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COMMUNICATION

Azopyridine-based chiral oxazolines with rare-earth metals for photoswitchable catalysis

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An azopyridine-based oxazoline was developed for utilizing azo group coordination and isomerization as a photoswitchable ligand. The ligand coordinated to rare-earth metal (RE) catalyst underwent efficient *E*/*Z* photoisomerization, suggesting tri- and bidentate coordination switch. The photoisomerization of the ligand enabled to modulate the enantioselectivity of RE-catalyzed aminal forming reaction.

Structural modification of ligands can modulate the electronic or steric property or coordination sphere[1] of a metal complex to promote a specific organic transformation.[2] Recent studies have described that modulating steric effect and coordination number of a ligand have a considerable impact on the regio-[3,4] or stereoselectivity.[5,6] As such, ligands with the above outlined properties are synthesized separately for each specific purpose. In contrast, the structural modification with external stimulus could rapidly provide insight into the suitable ligand for a reaction, or ultimately modulate reaction outcomes with a single ligand-metal catalyst. To this end, stimuli-responsive ligands[7,8] whose functions can be reversibly tuned have been extensively investigated. In particular, the use of a photoswitchable ligand[8] is an attractive method because light is a non-invasive stimulus to a target chemical process.

In the variety of unique photoswitchable ligands, *N*-heteroaryl azo compounds[9] are ideal photoresponsive molecules owing to their inherent coordination ability. Herges developed 3-azopyridine derivatives as photoswitchable ligands for the spin-state tuning of a metal porphyrin complex by manipulation of the pyridine-metal distance.[10a] Steric control of the 3-azopyridine coordination was also realized to be an effective approach (Fig. 1a).[10b-d] Alternatively, 2-azopyridines are inherently bidentate ligands that chelate metals with pyridine and azo groups. However, as metal ligands, they are difficult to transform from *E* to *Z* isomer probably due to strong chelation to a transition metal (Fig. 1b).[11] Additionally, the redox-active nature of the azo group can hamper photoisomerizaton.[12] Hence, it is a formidable task to design a photoswitchable ligand with an azo group coordination site. The combination of the azo group-assisted chelation and photoisomerization may pave alternative ways for controlling coordination mode, leading to actuate their catalytic functions.[8,13,14,15] Moreover, to the best of our knowledge, *N*-heteroaryl azo compounds have not been explored as ligands for chiral metal catalysts despite their several intriguing applications.[8b,9,10]

To incorporate 2-azopyridine chelation into photoswitchable catalysis, we designed azopyridine-based chiral oxazolines, inspired by oxazolinyl pyridine-type ligand (e.g., Pybox, Pyox, or Quinox).[3,4,6,16] We also envisioned a flexible coordination sphere of the rare-earth (RE) metal[17,18] that would allow ligand photoisomerization after azo group coordination, supported by a chiral oxazoline: the *E*/*Z* isomerization of the azo group can enable an interchange between tri- and bidentate coordination in response to photoirradiation (Fig. 1c). The RE complex consisted of only nitrogen atom coordination would also render ejection of azo group feasible during *E* to *Z* photoisomerization process without a predominant coordination of oxygen donors.[17a,18c]

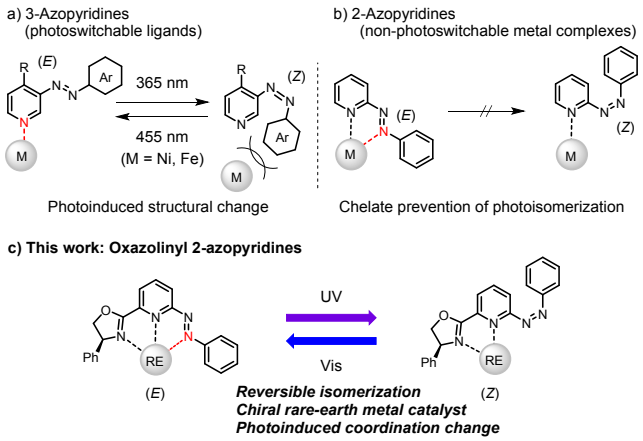

Fig. 1 Azopyridine-based ligands: (a) 3-azopyridines, (b) 2-azopyridines, (c) this work: oxazolinyl 2-azopyridines.

In this study, photo-modulation of the catalytic activity of a RE catalyst with the chiral photoswitchable ligand was explored in enantioselective cyclic aminal synthesis.

To commence our study, we established the synthesis of (*S*)-**2** (Scheme 1). Commercially available 6-amino picolinic acid was subjected to the Mills reaction under basic condition[10c,12c,19] to give

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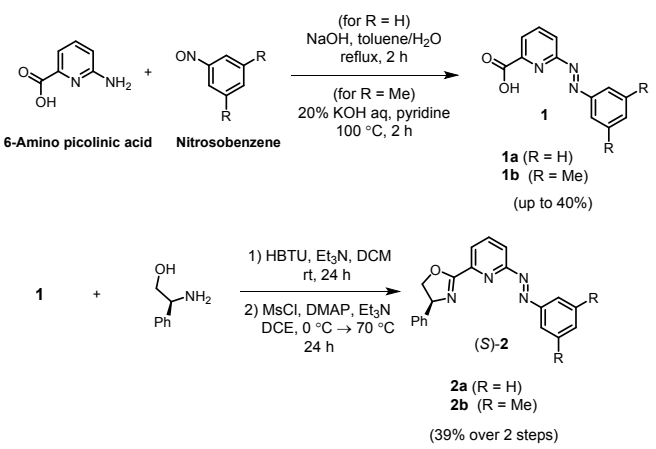
azopyridine carboxylic acids **1**. Subsequently, the condensation of **1** with (*S*)-phenyl glycinol followed by oxazoline cyclization provided the desired products, chiral **2a–b** (Scheme 1).



Scheme 1 Synthesis of (*S*)-**2** (for details, see ESI).

Initially, we examined the coordination of (*E*)-**2** to La(OTf)$_3$ (Fig. 2, S5 and S11). When (*E*)-**2a** was mixed with one equivalent of La(OTf)$_3$, a homogeneous solution was obtained, and all the ^{1}H-NMR peaks of pyridine ($H_{a–c}$), aryl azo moiety ($H_{d–f}$), and oxazoline ($H_{g–i}$) were shifted (Fig. 2a and 2b). These observations suggest that three nitrogens on pyridine, azo group, and oxazoline participate in the coordination to form the 1:1 complex, (*E*)-**2a**-La(OTf)$_3$. Additionally, we presumed the ligand coordination is quite similar to that of Pybox on the basis of the analysis of L_2-RE(OTf)$_3$ (L = Pybox) reported by Aspinall.[20a] From APCI-MS analysis of a solution of (*E*)-**2a**:La(OTf)$_3$ (2:1), we observed the L_2-La(OTf)$_2^+$ (L = (*E*)-**2a**) cationic species (Fig. S17).[20b]

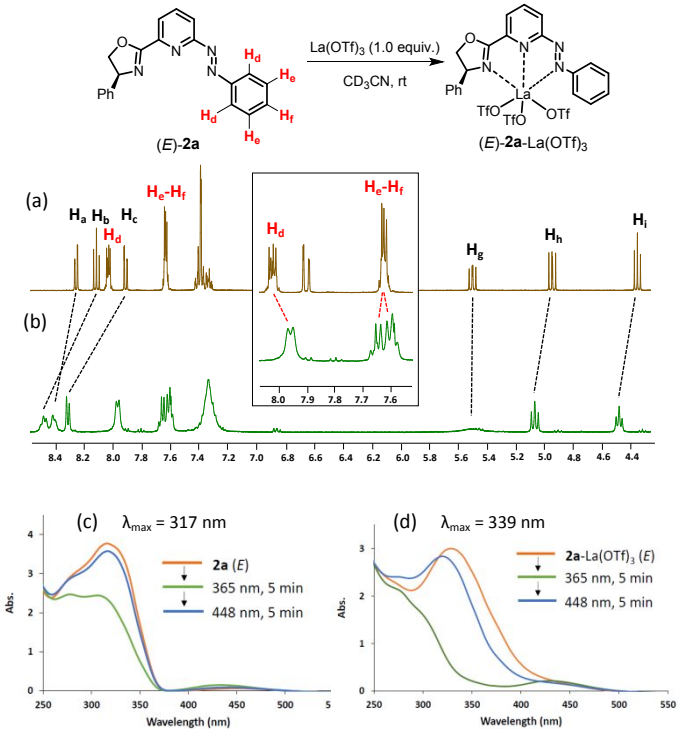


Fig. 2 Coordination and photoisomerization studies of **2a**: ^{1}H-NMR of (a) (*E*)-**2a** and (b) (*E*)-**2a**-La(OTf)$_3$ (8 mM in CD_3CN). UV-vis spectra of (c) **2a** and (d) **2a**-La(OTf)$_3$ before and after photoirradiation (250 μM in CH_3CN).

The photoisomerization of the ligand was evaluated by obtaining UV-vis spectra in CH_3CN. Irradiation of (*E*)-**2a** at 365 nm decreased the absorption of *E* isomer, instead of enhancing the absorbance corresponding to *Z* isomer (Fig. 2c). The absorbance in the UV-vis spectra would be attributable to π-π* and n-π* transition, respectively. Upon illumination with 448 nm LED, the initial absorption was recovered, indicating the reversible photoisomerization of the ligand. The addition of La(OTf)$_3$ to (*E*)-**2a** clearly led to a red-shifted absorbance (λ_{max} = 317 nm to 339 nm) and broadening of the longer wavelength, suggesting more feasible isomerization from *E* to *Z* complex by 365 nm irradiation (Fig. 2d). Indeed, irradiation of the complex at 365 nm immediately increased the absorbance of *Z* isomer, and 448 nm irradiation recovered *E* isomer. An identical absorbance shift upon photoisomerization was also observed for **2b**-(LaOTf)$_3$ (Fig. S7 and S9). A photostationary state (PSS) of **2** was achieved after 365 nm or 448 nm irradiation for 30 min in CD_3CN (Table 1). For **2a**, the ratios were 56:44 (*E*/*Z*) and 83:17 (*E*/*Z*) at 365 and 448 nm, respectively, based on ^{1}H-NMR analysis (entry 1 in Table 1 and Fig. S2). On the other hand, **2b** had a higher proportion of the *Z* isomer (*E*/*Z* = 24:76) than **2a** under UV irradiation (entry 2 in Table 1 and Fig. S8). This trend agrees with that reported by Herges for the 3-azopyridine ligand.[10c] In contrast, 448 nm irradiation of **2b** resulted in an almost identical *E*/*Z* ratio (*E*/*Z* = 84:16) to that of **2a** (*E*/*Z* = 83:17). There was no significant enhancement of isomerization efficiency in other solvents (Table S1). The half-life ($T_{1/2}$) of the *Z* isomer was 433 h for **2a** and 193 h for **2b** at 20 °C (entries 1 and 2 in Table 1).

Table 1 *E*/*Z* ratio and half-life ($T_{1/2}$) of Z isomer in the photostationary state (PSS).[a]

Entry	Compounds	PSS 365 nm *E*/*Z*	PSS 448 nm *E*/*Z*	$T_{1/2}$ of *Z* isomer at 20 °C (h)
1	**2a**	56:44	83:17	433
2	**2b**	24:76	84:16	193
3	**2a**-La(OTf)$_3$	8:92	77:23	10.5
4	**2b**-La(OTf)$_3$	8:92	77:23	7.7

[a] Determined by ^{1}H-NMR after photoirradiation for 30 min (8 mM in CD_3CN).

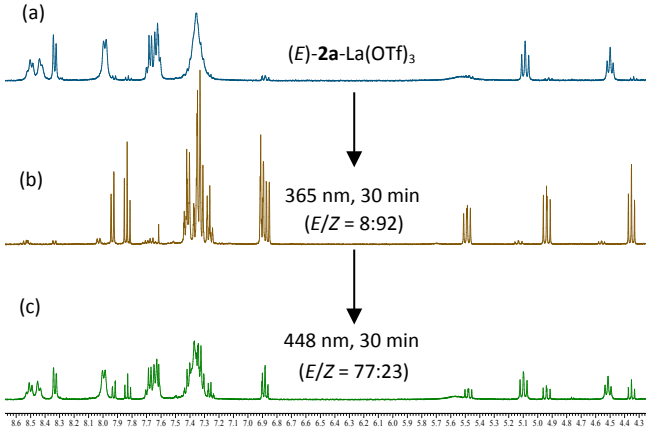
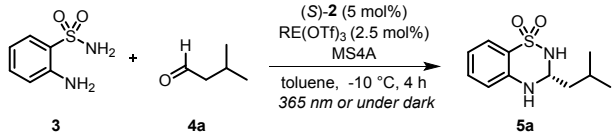


Fig. 3 Photoisomerization of **2a**-La(OTf)$_3$ monitored by ^{1}H-NMR (8 mM in CD_3CN). (a) (*E*)-**2a**-La(OTf)$_3$ before photoirradiation. (b) After 365 nm photoirradiation for 30 min. (C) After 448 nm photoirradiation for 30 min.

The photoisomerization of the **2**-La(OTf)$_3$ complex was also monitored by ^{1}H-NMR in CD_3CN. After 365 nm irradiation of (*E*)-**2a**- or (*E*)-**2b**-La(OTf)$_3$, PSS was attained in *E*/*Z* = 8:92 (entries 3 and 4 in Table 1 and Fig. 3a, 3b, and S10). The proportion of the *Z* isomer is therefore higher than that of before coordination. This feasible isomerization agrees well with the absorption shift in the UV-vis spectra, ensuring the La complex has photochemical properties different from those of the free ligand. Subsequently, we confirmed reisomerization of the **2**-La(OTf)$_3$ complex with 448 nm irradiation to recover the initial complex with *E*/*Z* = 77:23 (entries 3 and 4 in Table 1, Fig. 3c and S10). These observations indicate that N=N bond remains intact during isomerization. $T_{1/2}$ of *Z* isomer was shortened to 10.5 h for (*Z*)-**2a**-La(OTf)**$_3$** and 7.7 h for (*Z*)-**2b**-La(OTf)**$_3$** by complexation (entries 3 and 4 in Table 1). These drastic changes in $T_{1/2}$ indicate that ligand dissociation from La is minimal during isomerization. Furthermore, comparison of the ^{1}H-NMR spectra of (*Z*)-**2**-La(OTf)$_3$ and free (*Z*)-**2** shows that there is no obvious shift in the peaks of the aryl azo group (Fig. S6 and S12), supporting the absence of N=N bond coordination to La in the *Z* state.

Both coordinating and photoswitchable functions of **2** encouraged us to examine a photocontrol of catalytic enantioselective reaction. Since (*E*)-**2** is expected to have Pybox-type tridentate feature, we selected the enantioselective intermolecular cyclization of sulfonamide **3** and aldehyde **4a** as a model reaction (Table 2).

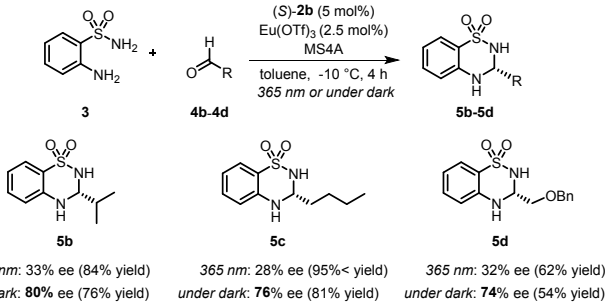
Table 2 Catalytic activity of rare-earth (RE) complexes as Lewis acids.[a]



Entry	**2**/RE	Condition	Isolated yield (%)	ee (%)[b]
1	**2a**/La	365 nm	62	29
2	**2a**/La	under dark	71	**68**
3	**2b**/La	365 nm	51	43
4	**2b**/La	under dark	70	**78**
5	**2b**/Eu	365 nm	88	32
6	**2b**/Eu	under dark	95	**72**

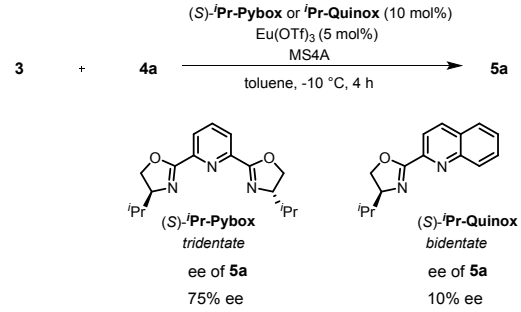
[a] Reaction conditions: **3** (0.07 mmol), **4a** (1.0 equiv.), (*S*)-**2** (5 mol%), RE(OTf)$_3$ (2.5 mol%), and MS4A (17 mg) in toluene (0.7 mL). [b] Determined by HPLC analysis using an OD-H column. Racemization of **5a** did not proceed during the reaction and HPLC measurements (Table S2 and Fig. S20). The absolute configuration of **5a** was determined by comparison with the reported retention time.[21]

After identifying the suitable reaction conditions and RE salts based on previous reports (Tables S3–S5),[21] we compared the catalytic activity of the *Z* (365 nm) and *E* isomers (under dark) of **2**-La(OTf)$_3$[22] in the reaction at –10 °C. With **2a** as a ligand, the reaction provided **5** in 62% yield and 29% ee under UV irradiation (entry 1). In contrast, the reaction in the dark gave the desired product **5** in 71% yield and 68% ee (entry 2), indicating that the (*E*)-**2a**-La(OTf)$_3$ catalyst is preferable over its *Z* isomer for the higher enantioinduction. The methyl-substituted **2b** as a ligand also provided moderate to good yield in 51% under UV and 70% yield under dark conditions (entries 3 and 4). The enantioselectivity exhibited the same trend with regard to photoisomerization of the catalyst (43% ee vs. 78% ee). Replacement of La with Eu, which has a higher Lewis acidity, improved the conversion of **3**, affording the product **5a** in 88% yield with UV irradiation and 95% yield under dark conditions (entries 5 and 6). This Eu catalyzed reaction also modulated enantioselectivity by photoisomerization of the catalyst (32% ee vs. 72% ee).[23] The same trend in the enantioselectivity was observed for the products from different aldehydes **4b**-**4d** with good to moderate yields (54-95%< yields, Scheme 2). From the α-branched aldehyde **4b**, the aminal **5b** was formed in 80% ee under dark conditions despite the lower ee under UV irradiation (33% ee). The linear aldehyde **4c** provided **5c** with the most significant difference of ee by 48% (28% ee vs. 76% ee). The aldehyde with benzyloxy substituent (**4d**) was also applicable to give the ee modulation of **5d** (32% ee vs. 74% ee).



Scheme 2 Evaluation of the ee modulation with different aldehydes. [a]
[a] Reaction conditions: **3** (0.07 mmol), **4b**-**4d** (1.0 equiv.), (*S*)-**2b** (5 mol%), Eu(OTf)$_3$ (2.5 mol%), and MS4A (17 mg) in toluene (0.7 mL).

To gain insight into the photo-modulation of enantioselectivity by the coordination mode, control experiments were conducted with known tridentate and bidentate oxazoline ligands. Initially, the reaction with the tridentate ^{i}Pr-Pybox-Eu catalyst was revealed to provide **5a** in 75% ee (Scheme 3).[24] Additionally, the bidentate ^{i}Pr-Quinox provided lower ee (10% ee) than the tridentate ^{i}Pr-Pybox. The reaction using **2** under UV irradiation also lowered ee because the N=N bond ejection from RE may result in the bidentate Quinox-type coordination mode.



Scheme 3 Control experiments.

In conclusion, we successfully prepared azopyridine-based chiral oxazoline ligands. The ligands exhibited reversible isomerization despite the chelation to lanthanum. As a catalytic application of the chiral photoswitchable ligands, we demonstrated that the RE complex can modulate the enantioselectivity in cyclic aminal synthesis. Further investigation of the structure of **2**-RE complex and its catalytic application are ongoing in our laboratory.

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Conflicts of interest

There are no conflicts of interest to declare.

Notes and references

1. (*a*) J. M. Smith, R. J. Lachicotte and P. L. Holland, *Chem. Commun.*, 2001, **1**, 1542–1543; (*b*) Z. Freixa and P. W. N. M. van Leeuwen, *Dalton Trans.*, 2003, 1890–1901; (*c*) H. V. Huynh, S. S. H. Chia and N. Y. S. Leong, *Organometallics*, 2020, **39**, 3999–4005.
2. (*a*) C. Popeney and Z. Guan, *Organometallics*, 2005, **24**, 1145–1155; (*b*) M. G. Sommer, S. Marinova, M. J. Krafft, D. Urankar, D. Schweinfurth, M. Bubrin, J. Košmrlj and B. Sarkar, *Organometallics*, 2016, **35**, 2840–2849.
3. D. Qian and X. Hu, *Angew. Chem., Int. Ed.*, 2019, **58**, 18519–18523.
4. X. Liu, C. Hou, Y. Peng, P. Chen and G. Liu, *Org. Lett.*, 2020, **22**, 9371–9375.
5. G. Zhou, A. H. Aboo, C. M. Robertson, R. Liu, Z. Li, K. Luzyanin, N. G. Berry, W. Chen and J. Xiao, *ACS Catal.*, 2018, **8**, 8020–8026.
6. H. Wen, K. Wang, Y. Zhang, G. Liu and Z. Huang, *ACS Catal.*, 2019, **9**, 1612–1618.
7. (*a*) M. R. Kita and A. J. M. Miller, *J. Am. Chem. Soc.*, 2014, **136**, 14519–14529; (*b*) G.-H. Ouyang, Y.-M. He, Y. Li, J.-F. Xiang and Q.-H. Fan, *Angew. Chem. Int. Ed.*, 2015, **54**, 4334–4337; (*c*) A. M. Camp, M. R. Kita, P. T. Blackburn, H. M. Dodge, C.-H. Chen and A. J. M. Miller, *J. Am. Chem. Soc.*, 2021, **143**, 2792–2800.
8. For reviews on photoswitchable ligands and organometallic complexes, see: (*a*) A. Bianchi, E. Delgado-Pinar, E. García-España, C. Giorgi and F. Pina, *Coord. Chem. Rev.*, 2014, **260**, 156-215; (*b*) Z. Freixa, *Catal. Sci. Technol.*, 2020, **10**, 3122–3139; (*c*) F. Medici, N. Goual, V. Delattre, A. Voituriez and A. Marinetti, *ChemCatChem*, 2020, **12**, 5573–5589.
9. S. Crespi, N. A. Simeth and B. König, *Nat. Rev. Chem.*, 2019, **3**, 133–146.
10. (*a*) S. Venkataramani, U. Jana, M. Dommaschk, F. D. Sönnichsen, F. Tuczek and R. Herges, *Science*, 2011, **311**, 445–449; (*b*) S. Thies, H. Sell, C. Schütt, C. Bornholdt, C. Näther, F. Tuczek and R. Herges, *J. Am. Chem. Soc.*, 2011, **133**, 16243–16250; (*c*) S. Thies, H. Sell, C. Bornholdt, C. Schütt, F. Köhler, F. Tuczek and R. Herges, *Chem. - Eur. J.*, 2012, **18**, 16358–16368; (*d*) S. Shankar, M. Peters, K. Steinborn, B. Krahwinkel, F. D. Sönnichsen, D. Grote, W. Sander, T. Lohmiller, O. Rüdiger and R. Herges, *Nat. Commun.*, 2018, **9**, 4750.
11. C. Deo, N. Bogliotti, R. Métivier, P. Retailleau and J. Xie, *Organometallics*, 2015, **34**, 5775–5784.
12. (*a*) A. Sanyal, S. Chatterjee, A. Castiñeiras, B. Sarkar, P. Singh, J. Fiedler, S. Záliš, W. Kaim and S. Goswami, *Inorg. Chem.*, 2007, **46**, 8584–8593; (*b*) D. Sengupta, N. S. Saha Chowdhury, S. Samanta, P. Ghosh, S. K. Seth, S. Demeshko, F. Meyer and S. Goswami, *Inorg. Chem.*, 2015, **54**, 11465–11476; (*c*) A. E. Rudenko, N. E. Clayman, K. L. Walker, J. K. Maclaren, P. M. Zimmerman and R. M. Waymouth, *J. Am. Chem. Soc.*, 2018, **140**, 11408–11415.
13. For selected reports on photoswitchable ligands for metal catalysts, see: (*a*) D. Sud, T. B. Norsten and N. R. Branda, *Angew. Chem., Int. Ed.*, 2005, **44**, 2019–2021; (*b*) B. M. Neilson and C. W. Bielawski, *Organometallics*, 2013, **32**, 3121–3128; (*c*) Z. S. Kean, S. Akbulatov, Y. Tian, R. A. Widenhoefer, R. Boulatov and S. L. Craig, *Angew. Chem., Int. Ed.*, 2014, **53**, 14508–14511; (*d*) A. Telleria, P. W. N. M. van Leeuwen and Z. Freixa, *Dalton Trans.*, 2017, **46**, 3569–3578; (*e*) T. Arif, C. Cazorla, N. Bogliotti, N. Saleh, F. Blanchard, V. Gandon, R. Métivier, J. Xie, A. Voituriez and A. Marinetti, *Catal. Sci. Technol.*, 2018, **8**, 710–715. (*f*) W. Fu, Y. Pi, M. Gao, W. Wang, C. Li, R. Tan and D. Yin, *Chem. Commun.*, 2020, **56**, 5993–5996.
14. For reviews on switchable catalysts, see: (*a*) B. M. Neilson and C. W. Bielawski, *ACS Catal.*, 2013, **3**, 1874–1885; (*b*) V. Blanco, D. A. Leigh and V. Marcos, *Chem. Soc. Rev.*, 2015, **44**, 5341–5370; (*c*) G. Romanazzi, L. Degennaro, P. Mastrorilli and R. Luisi, *ACS Catal.*, 2017, **7**, 4100–4114; (*d*) R. Dorel and B. L. Feringa, *Chem. Commun.*, 2019, **55**, 6477–6486; (*e*) D. Majee and S. Presolski, *ACS Catal.*, 2021, **11**, 2244–2252.
15. M. Kondo, K. Nakamura, C. G. Krishnan, S. Takizawa, T. Abe and H. Sasai, *ACS Catal.*, 2021, **11**, 1863–1867.
16. For reviews on oxazolinyl pyridine-type ligands and their catalytic applications, see: (*a*) S. A. Babu, K. K. Krishnan, S. M. Ujwaldev and G. Anilkumar, *Asian J. Org. Chem.*, 2018, **7**, 1033–1053; (*b*) G. Yang and W. Zhang, *Chem. Soc. Rev.*, 2018, **47**, 1783–1810.
17. For selected reviews on the coordination chemistry of rare-earth metals and their synthetic applications, see: (*a*) T. Moeller, D. F. Martin, L. C. Thompson, R. Ferrús, G. R. Feistel and W. J. Randall, *Chem. Rev.*, 1965, **65**, 1–50; (*b*) M. Shibasaki, H. Sasai and T. Arai, *Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 1236–1256; (*c*) S. Kobayashi, M. Sugiura, H. Kitagawa and W. W. L. Lam, *Chem. Rev.*, 2002, **102**, 2227–2302; (*d*) K. Dehnicke and A. Greiner, *Angew. Chem., Int. Ed.*, 2003, **42**, 1340–1354; (*e*) J. A. Kitchen, *Coord. Chem. Rev.*, 2017, **340**, 232–246; (*f*) F. Saraci, V. Quezada-Novoa, P. R. Donnarumma and A. J. Howarth, *Chem. Soc. Rev.*, 2020, **49**, 7949–7977.
18. (*a*) H. Sasai, T. Suzuki, N. Itoh, S. Arai and M. Shibasaki, *Tetrahedron Lett.*, 1993, **34**, 2657–2660; (*b*) D. A. Evans, K. R. Fandrick, H.-J. Song, K. A. Scheidt and R. Xu, *J. Am. Chem. Soc.*, 2007, **129**, 10029–10041; (*c*) K. Matsumoto, K. Suzuki, T. Tsukuda and T. Tsubomura, *Inorg. Chem.*, 2010, **49**, 4717–4719.
19. S. J. Dougan, M. Melchart, A. Habtemariam, S. Parsons and P. J. Sadler, *Inorg. Chem.*, 2006, **45**, 10882–10894.
20. (*a*) Tridentate ligand (L) can dissociate one of the triflate anion to generate L_2-RE$(OTf)_2^+$ cationic species, see: H. C. Aspinall, J. F. Bickley, N. Greeves, R. V. Kelly and P. M. Smith, *Organometallics*, 2005, **24**, 3458–3467. (*b*) ^{1}H-NMR analysis of (*E*)-**2a**:La$(OTf)_3$ (2:1) in CD_3CN showed a different peak shift from 1:1 complex, which also supports the formation of 2:1 complex (Fig. S19). However, the complexation was difficult to detect in toluene-d_8, the optimal solvent in the enantioselective aminal forming reaction, due to the low solubility of La$(OTf)_3$.
21. (*a*) X. Cheng, S. Vellalath, R. Goddard and B. List, *J. Am. Chem. Soc.*, 2008, **130**, 15786–15787; (*b*) P. Du, H. Zhou, Y. Sui, Q. Liu and K. Zou, *Tetrahedron*, 2016, **72**, 1573–1578; (*c*) Y. Sui, P. Cui, S. Liu, Y. Zhou, P. Du and H. Zhou, *Eur. J. Org. Chem.*, 2018, 215–218.
22. Ligand:RE (1:1) complex is proposed to be catalytic species according to Pybox-Sc$(OTf)_3$ system reported by Zhou although Ligand:RE (2:1) cannot be excluded as a catalytic species. The plausible stereochemical model for 1:1 complex is proposed based on the ref. 18b and 21b (Fig. S22).
23. Replacing UV with visible light irradiation right before starting the reaction resulted in the identical level of enantioinduction (73% ee) to that of entry 6 in Table 2 (72% ee). The result suggests that the recovery of the *E* isomer provided a good enantioselectivity.
24. The reaction with ^{i}Pr-Pybox-Eu catalyst under 365 nm irradiation also provided **5a** in 75% ee, suggesting photo- or thermal activation of substrates did not affect the enantioselectivity.

