Catalytic Enantioselective Synthesis of Planar Chiral Pillar[5]arenes via Asymmetric Sonogashira Coupling

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Abstract

As a novel type of macrocycles with attractive planar chirality, pillar[5]arenes have gained increasing research interest over the past decades, enabling their widespread applications in diverse fields such as porous materials, molecular machines, and chiral luminescence materials. However, the catalytic methodology towards the enantioselective synthesis of planar chiral pillar[5]arenes remains elusive. Here we report a novel method for the enantioselective synthesis of planar chiral pillar[5]arenes via asymmetric Sonogashira coupling, giving access to a wide range of highly functionalized planar chiral pillar[5]arenes, including both homo- and hetero-rimmed ones, with excellent enantioselectivities. Attractively, the resultant planar chiral pillar[5]arenes show great potential for widespread use in many areas such as chiral luminescent materials. This work not only enables the successful synthesis of planar chiral pillar[5]arenes with abundant structural and functional diversity as key building blocks for practical applications but also enriches the asymmetric cross-coupling methodologies in organic

synthetic chemistry.

Introduction

As a continuous research hotspot in supramolecular chemistry, the design and construction of novel macrocycles remains an attractive topic since they are not only privileged platforms for the investigations on fundamental issues such as noncovalent interactions and host-guest chemistry but also key building blocks towards higher-level assembles at different scale through hierarchical self-assembly.[1-3] In particular, the further introduction of chirality into macrocycles endows the resultant chiral macrocycles with both intriguing properties and emergent applications in diverse fields such as asymmetric catalysis, chiral sensing and separation, and chiral luminescence materials.[4-7] Thus, the development of novel synthetic strategy towards chiral macrocycles is of great importance.[8-11]

Among diverse typical chiral macrocycles, pillar[n]arenes, attributed to their interesting dynamic planar chirality, have attracted more and more attentions.[12-15] For pillar[5]arenes with five repeating paraphenylene methylene units, theoretically eight conformers co-exist in solution state attributed to the free rotation of each repeating unit. To achieve stable enantiomers, bulky substituent groups are typically introduced into one of repeat units to inhibit the unit rotation, thus leading to the planar chiral A1/A2-difunctionalized pillar[5]arenes (Figure 1a).[16-18] Due to their synthetic accessibility, A1/A2-difunctionalized pillar[5]arenes have emerged as the mostly investigated systems, which serve as key building blocks for wide applications in porous materials,[19-21] chiral luminescence materials,[22-25] and molecular machines.[26-30] For instance, the introduction of diverse fluorophores into planar chiral pillar[5]arenes make the resultant emissive pillar[5]arenes promising circularly polarized luminescence (CPL) emitters (Figure 1b). However, most of optically pure A1/A2-difunctionalized pillar[5]arenes were obtained through resolution using chiral stationary phase-high performance liquid chromatography (CSP-HPLC), and only handful examples of chemical resolution through the formation of diastereomers were demonstrated.[20, 31-32] Compared with both of these methods that suffer from obvious limitations in atom economy and synthetic efficiency, catalytic enantioselective synthesis

will definitely be an ideal choice. Considering their great importance and wide potential applications, it is urgent to develop new catalytically synthetic strategy for the highly stereoselective synthesis of planar chiral pillar[5]arenes, particularly functionalized ones, for further desired applications.

Herein, based on our on-going research interests in pillar[5]arene-based mechanically interlocked molecules (MIMs), especially rotaxane dendrimers[33-37] and CPL-active chiral rotaxanes,[38-40] we assumed that the asymmetric Sonogashira coupling reaction[41-42] would be a suitable choice for the synthesis of novel planar chiral pillar[5]arenes. On the one hand, the further extension of the conjugated skeletons of the resultant products would endow them with attractive tunable chiroptical properties, making them promising platforms as novel chiral luminescent materials for practical applications. On the other hand, the introduction of ethynyl moieties near the cavity would only slightly influence the host-guest chemistry of pillar[5]arenes, thus making the further construction of higher-order structures (*e.g.* rotaxanes) or assemblies (*e.g.* supramolecular polymers) feasible, which will further greatly expand their application scopes. Notably, for such reaction, the key challenge is that the free rotation of the reactive site around the crowded confined cavity of pillar[5]arenes would not only reduced the reaction efficiency but also make the stereochemical control even more difficult. Thus the key to success will be the identification of an efficient chiral metal catalyst that can access to the pillar[5]arene cavity to induce high enantioselectivity. To our great delight, by using a commercially available and relatively cheap phosphoramidite ligand, we have successfully realized the catalytic enantioselective synthesis of planar chiral pillar[5]arenes via asymmetric Sonogashira coupling, leading to the synthesis of a variety of A1/A2-difunctionalized pillar[5]arenes (both homo- and hetero-rimmed ones) with good to excellent yields and high enantioselectivities (up to 95% yield and up to 97% *e.e.*) (Figure 1c).
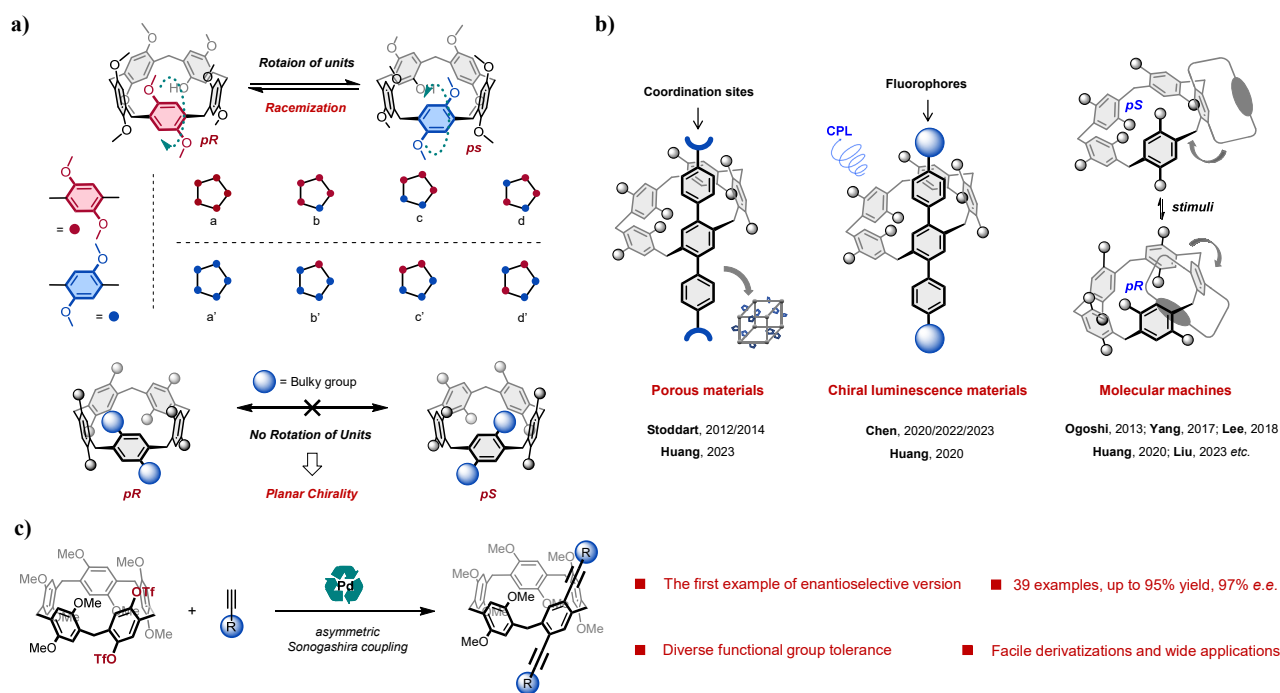
Figure 1. Design strategy for the catalytic enantioselective synthesis of planar chiral pillar[5]arenes via asymmetric Sonogashira coupling. (a) The interesting planar chirality of pillar[5]arenes and A1/A2-difunctionalized pillar[5]arenes with bulky groups. (b) The wide applications of planar chiral A1/A2-difunctionalized pillar[5]arenes in diverse fields. (c) The design strategy and key highlights of this work.

Results and Discussion

Reaction development

Aiming at the enantioselective synthesis of functionalized planar chiral pillar[5]arenes with attractive CPL performances, in our initial attempts, 9-ethynylanthracene was selected as the model alkyne to doubly couple with ditriflate pillar[5]arene under the reaction conditions of Sonogashira coupling (10 mol% Pd(dba)$_2$, CuI, and Et$_3$N as a base). Unfortunately, no reaction was found for a variety of classical phosphine ligands such as **BINAP** (**L1**), **JosiPhos** (**L2**), **MOP** (**L3**), and **TADDOL**-based phosphoramidite ligand (**L4**), mainly owing to their rigid skeletons that inhibit the formation of catalytic species (Table 1, *left*, entries 1-4). To our delight, upon the use of a **BINOL**-based phosphoramidite ligand (**L5**) (Table 1, *left*, entry 5), the desired product **3a** was successfully obtained

in 56% yield and 62% *e.e.*, together with the corresponding mono-alkynylated product **3a'** in 27% yield. Such attractive result further encouraged us to test corresponding phosphoramidite ligand with less rigid skeletons, thus the phosphoramidite ligand (**L6**) derived from **H$_8$-BINOL** was then tested, leading to a dramatic increase in *e.e.* value to 84%. The further increasing the steric hindrance of the amidate moiety from dimethylamine (**L6**) to piperidine (**L7**) afforded 82% *e.e.* (Table 1, *left*, entries 6 and 7), while the introducing bigger amine only led to dramatically reduced *e.e.* value to 55% and lower yield to 27% (for **L8**) or even totally inhibited the coupling reaction (for **L9**).

On the basis of such promising results, considering the bulkiness of 9-ethynylanthracene, we then chosen the smaller ethynylbenzene as the model alkyne for the reaction development. To avoid the typical homocoupling of the alkyne in the reaction, both 8 eq. of ethynylbenzene and 8 eq. Et$_3$N were employed, leading to the desired product **3b** in 56% yield and 87% *e.e.* under the optimized condition with **L6** as the chiral ligand (Table 1, *right*, entry 2). Interestingly, when **L7** was used, an increase in both yield (to 61%) and *e.e.* value (to 95%) was achieved (Table 1, *right*, entry 3), while neither **L8** nor **L9** led to no reaction at all. Notably, in above two cases, mono-alkynylated product **3b'** was also isolated in 34% and 24% yields due to the formation of homocoupling product of ethynylbenzene, thus we further tried to avoid this by reducing the loading amount of CuI. However, upon decreasing CuI to 5.0 mol% or 2.5 mol%, the yields were remarkably reduced to 52% and 34%. But the good thing is the *e.e.* values were maintained at 95% and 96%, respectively, indicating an excellent stereochemical control of the chiral ligand **L7**. Considering that two Sonogashira coupling are needed to obtain the desired doubly-alkynylated product, the further increase in the loading amounts of both Pd(dba)$_2$ to 30 mol% and **L7** to 60 mol% were performed, leading to a remarkably enhanced yield to 91% and maintained *e.e.* value of 95% (Table 1, *right*, entry 9). Notably, the absolute configuration of targeted product is assigned as *pS* unambiguously confirmed by single-crystal X-ray diffraction (Figure 2). Moreover, after successfully determining such optimal reaction condition, a gram-scale reaction of model substrate ethynylbenzene was conducted, giving rising to desired product in 86% yield without

the decrease of enantioselectivity (95% *e.e.*) (see Section 7 in Supporting Information for details).

Table 1. Optimization of reaction conditions[a]

Entry	L	CuI [mol%]	Yield (3a) [%][b]	Yield (3a') [%][b]	*e.e.* [%][c]		Entry	L	CuI [mol%]	Yield (3b) [%][b]	Yield (3b') [%][b]	*e.e.* [%][c]
1	L1	10	ND	ND	-		1	L5	10	ND	ND	-
2	L2	10	ND	ND	-		2	L6	10	56	34	87
3	L3	10	ND	ND	-		3	L7	10	61	24	95
4	L4	10	ND	ND	-		4	L8	10	ND	ND	-
5	L5	10	56	27	62		5	L9	10	ND	ND	-
6	L6	10	39	44	84		6	L7	5	52	44	95
7	L7	10	31	40	82		7	L7	2.5	34	40	96
8	L8	10	27	63	55		8	L7	0	trace	ND	-
9	L9	10	ND	ND	-		9[d]	L7	10	91	trace	95

Left. Prelimialry screening of ligands. [a] Reaction conditions: **1a** (0.03 mmol), **2a** (0.09 mmol), Pd(dba)$_2$ (10 mol%), CuI (10 mol%), **L** (20 mol%), and Et$_3$N (4.0 equiv.) in DMF (1.0 mL) at 60 °C under N$_2$ for 48 h. [b] Isolated Yield. [c] The *e.e.* value was determined by chiral-phase HPLC. ND = not detected. ***Right.*** Further reaction optimization. [a] Reaction conditions: **1a** (0.03 mmol), **2b** (0.24 mmol), Pd(dba)$_2$ (10 mol%), CuI (10 mol%), **L** (20 mol%), and Et$_3$N (8.0 equiv.) in DMF (1.0 mL) at 60 °C under N$_2$ for 48 h. [b] Isolated Yield. [c] The *e.e.* value was determined by chiral-phase HPLC. [d] Pd(dba)$_2$ (30 mol%) and L (60 mol%) were added. ND = not detected.

For this reaction, after the first Sonogashira coupling to afford the mono-alkynylated intermediates (*i.e.* **3a'** and **3b'**), the unreacted triflate rim could still rotate, thus the planar chirality should be emerged when the oxidative addition of the chiral ligated palladium complex to the triflate. To gain a better understanding of such excellent enantiocontrol for the second Sonogashira coupling, DFT calculations were conducted at the SMD (*N*, *N*-Dimethylformamide) M06L/def2TZVP//M06L/6-31G(d,p)-SDD(Pd) level of theory.[43-44] To our delight, as revealed by the computed transition states, the

activation free energy of the transition state (**TS-1**) (17.6 kcal/mol) leading to the *pS* enantiomer was lower than that resulting in *pR* enantiomer (**TS-2**) (20.3 kcal/mol) by 2.7 kcal/mol, which agrees well with the excellent enantioselectivities observed in the experiments. By carefully analyzing these transition states, the origin of the enantiocontrol was then revealed. IRI (interaction region indicator) analysis[45] of the diastereomeric transition state structures showed that Pd center of **Pd/(R)-L7** experiences substantial steric repulsion with phenyl groups of *pR*-**3b'** in **Ts-2**. By contrast, the repulsion between the Pd center of **Pd/(R)-L7** and *pS*-**3b'** is reduced in **Ts-1** (Figure 2). Therefore, the weaker spatial repulsion lowers the activation energy of **TS-1** and consequently lead to high enantioselectivity. According to these results, the whole reaction likely takes place through a dynamic kinetic resolution process as shown in Figure 2. To confirm this, the transformation from mono-alkynylated intermediate **3b'** to **3b** under the standard condition was then performed, leading to expected near quantitative yield (99%) and comparable *e.e.* value (91%) (Table 3, and see Section 5 in Supporting Information for details).
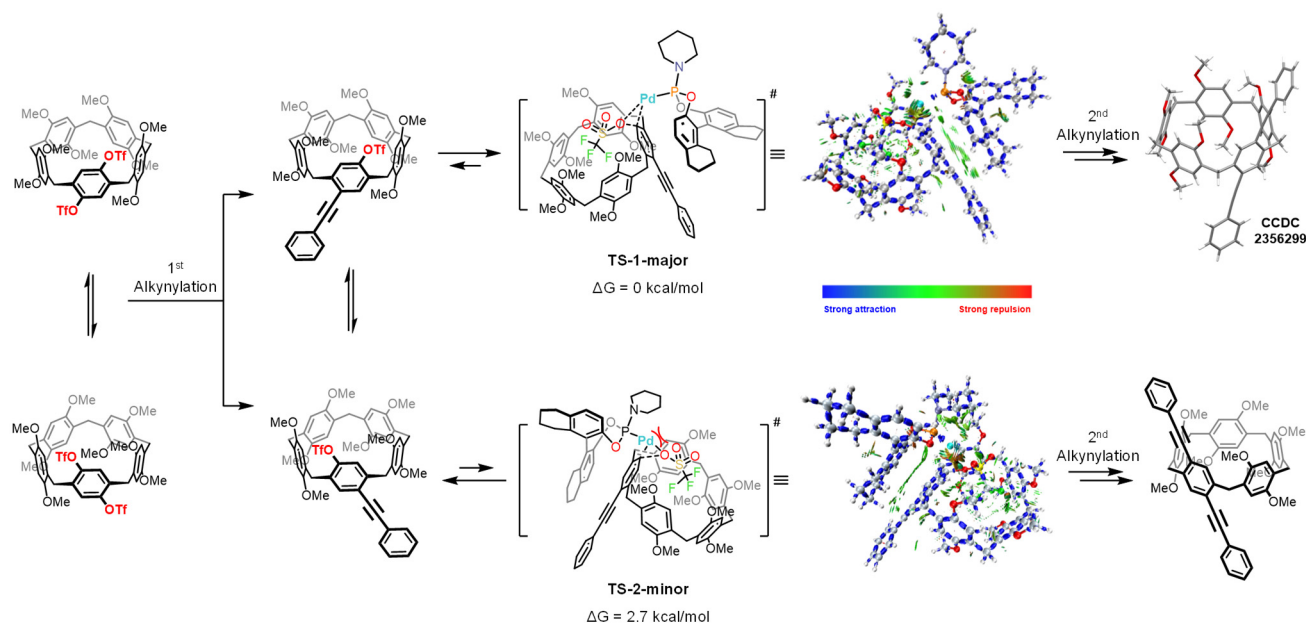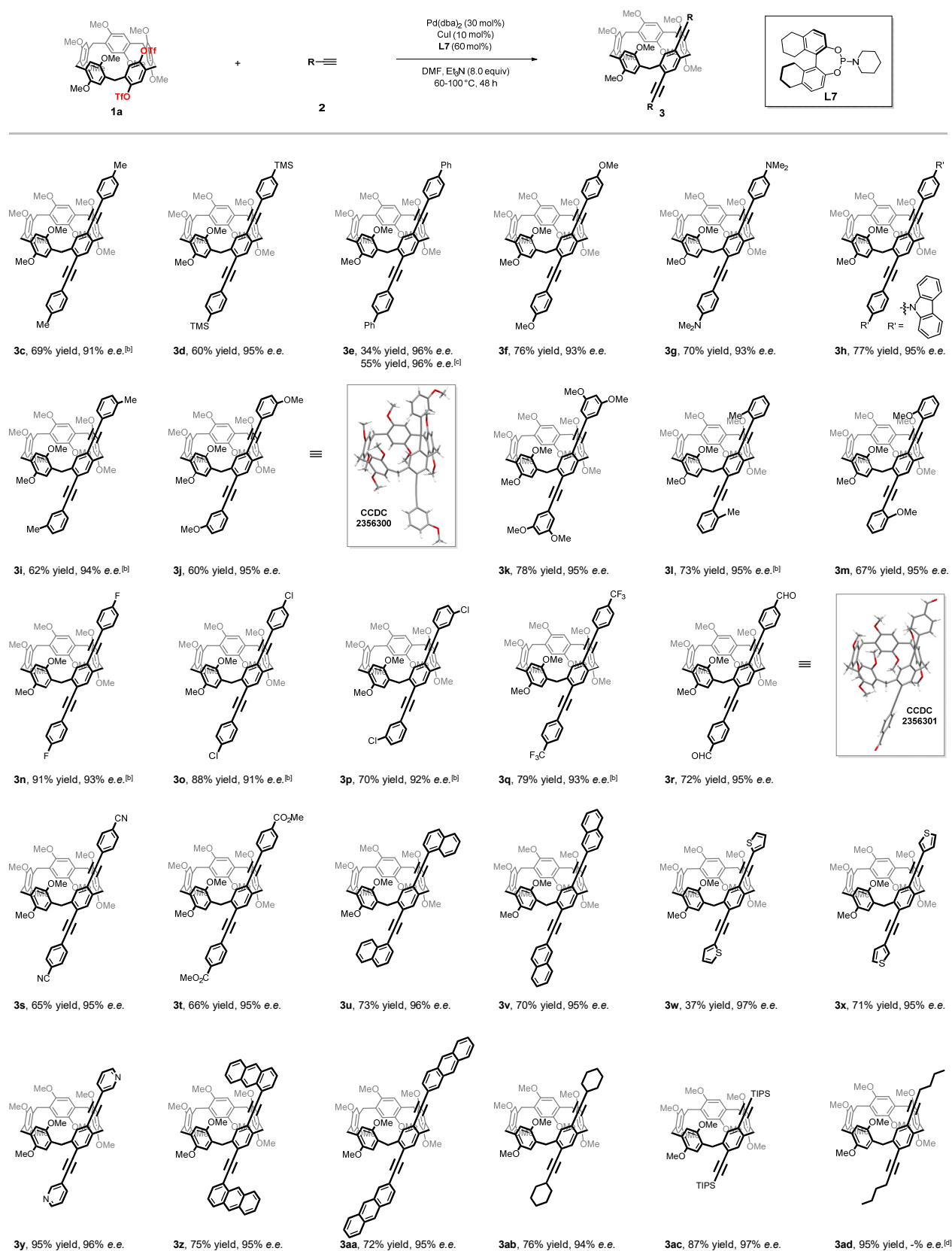

Figure 2. Computational studies on the origin of enantioselectivity and interaction region indicator (IRI) analysis of the diastereomeric transition states.

Substrate scope

Having successfully established the best catalytic system, the scope of this newly-developed asymmetric Sonogashira coupling for the enantioselective synthesis of planar chiral pillar[5]arene was then explored. To our delight, a wide range of substrates bearing different functional groups and skeletons were compatible (Table 2). For ethynylbenzene with electron-neutral or electron-donating functionalities, such as methyl, trimethylsilyl, phenyl, methoxyl, dimethylamino, and carbazolyl, at the *para* position of ethynyl site, the corresponding planar chiral pillar[5]arenes (**3c-3h**) were obtained in good yields (55%-77%) and excellent enantioselectivities (91%-96% *e.e.*). Notably, the change of the methyl or methoxyl moieties to either *meta* or *ortho* position in the substrates has no obvious negative effects (**3i-3m**), resulting in comparable yields (60%-78%) and enantioselectivities (94%-95% *e.e.*). In the case of ethynylbenzene with electron-withdrawing substitutes, such as fluorine, chlorine, trifluoromethyl, cyan, aldehyde, and ester (**3n-3t**), products with good to excellent yields (65%-91%) and excellent enantioselectivities (91%-95% *e.e.*) were obtained. For alkynes substituted with heterocycles such as thienyl or pyridyl and polyaromatic hydrocarbon such as naphthyl (**3u-3y**), up to 95% yield and 97% *e.e.* were achieved. Notably, for another two anthracyl substituted alkynes at 1- and 2- position (**3z** and **3aa**), remarkably enhanced yields (above 70%) and excellent enantioselectivities (95% *e.e.*) were achieved, indicating an interesting substitute effect. The possible reason might be attributed to the less steric hindrance of the corresponding products at 1- and 2- position than that of 9-position, since the aromatic ring of the 9-position anthracyl product locates within the crowned cavity of pillar[5]arenes. In addition to above aromatic alkyne substrates, alkynes bearing cyclohexyl (**3ab**) and triisopropylsilyl (TIPS-) (**3ac**) also worked very well, while 1-hexyne (**3ad**) only afforded racemic products attributed to the heating-induced racemization process during the reaction originated from the flexible substitute, even though the yield is 95%.

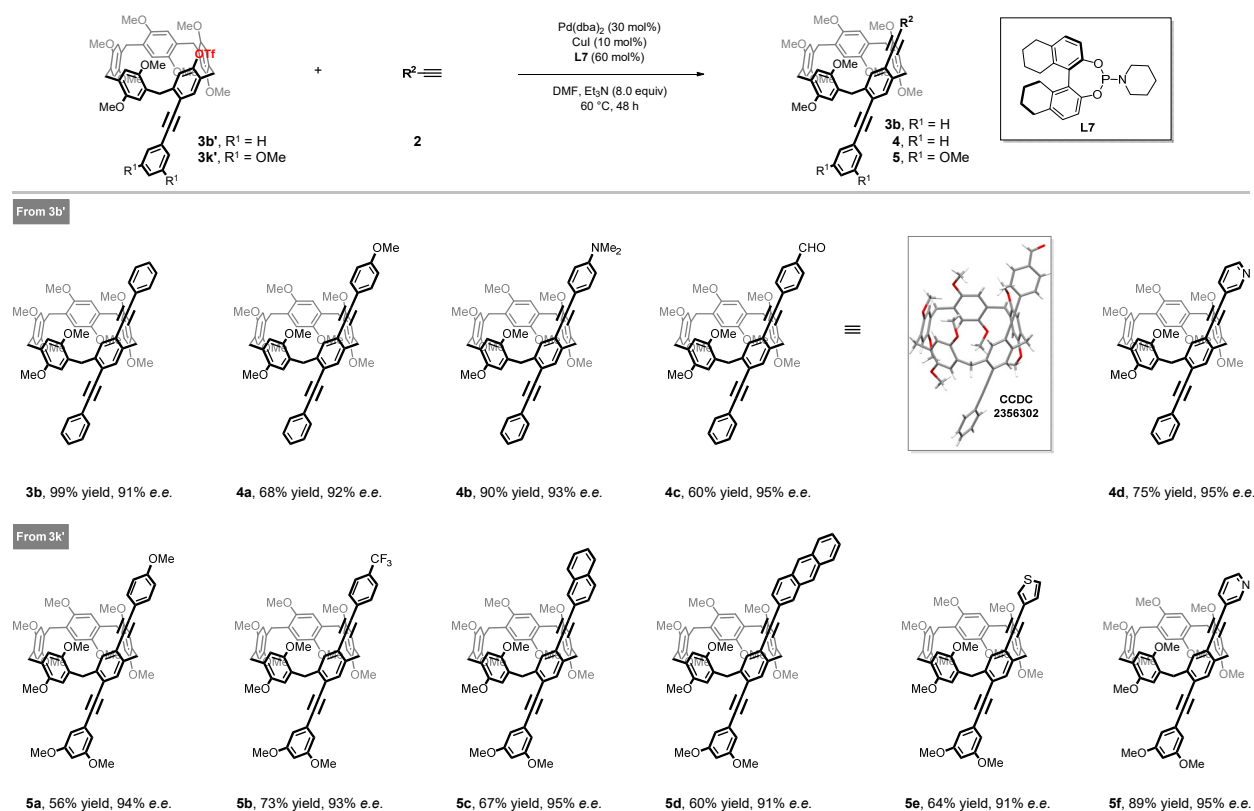**Table 2**. Scope of homo-rimmed planar chiral pillar[5]arenes[a]

3c, 69% yield, 91% *e.e.*[b]

3d, 60% yield, 95% *e.e.*

3e, 34% yield, 96% *e.e.*
55% yield, 96% *e.e.*[c]

3f, 76% yield, 93% *e.e.*

3g, 70% yield, 93% *e.e.*

3h, 77% yield, 95% *e.e.*

3i, 62% yield, 94% *e.e.*[b]

3j, 60% yield, 95% *e.e.*

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3k, 78% yield, 95% *e.e.*

3l, 73% yield, 95% *e.e.*[b]

3m, 67% yield, 95% *e.e.*

3n, 91% yield, 93% *e.e.*[b]

3o, 88% yield, 91% *e.e.*[b]

3p, 70% yield, 92% *e.e.*[b]

3q, 79% yield, 93% *e.e.*[b]

3r, 72% yield, 95% *e.e.*

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3s, 65% yield, 95% *e.e.*

3t, 66% yield, 95% *e.e.*

3u, 73% yield, 96% *e.e.*

3v, 70% yield, 95% *e.e.*

3w, 37% yield, 97% *e.e.*

3x, 71% yield, 95% *e.e.*

3y, 95% yield, 96% *e.e.*

3z, 75% yield, 95% *e.e.*

3aa, 72% yield, 95% *e.e.*

3ab, 76% yield, 94% *e.e.*

3ac, 87% yield, 97% *e.e.*

3ad, 95% yield, -% *e.e.*[d]

[a] Reaction conditions: **1a** (0.03 mmol), alkyne (0.24 mmol), Pd(dba)$_2$ (30 mol%), CuI (10 mol%), **L7** (60 mol%), Et$_3$N

(8.0 equiv.) in DMF (1.0 mL) at 60-100 °C under N_2 for 48 h. Isolated yield. The *e.e.* value was determined by chiral-phase HPLC. [b] The reaction was run at 100 °C. [c] THF (1 mL) as solvent. [d] Racemization under reaction condition.

For all above substrate, the newly-developed asymmetric Sonogashira coupling led to the successful enantioselective synthesis of homo-rimmed planar chiral pillar[5]arenes with the same functionalities at both rims. Moreover, starting from the mono-alkynylated substrates **3b'** or **3k'**, the employment of the optimized condition led to the successful synthesis of hetero-rimmed planar chiral pillar[5]arenes with different functionalities at two rims, which is applicable for alkynes bearing electron-donating (**4a-4b**, **5a**), electron-withdrawing (**4c**, **5b**), or heterocyclic substitutes (**4d**, **5c-5f**), all giving rise to excellent enantioselectivities (91%-95% *e.e.*) (Table 3). According to these results, the synthesis of diverse planar chiral pillar[5]arenes with varied functionalities would be feasible by the simply combining different functionalized alkynes in a modular manner, which will greatly promote the structure and property diversity and expand the application scopes of the corresponding accessible planar chiral pillar[5]arenes.

**Table 3**. Scope of hetero-rimmed planar chiral pillar[5]arenes[a]

3b, 99% yield, 91% *e.e.*   **4a**, 68% yield, 92% *e.e.*   **4b**, 90% yield, 93% *e.e.*   **4c**, 60% yield, 95% *e.e.*   **4d**, 75% yield, 95% *e.e.*

5a, 56% yield, 94% *e.e.*   **5b**, 73% yield, 93% *e.e.*   **5c**, 67% yield, 95% *e.e.*   **5d**, 60% yield, 91% *e.e.*   **5e**, 64% yield, 91% *e.e.*   **5f**, 89% yield, 95% *e.e.*

[a] Reaction conditions: **3b'** or **3k'** (0.03 mmol), alkyne (0.24 mmol), Pd(dba)$_2$ (30 mol%), CuI (10 mol%), **L7** (60 mol%), Et$_3$N (8.0 equiv.) in DMF (1.0 mL) at 60 ℃ under N$_2$ for 48 h. Isolated yield. The *e.e.* value was determined by chiral-phase HPLC.

Synthetic applications

For the resultant planar chiral pillar[5]arenes, particularly ones with functional groups, they could directly serve as key building blocks for wide applications. For instance, for **3r** with two aldehyde groups, it can be used for the construction of novel chiral covalent-organic frameworks (COFs). For **3y** bearing two pyridyl groups, it would be excellent building block for both discrete coordination architectures such as metallacycles and metallacages as well as infinite metal-organic frameworks (MOFs). In addition, in the case of **3t** with two methyl benzoate units, after converting to corresponding chiral bis-benzoic acid building block after hydrolysis, it can be employed for the construction of diverse MOFs or hydrogen-bonded organic frameworks (HOFs). For all these feasible and diverse reticular frameworks, the existence of chiral pillar[5]arene cavity will definitely enrich their porous features and therefore endow them with promising applications. In addition, from these functionalized planar chiral pillar[5]arenes, more functional groups would be introduced through facile and efficient chemical transformations, thus further enriching their structural and functional diversity. For instance, the two aldehyde groups in **3r** have been further converted into alcohol **6** (through reduction, 99% yield), olefin **7** (through Wittig reaction, 89% yield), alkyne **8** (through Corey-Fuchs reaction, 99% yield), and bromine-substituted cyanostilbene as potential AIEgen **9** (through Knoevenagel condensation, 66% yield). All reactions proceeded smoothly at room temperature with maintained enantioselectivity (Figure 3a).

In order to further extend the applications of the resultant planar chiral pillar[5]arenes, the further synthesis of pillar[5]arene-based chiral rotaxanes was then performed. Notably, although lots of pillar[5]arene-based rotaxanes have been reported, almost all optical pure ones were isolated by optical resolution. Based on the highly stereoselective synthesis of functionalized planar chiral pillar[5]arenes with our newly-developed methodology, the corresponding chiral rotaxanes (and other type of MIMs)

could be directly synthesized. For instance, starting from **3aa** with anthracyl groups, corresponding [2]rotaxane with two exchangeable pentafluorophenyl ester **3aa-R1** stoppers was successfully synthesized. Moreover, by the sequential stopper-exchange reactions, new [2]rotaxanes with anthracene (**3aa-R2**) or pyrene (**3aa-R3**) stoppers were then obtained, resulting in the successful of diverse emissive chiral [2]rotaxanes with precisely-arranged chromophores (Figure 3b). Impressively, compared with **3aa**, possibly attributed to the conformation locking effect upon the formation of mechanical bonds, boosted CPL performances of these resultant [2]rotaxanes with dissymmetry factors (g_{lum}) up to 0.005 (for **3aa-R2**) was achieved for these chiral emissive [2]rotaxanes (Figure 3c and 3d), highlighting their great potential as novel chiral luminescent materials for practical applications.
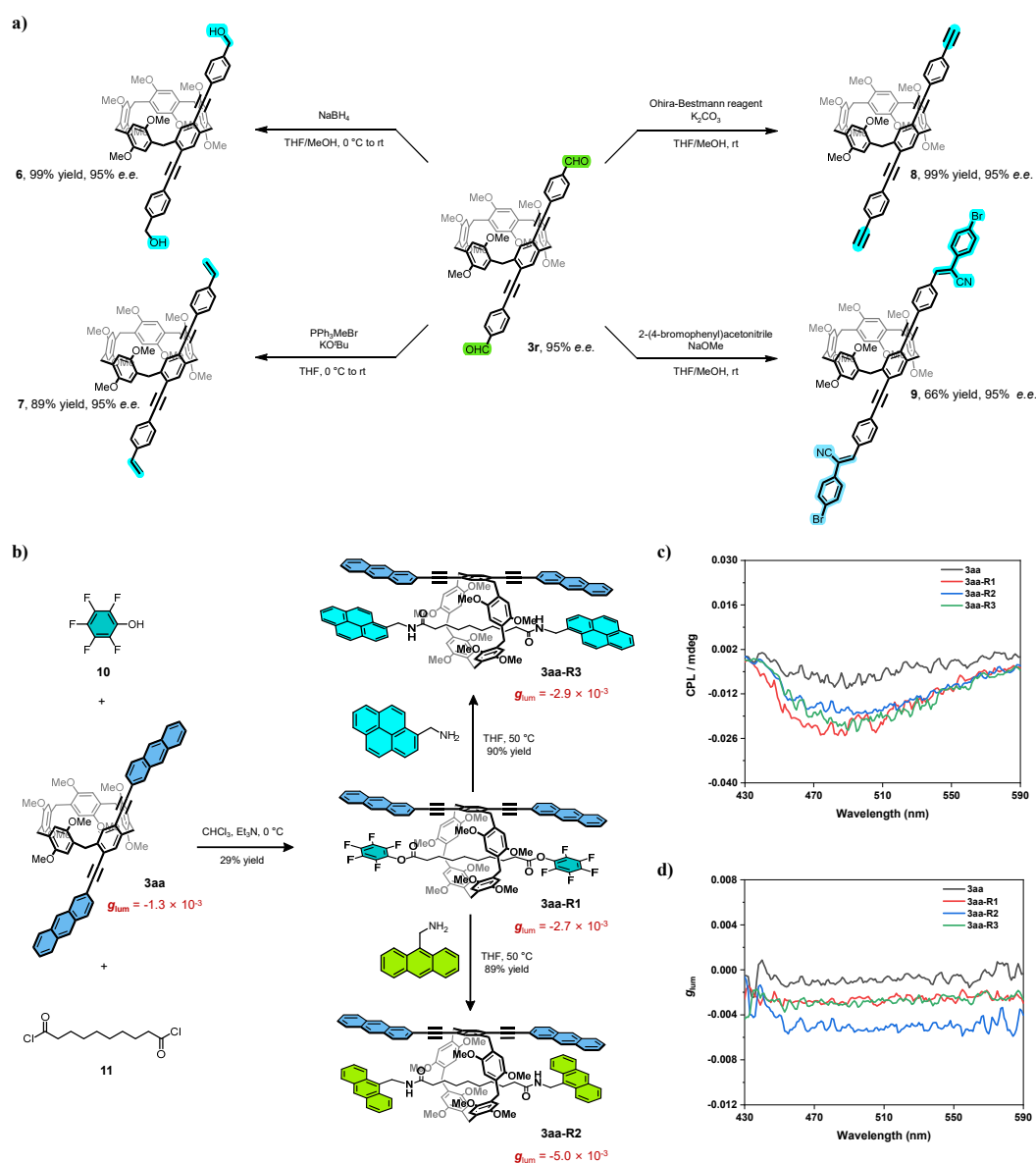
Figure 3. Synthetic applications of the resultant planar chiral pillar[5]arenes obtained by the newly-developed synthetic methodology. (a) Facile derivatizations of **3r** to diverse functionalized planar chiral pillar[5]arenes with maintained enantioselectivity. (b) The synthesis of chiral [2]rotaxanes **3aa-R1**, **3aa-R2**, and **3aa-R3** with **3aa** as the chiral wheel that reveal boosted CPL performances. CPL emission (c) and g_{lum} spectra (d) of **3aa** and the resultant chiral [2]rotaxanes **3aa-R1**, **3aa-R2**, and **3aa-R3**.

Conclusion

Based on the largely unexplored asymmetric Sonogashira coupling,[45-50] we have successfully developed a new synthetic methodology towards the successful synthesis of a wide range of highly functionalized planar chiral pillar[5]arenes, including both homo- and hetero-rimmed ones, with excellent enantioselectivities. Impressively, attributed to both the attractive functionality diversity and facile chemical transformations, the resultant planar chiral pillar[5]arenes show great potential for widespread use in many areas such as chiral reticular frameworks and chiral luminescent materials. This work not only contributes a novel synthetic methodology towards the synthesis of novel chiral macrocycles as promising building blocks for practical use but also provides additional key insights into the development of asymmetric cross-coupling in organic synthetic chemistry. Notably, preliminary results demonstrated that such synthetic methodology is also applicable for the four-fold asymmetric Sonogashira coupling that results in the successful synthesis of tetra-functionalized planar chiral pillar[5]arenes with two chiral planes, resulting in an excellent enantioselectivity (>99% *e.e.*) (see Section 8 in Supporting Information for details), highlighting its great power for the synthesis of attractive chiral building blocks for widespread use.

Methods

General procedure for the enantioselective synthesis of planar chiral pillar[5]arenes via asymmetric Sonogashira coupling. **For homo-rimed ones**: A 10 mL Schlenk tube flask equipped with a magnetic stirrer bar was charged with **1a** (29.5 mg, 0.03 mmol), alkyne (0.24 mmol, 8.0 equiv.),

Pd(dba)$_2$ (5.1 mg, 30 mol%), CuI (0.6 mg, 10 mol%), **L7** (7.5 mg, 60 mol%), Et$_3$N (24.0 mg, 0.24 mmol, 8.0 equiv.), and DMF (1.0 mL) under argon atmosphere. Then the reaction mixture was stirred at 60-100 °C for 48 h. Then the reaction mixture was concentrated and purified by column chromatography to afford the target products; **For hetero-rimed ones:** A 10 mL Schlenk tube flask equipped with a magnetic stirrer bar was charged with **3b'** (28.5 mg, 0.03 mmol) or **3k'** (30.0 mg, 0.03 mmol), alkyne (0.24 mmol, 8.0 equiv.), Pd(dba)$_2$ (5.1 mg, 30 mol%), CuI (0.6 mg, 10 mol%), **L7** (7.5 mg, 60 mol%), Et$_3$N (24.0 mg, 0.24 mmol, 8.0 equiv.), and DMF (1.0 mL) under argon atmosphere. Then the reaction mixture was stirred at 60 °C for 48 h. Then the reaction mixture was concentrated and purified by column chromatography to afford the target products.

Data Availability

The data that support the findings of this study are available within the paper and its Supplementary Information files. Raw data are also available from the corresponding author on reasonable request. Materials and methods, experimental procedures, characterization data, NMR spectra and mass spectrometry data are available in the Supplementary Information. The X-ray crystallographic coordinates for structures reported in this study have been deposited at the Cambridge Crystallographic Data Centre (CCDC), under deposition numbers CCDC 2356299 (**3b**), 2356300 (**3j**), 2356301 (**3r**), and 2356302 (**4c**). These data can be obtained free of charge from the CCDC via www.ccdc.cam.ac.uk/data_request/cif.

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Author contributions

W. W., H.-B. Y., and X.-Q. W. conceived and designed the project. X.-H. Z. designed and performed the synthetic experiments with the help of Y.-R. S., L.-T. B., and W.-T. X.. X. Z. and X. L. designed and performed the computational studies. W. W. and X.-H. Z. prepared the manuscript with the help from all other authors.

Competing interests

The authors declare no competing interests.