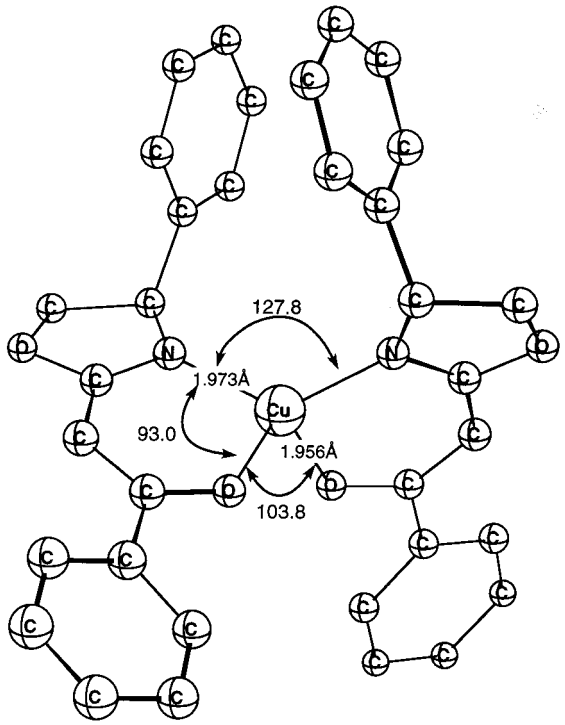
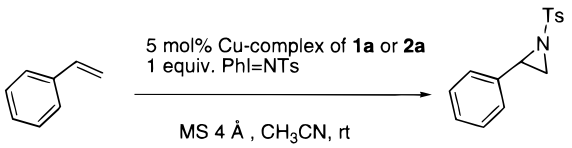


Figure 2. C_2-symmetric copper complex **6** (ligand **1a**) after optimization using a Becke-type three-parameter hybrid functional (B3PW91). The basis set used was D95V for all atoms except for copper (6-311+G).

Table 1. Asymmetric Aziridination of Styrene with Ligand 1a and 2a



entry no.	ligand	complex	% yield[a]	% ee[b]	reaction time/ min
1	**1a**	preformed	90	34	10
2	**1a**	in situ	40	racemic	20
3	**2a**	in situ	100	15	10

[a] Isolated yield after column chromatography. [b] Determined by HPLC analysis (WHELK-O column, hexane/2-propanol (88/12), 1 mL/min).

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(24) The calculations were performed using Gaussian 94 with a Becke-type three-parameter hybrid functional (B3PW91); see: Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648. The basis set used was D95V for all atoms except for Cu (6-311+G). For Gaussian 94 Revision B.3, see: Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T.; Petersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Peng, C. Y.; Ayala, P. Y.; Chen, W.; Wong, M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, J. A. Gaussian, Inc., Pittsburgh, PA, 1995.

(25) The complex was generated in situ by adding the ligand (**1a** or **2a**) dissolved in styrene to the copper salt (CuOTf or $Cu(OTf)_2$) under nitrogen. The mixture was stirred for 30 min and then transferred via cannula to a flask containing PhI=NTs and molecular sieves 4A.

Conclusions

We synthesized a new type of oxazoline-derived ligands and isolated three different transition-metal complexes. The ligands **1a** and **2a** were evaluated in the aziridination reaction of styrene, and the best results were obtained using the N,O-ligand type **1a**. The asymmetric induction in this reaction is moderate but promising, and we are currently searching for other applications of these chiral ligands.

Experimental Section

General Comments. All reactions were run under a nitrogen atmosphere, using dry glassware. THF and ether were distilled from a deep blue solution of sodium−benzophenone ketyl under nitrogen. Dichloromethane, acetonitrile, ethyl orthoacetate, and diisopropylamine were distilled from calcium hydride under nitrogen. Acid chlorides were distilled from PCl_5. Amino alcohols were purchased from Lancaster Chemical Co. *n*-Butyllithium was purchased as a 1.6 M solution in hexane from Lancaster Chemical Co. For analytical thin-layer chromatography, Macherey-Nagel 0.25 mm SIL G-60 UV_{254} 60-F precoated plates were used. The spots were visualized by using UV light or iodine. Flash column chromatography and medium-performance liquid chromatography (MPLC) were performed using Matrex silica gel 60A (37−70 μm). Melting points were recorded on a Leitz apparatus and are uncorrected. ^{1}H and ^{13}C NMR spectra are for $CDCl_3$ solutions, using either a Varian XL 300 or a Varian Unity 400 spectrometer. Chemical shifts for protons are reported using the residual $CHCl_3$ as the internal reference (δ 7.26). Carbon shifts are given with the ^{13}C signal of $CDCl_3$ (δ 77.0) as reference. Absorbance measurements were made on a Cary-3bio UV/vis spectrophotometer using CH_2Cl_2 as solvent, λ values are reported in nm. Mass spectra were recorded by direct inlet on an INCOS 50 mass spectrometer.

Acetimidoethyl Ether Hydrochloride.[26] To a cooled (−20 to −10 °C) suction flask, containing dry acetonitrile (10.0 g, 240 mmol) and absolute ethanol (11.5 g, 250 mmol), dry hydrogen chloride gas was introduced. The hydrogen chloride was bubbled into the solution until absorption of the gas ceased (about 5 h). The reaction mixture was brought to room temperature and left to crystallize (1−2 days). The crystals were filtered and washed with dry ether to give 28.0 g (94% yield) of pure product. ^{1}H NMR: δ 12.40 (br s, 1H), 11.45 (br s, 1H), 4.62 (q, J = 7.0 Hz, 2H), 2.47 (s, 3H), 1.48 (t, J = 7.0 Hz, 3H).

General Procedures for Formation of Oxazolines 4a,b. For the oxazoline preparation, two methods developed by Meyers et al.[27] were used.

Method A. In a flask containing acetimidoethyl ether hydrochloride (5.09 g, 41.2 mmol) and dry CH_2Cl_2 (30 mL), the amino alcohol **3a** (5.00 g, 36.5 mmol) was added in one portion at 0 °C. The reaction mixture was stirred for 3 h at 0 °C and then slowly warmed to room temperature. After 5 h the reaction was quenched by pouring the solution into ice−water (30 mL). The organic layer was separated and the aqueous phase extracted with CH_2Cl_2 (2 × 20 mL). The combined organic layers were dried ($MgSO_4$), filtered, and concentrated under reduced pressure.

Method B. Amino alcohol **3a** or **3b** (36.5 mmol) dissolved in 1,2-dichloroethane (30 mL) was treated with ethyl orthoacetate (4.95 g, 41.2 mmol) and then refluxed for 5 h. The reaction mixture was then cooled to room temperature and concentrated under reduced pressure.

***(4S)*-2-Methyl-4-phenyl-4,5-dihydrooxazole (4a).** The oxazoline was obtained in 93% yield (5.50 g) using method A, whereas method B gave 5.80 g (98%) of crude product. The product was used without purification in the ligand synthesis. ^{1}H NMR: δ 7.40−7.22 (m, 5H), 5.16 (dd, J = 10.2, 8.4 Hz, 1H), 4.60 (dd, J = 10.2, 8.4 Hz, 1H), 4.08 (t, J = 8.4 Hz, 1H), 2.09 (s, 3H). ^{13}C NMR: δ 165.8, 142.4, 128.4, 127.5, 126.5, 74.7, 69.8, 13.9. IR (CH_2Cl_2): 2986, 1672 cm^{-1}.

***(4S)*-4-Benzyl-2-methyl-4,5-dihydrooxazole (4b).** Method B afforded 6.14 g (96%) of crude **4b**. The crude product was used without further purification in the ligand synthesis. ^{1}H NMR: δ 7.30−7.11 (m, 5H), 4.32 (m, 1H), 4.13 (dd, J = 9.2, 8.5, 1H), 3.90 (dd, J = 8.5, 7.3, 1H), 3.04 (dd, J = 13.7, 5.4, 1H), 2.61 (dd, J = 13.7, 8.4, 1H), 1.93 (s, 3H). ^{13}C NMR: δ 165.3, 138.2, 129.3, 128.7, 126.7, 72.0, 67.5, 41.9, 14.1.

General Procedure for the Preparation of Imidoyl Chlorides.[28] PPh_3 (34.5 g, 132 mmol), Et_3N (7.30 mL, 53.0 mmol), and CCl_4 (21.1 mL, 220 mmol) were added to a flask equipped with a condenser. The carboxylic acid (44.0 mmol) was introduced and the mixture stirred at 0 °C. After 20 min, *p*-toluidine (5.68 g, 53.0 mmol) dissolved in CCl_4 (21.1 mL) was slowly added (over 20 min). The reaction mixture was refluxed for 3 h, whereupon the solvent was removed under reduced pressure. Hexane (50 mL) was added, and the residual Ph_3PO, Ph_3P, and Et_3N−HCl were filtered off and washed free of product with additional hexane (4 × 20 mL). The combined filtrate and washings were concentrated under reduced pressure to afford the crude imidoyl chloride.

***N*-*p*-Tolylbenzimidoyl Chloride (5a).** The crude product was obtained as a yellow solid in 71% yield (7.18 g) and was not further purified. ^{1}H NMR: δ 8.16−7.33 (m, 5H), 7.20 (d, J = 8.2 Hz, 2H), 6.95 (d, J = 8.2 Hz, 2H), 2.34 (s, 3H). IR (CCl_4): 1648, 1560 cm^{-1}.

2,2,2-Trifluoro-*N*-*p*-tolylacetimidoyl Chloride (5b). Bulb-to-bulb distillation (125 °C, 38 Torr) of the crude product afforded 6.86 g (70% yield) of the pure compound as a colorless oil. ^{1}H NMR: δ 7.27 (d, J = 8.5 Hz, 2H), 7.10 (d, J = 8.5 Hz, 2H), 2.41 (s, 3H). ^{13}C NMR: δ 140.7, 137.7, 130.4 (q, J_{C-C-F} = 40.0 Hz), 129.5, 121.4, 116.7 (q, J_{C-F} = 265 Hz), 21.0. IR (neat): 3034, 1684 cm^{-1}.

General Procedure for the Synthesis of Oxazoline Ligands 1a−e. In a flask equipped with a magnetic stirrer bar, freshly distilled diisopropylamine (1.40 mL, 10.0 mmol) and THF (10 mL) were added. The solution was cooled to −78 °C and butyllithium (6.26 mL, 10.0 mmol) added dropwise during 15 min. The solution was then stirred for 30 min at −78 °C before the oxazoline (4.54 mmol), dissolved in THF (3 mL), was added. On addition of the oxazoline, a color change from yellow to dark red was observed. The reaction mixture was stirred for 2 h, followed by slow addition (20 min) of freshly distilled acid chloride (4.54 mmol) dissolved in THF (2 mL). During addition the solution turned bright orange. After about 1 h the reaction was quenched by addition of saturated ammonium chloride solution (5 mL) and then brought to room temperature. The reaction mixture was transferred to a separatory funnel and the organic phase separated. The aqueous layer was extracted with methylene chloride (3 × 10 mL). The combined organic layers were washed with brine (10 mL) and dried ($MgSO_4$). After filtration, the solvent was removed under reduced pressure.

1-Phenyl-2-[(4*S*)-phenyl-4,5-dihydrooxazol-2-yl]propen-2-ol (1a). Purification by MPLC using pentane/EtOAc (5/1) furnished the product as white crystals in 62% yield (0.75 g). Only the enol product was observed in ^{1}H NMR. R_f = 0.37 (pentane/EtOAc (3/2)). $[\alpha]^D_{21}$ = −204.7 (*c* 1.05, CH_2Cl_2). Mp: 68−70 °C. ^{1}H NMR: δ 10.28 (br s, 1H), 7.90 (m, 2H), 7.47−

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7.29 (m, 8H), 5.72 (s, 1H), 5.17 (dd, J = 8.7, 6.9 Hz, 1H), 4.81 (t, J = 8.7 Hz, 1H), 4.28 (dd, J = 8.7, 6.9 Hz, 1H). ^{13}C NMR: δ 187.8, 170.5, 139.7, 138.9, 130.7, 129.1, 128.8, 128.1, 126.9, 126.1, 74.8, 74.0, 59.2. IR (CCl_4): 3065, 2290, 1634, 1548, 1253 cm^{-1}. UV/vis: 317, 237 nm. MS (EI): *m/z* (relative intensity) 265 (M^+, 31), 264 (55), 120 (23), 105 (100), 77 (62). Anal. Calcd for $C_{17}H_{15}NO_2$: C, 76.96; H, 5.70; N, 5.28. Found: C, 76.70; H, 5.48; N, 5.18.

2-[(4*S*)-Benzyl-4,5-dihydrooxazol-2-yl]-1-phenylethenol (1b). Purification by flash chromatography with pentane/EtOAc/Et_3N (9/1/0.1) afforded the ligand as white crystals in 32% yield (0.41 g). Only the enol product was observed in ^{1}H NMR. R_f = 0.28 (pentane/EtOAc (5/2)). $[\alpha]^D_{21}$ = +68.91 (*c* 0.76, CH_2Cl_2). Mp: 147−149 °C. ^{1}H NMR: δ 10.13 (br s, 1H), 7.85 (m, 2H), 7.46−7.20 (m, 8H), 5.60 (s, 1H), 4.48 (dt, J = 8.4, 8.1 Hz, 1H), 4.34 (dq, J = 8.1, 6.8 Hz, 1H), 4.22 (dd, J = 8.4, 6.8 Hz, 1 H), 2.99 (dd, J = 13.8, 6.8 Hz, 1 H), 2.90 (dd, J = 13.8, 6.8 Hz, 1H). ^{13}C NMR: δ 187.6, 170.1, 139.9, 136.0, 130.6, 129.0, 128.9, 128.1, 127.3, 126.8, 74.1, 71.8, 56.9, 40.9. IR (CCl_4): 3020, 2290, 16322, 1538 cm^{-1}. UV/vis: 316, 234 nm. MS (EI): *m/z* (relative intensity) 251 (M^+ − 28, 3), 188 (73), 105 (100), 77 (40). Anal. Calcd for $C_{18}H_{17}NO_2$: C, 77.39; H, 6.13; N, 5.01. Found: C, 77.57; H, 6.21; N, 4.84.

1-[(4*S*)-Phenyl-4,5-dihydrooxazol-2-yl]propen-2-ol (1c). Purification by flash chromatography with hexane/EtOAc/Et_3N (9/1/0.1 to 7/3/0.1) gave 0.29 g (31% yield) of **1c** as a colorless oil. The product was obtained as a 90/10 mixture of the enol/keto form. R_f = 0.13 (pentane/EtOAc (3/2)). $[\alpha]^D_{21}$ = −330.1 (*c* 0.99, $CHCl_3$). Mp: 66−69 °C. ^{1}H NMR: δ 9.82 (br s, 1H), 7.47−7.15 (m, 5H), 5.07 (dd, J = 8.4, 7.0 Hz, 1H), 5.02 (s, 1H), 4.72 (t, J = 8.4 Hz, 1H), 4.19 (dd, J = 8.4, 7.0 Hz, 1H), 2.07 (s, 3H). The methylene protons in the keto form appear at δ 3.56 (s, 2H). ^{13}C NMR: δ 194.6, 169.2, 139.2, 129.1, 128.7, 126.1, 74.5, 59.1, 28.8. IR (CCl_4): 3600−3200, 3032, 1734, 1642, 1552, 1492 cm^{-1}. UV/vis: 283 nm. MS (EI): *m/z* (relative intensity) 204 (M^+, 3), 91 (100), 69 (70). Anal. Calcd for $C_{12}H_{13}NO_2$: C, 70.92; H, 6.45; N, 6.89. Found: C, 70.79; H, 6.60; N, 7.00.

3,3,3-Trifluoro-1-[(4*S*)-phenyl-4,5-dihydrooxazol-2-yl]-propen-2-ol (1d). Flash chromatography of the crude product with pentane/EtOAc (9/1 to 7/3) afforded a yellow solid in 45% yield (0.53 g). Only the enol product was observed in ^{1}H NMR. R_f = 0.47 (pentane/EtOA (3/2)). $[\alpha]^D_{25}$ = −428.8 (*c* 0.61, CH_2Cl_2). Mp: 63−65 °C. ^{1}H NMR: δ 9.92 (br s, 1H), 7.46−7.37 (m, 3H), 7.32−7.24 (m, 2H), 5.36 (s, 1H), 5.21 (dd, J = 9.1, 6.9 Hz, 1H), 4.90 (dt, J = 9.1, 3.0 Hz, 1H), 4.38 (ddd, J = 9.1, 6.9, 3.0 Hz, 1H). ^{13}C NMR: δ 176.6 (q, J_{C-C-F} = 33 Hz), 171.7, 137.9, 129.4, 129.2, 126.1, 117.7 (q, J_{C-F} = 288 Hz), 75.7, 72.5, 59.2. IR (CCl_4): 3300−3200, 3035, 1651, 1564 cm^{-1}. UV/vis: 293 nm. MS (EI): *m/z* (relative intensity) 257 (M^+, 48), 188 (67), 120 (100), 103 (32), 77 (22). Anal. Calcd for $C_{12}H_{10}F_3NO_2$: C, 56.04; H, 3.92; N, 5.45. Found: C, 55.95; H, 4.06; N, 5.58.

3,3-Dimethyl-1-[(4*S*)-phenyl-4,5-dihydrooxazol-2-yl]but-1-en-2-ol (1e). The crude product was purified by MPLC using the eluent pentane/EtOAc (5/1). The product was obtained in 70% yield (0.78 g) and as a 82/18 mixture of the enol/keto forms. R_f = 0.46 (pentane/EtOAc (3/2)). $[\alpha]^D_{21}$ = −287.0 (*c* 0.88, CH_2Cl_2). Mp: 140−142 °C. ^{1}H NMR: δ 9.95 (br s, 1H), 7.42−7.19 (m, 5H), 5.19 (s, 1H), 5.07 (app t, J = 7.8 Hz, 1H), 4.71 (app t, J = 8.6 Hz, 1H), 4.18 (app t, J = 7.7 Hz, 1H), 1.16 (s, 9H). The methylenic protons in the keto form appear at δ 3.67 (s, 2H). ^{13}C NMR: δ 203.4, 170.0, 138.9, 129.0, 128.7, 128.6, 126.2, 74.4, 72.6, 59.2, 41.2, 27.8. IR (CH_2Cl_2): 3400−3200, 3052, 1732, 1632, 1527 cm^{-1}. UV/vis: 283 nm. MS (EI): *m/z* (relative intensity) 245 (M^+, 6), 188 (100), 120 (75), 77 (12). Anal. Calcd for $C_{15}H_{19}NO_2$: C, 73.44; H, 7.81; N, 5.71. Found: C, 73.19; H, 7.78; N, 5.89.

General Procedure for the Synthesis of Oxazoline Ligands 2a,b. To a solution of freshly distilled diisopropylamine (1.40 mL, 10.0 mmol) in dry THF (4 mL), cooled at −78 °C, a 1.6 M solution of *n*-butyllithium (6.26 mL, 10.0 mmol) in hexane was added dropwise over 15 min. The solution was then stirred for 30 min at −78 °C before the oxazoline (736 mg, 4.54 mmol) dissolved in THF (4 mL) was added. On addition of the oxazoline, a color change from yellow to dark red was observed. The reaction mixture was stirred for 2 h, followed by slow addition (30 min) of the imidoyl chloride (4.54 mmol) dissolved in THF (4 mL). When TLC indicated complete disappearance of the starting material (about 2 h), the reaction was quenched by addition of saturated aqueous ammonium chloride solution (5 mL) and then brought to room temperature. The organic phase was separated, and the aqueous layer was extracted with methylene chloride (3 × 10 mL). The combined organic layers were washed with brine (1 × 10 mL), dried ($MgSO_4$), and concentrated at reduced pressure to give the crude product.

[1-Phenyl-2-((4*S*)-phenyl-4,5-dihydrooxazol-2-yl)vinyl]-*p*-tolylamine (2a). The crude product was purified by flash chromatography, using hexane/EtOAc/Et_3N (9/1/0.1 to 7/3/0.1) to give 0.64 g of pure product as a colorless oil (40% yield). R_f = 0.58 (pentane/EtOAc (3/1)). $[\alpha]^D_{21}$ = +28.2 (*c* 1.02, CH_2Cl_2). Mp: 131−133 °C. ^{1}H NMR: δ 10.79 (br s, 1H), 7.41−7.20 (m, 10H), 6.86 (d, J = 8.2 Hz, 2H), 6.56 (d, J = 8.2 Hz, 2H), 5.35 (dd, J = 9.7, 8.2 Hz, 1H), 5.00 (s, 1H), 4.59 (dd, J = 9.7, 8.2 Hz, 1H), 4.01 (t, J = 8.2 Hz, 1H), 2.20 (s, 3H). ^{13}C NMR: δ 166.3, 154.8, 143.1, 138.2, 136.7, 131.6, 129.0, 128.9, 128.6, 128.2, 128.1, 127.3, 126.6, 121.9, 87.2, 73.0, 69.6, 28.6. IR (CCl_4): 3027, 1629, 1598, 1517 cm^{-1}. MS (EI): *m/z* (relative intensity) 306 (M^+ − 48, 74), 305 (52), 291 (97), 194 (29), 104 (65), 77 (94), 65 (100), 55 (100). Anal. Calcd for $C_{24}H_{22}N_2O$: C, 81.33; H, 6.26; N, 7.90. Found: C, 81.20; H, 6.42; N, 8.05.

[2-((4*S*)-Phenyl-4,5-dihydrooxazol-2-yl)-1-(trifluoromethyl)vinyl]-*p*-tolyl-amine (2b). Purification by flash chromatography with pentane/EtOAc/Et_3N (9/1/0.1 to 7/3/0.1) afforded the ligand in 56% yield (0.88 g). Recrystallization of the flashed product from pentane/EtOAc gave sharp, long crystals. R_f = 0.66 (pentane/EtOAc (3/1)). $[\alpha]^D_{25}$ = +411.1 (*c* 0.36, CH_2Cl_2). Mp: 50−51 °C. ^{1}H NMR: δ 10.44 (br s, 1H), 7.42−7.23 (m, 5H), 7.09 (m, 4H), 5.38 (s, 1H), 5.34 (dd, J = 10.0, 8.3 Hz, 1H), 4.61 (dd, J = 10.0, 8.3 Hz, 1H), 4.05 (t, J = 8.3 Hz, 1H), 2.34 (s, 3H). ^{13}C NMR: δ 165.7, 143.6 (q, J_{C-C-F} = 31 Hz), 142.6, 136.4, 135.8, 129.4, 128.7, 127.6, 126.5, 125.8, 120.5 (q, J_{C-F} = 276 Hz), 84.5 (q, $J_{C-C-C-F}$ = 6 Hz), 73.4, 69.5, 20.9; IR (CCl_4): 3031, 1645, 1548 cm^{-1}. UV/vis: 233, 299 nm. MS (EI): *m/z* (relative intensity) 200 (M^+ − oxazoline, 16), 105 (100), 77 (91), 67 (28). Anal. Calcd for $C_{19}H_{17}F_3N_2O$: C, 65.89; H, 4.95; N, 8.09. Found: C, 65.79; H, 5.08; N, 8.23.

Bis[1-phenyl-2-[(4*S*)-phenyl-4,5-dihydrooxazol-2-yl]propen-2-ol]copper (6).[12] $Cu(OAc)_2 \cdot H_2O$ (75.4 mg, 380 μmol) was added to a suspension of ligand **1a** (200 mg, 750 μmol) in methanol (5 mL). The dark green solution was stirred at room temperature for 40 min. After the solvent was evaporated, the residue was dissolved in CH_2Cl_2 and washed with a 0.1 M solution of KH_2PO_4 (4 mL). The solution was dried ($MgSO_4$) and concentrated in vacuo. The crude product was recrystallized from hexane/EtOAc to give 55.0 mg of the complex as sharp, green needles (55% yield). R_f = 0.67 (pentane/EtOAc (3/2)). $[\alpha]^D_{25}$ = +577.3 (*c* 0.093, CH_2Cl_2). Mp: 206−208 °C. IR (CCl_4): 2290, 1600, 1548, 1252 cm^{-1}. UV/vis: 324, 291, 233 nm. Anal. Calcd for $C_{34}H_{28}CuN_2O_4$: C, 68.96; H, 4.77; N, 4.73. Found: C, 68.83; H, 4.62; N, 4.89.

Bis[1-phenyl-2-[(4*S*)-phenyl-4,5-dihydrooxazol-2-yl]propen-2-ol]cobalt (7). The ligand **1a** (50.0 mg, 188 μmol), $CoCl_2 \cdot 6H_2O$ (12.0 mg, 94.0 μmo), and absolute ethanol (2 mL) were placed in a 10 mL flask and stirred for 10 min. An aqueous solution of NaOH (10 μL, 13 M) was added. On the addition of NaOH, a change in color from blue to orange-red was observed. The reaction mixture was stirred for 4 h before addition of H_2O (2 mL) and filtration. The residue was washed several times with H_2O and then dried under vacuum before recrystallization from hexane/EtOAc. The recrystallization afforded sharp red crystals in 11% yield (12.1 mg). R_f = 0.31 (pentane/EtOAc (3/2)). $[\alpha]^D_{25}$ = −291.0 (*c* 0.10, THF). Mp:

214−217 °C. IR (CCl_4): 2290, 1600, 1548, 1253 cm^{-1}. UV/vis: 318, 229 nm. Anal. Calcd for $C_{34}H_{28}CoN_2O_4$: C, 69.51; H, 4.80; N, 4.77. Found: C, 69.58; H, 4.97; N, 4.55.

Bis[1-phenyl-2-[(4*S*)-phenyl-4,5-dihydrooxazol-2-yl]propen-2-ol]palladium (8). The ligand **1a** (100 mg, 330 μmol) was dissolved in 1 mL of acetic acid, and $Pd(OAc)_2$ (37.3 mg, 170 μmol) was added. On the addition, a color change from yellow to orange occurred. The reaction mixture was stirred for about 30 min (until everything dissolved) and then left to crystallize (1 day). Filtration gave 59.0 mg of small, yellow crystals (50% yield). $R_f = 0.67$ (pentane/EtOAc (3/2)). $[\alpha]^{D}_{25} = -542.2$ (*c* 0.11, CH_2Cl_2). Mp: 185−187 °C dec. ^{1}H NMR: δ 7.49−7.20 (m, 10H), 5.42 (dd, J = 9.1, 3.4 Hz, 1H), 5.27 (s, 1H), 4.67 (dd, J = 9.1, 2.8 Hz, 1H), 4.32 (dd, J = 8.2, 2.8 Hz, 1H). ^{13}C NMR: δ 177.5, 165.5, 1143.3, 138.6, 129.4, 128.5, 127.8, 127.3, 126.5, 125.8, 79.5, 75.7, 63.0. IR (CCl_4): 2291, 1600, 1548, 1253 cm^{-1}. UV/vis: 244, 341 nm. Anal. Calcd for $C_{34}H_{28}PdN_2O_4$: C, 64.31; H, 4.44; N, 4.41. Found: C, 64.55; H, 4.33; N, 4.63.

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