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# 无过渡金属参与的偕二氟环丙烷双脱氟烷氧基化合成环丙酮缩酮

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**摘要** 在不发生高张力C—C键断裂的情况下实现偕二氟环丙烷中C—F键的转化是一个棘手的挑战. 在无过渡金属参与的碱性条件下, 发展了通过偕二氟环丙烷的双脱氟化合成环丙酮缩酮的实例. 多种偕二氟环丙烷与醇可以用于目前的反应, 以高收率合成相应的产物. 在机理研究的基础上说明该反应是通过消除加成而不是直接取代进行的. 这不仅为环丙酮缩酮的合成提供了一种新的策略, 而且为偕二氟环丙烷的非开环C—F键转化提供了一种新的范例.
**关键词** 偕二氟环丙烷; 脱氟化; 烷氧基化; 环丙酮缩酮; 消除与加成

# Transition-Metal Free Synthesis of Cyclopropanone Ketals via Double Defluorinative Alkoxylation of *gem*-Difluorinated Cyclopropanes

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**Abstract** The C—F bond transformation of *gem*-difluorinated cyclopropanes without cleavage of the highly strained C—C bond is an intractable challenge. The synthesis of cyclopropanone ketals via double defluorination of *gem*-difluorinated cyclopropanes under transition-metal free and basic conditions has been developed. A broad range of *gem*-difluorinated cyclopropanes and alcohols are amenable in present reaction to permit the synthesis of corresponding products in high yields. The reaction is elucidated to proceed via elimination and addition other than direct substitution based on the mechanistic studies. This transformation not only provides a new strategy for the construction of cyclopropanone ketals, but also reveals a new paradigm on C—F bond transformation without ring-opening of *gem*-difluorinated cyclopropanes.
**Keywords** *gem*-difluorinated cyclopropanes; defluorination; alkoxylation; cyclopropanone ketals; elimination and addition

## 1 Introduction

Recently, *gem*-difluorinated cyclopropanes (*gem*-DFCPs) received considerable attention due to their unique set of reactivities in organic synthesis especially under the transition-metal catalysis.[1] These compounds feature an inherently strained cyclopropane, whose ring-strain is further enhanced by incorporation of two fluorine atoms in the same carbon atom of the three-membered ring.[2] In this context, *gem*-DFCPs are more prone to undergo ring-opening transformations. According to the cleavage of the C—F bond, the ring-opening transformation of *gem*-DFCPs can be divided into the following three categories. The first pattern involves ring-opening of *gem*-DFCPs without C—F bond cleavage, which is achieved through transition-metal catalysis,[3] organocatalysis[4] and photocatalysis[5] and others[6] (Scheme 1a). The second mode involves ring-opening with cleavage of a single C—F bond under palladium,[7,8] rhodium[9] and others,[10] which has been extensively studied in recent years (Scheme 1b). The reactions are predominantly realized via oxidative addition and *β*-fluoride elimination processes to enable the synthesis of a large range of monofluoroolefin derivatives, which in some cases a cascade cyclization via C—F bond cleavage

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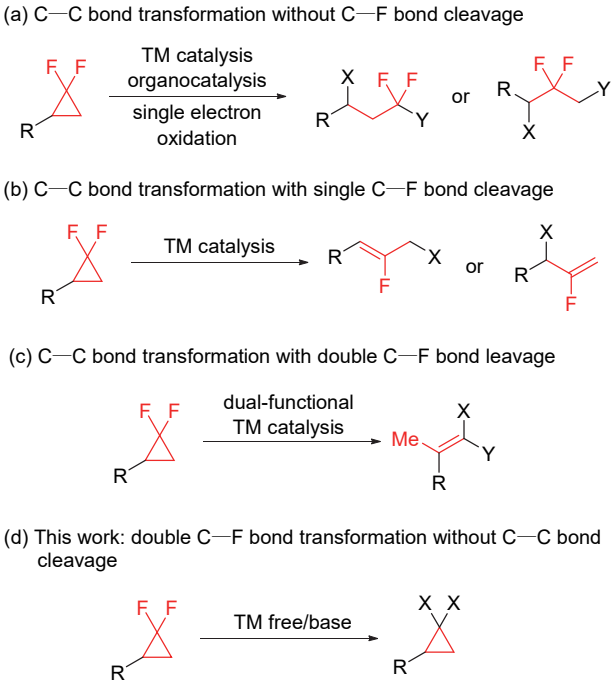
occurs to formally give double C—F cleavage products.[7c,7l,8b,11] The third paradigm entails ring-opening reactions with cleavage of the two C—F bonds in a single transformation (Scheme 1c). In this regard, our group recently developed a copper-catalyzed three-component coupling reaction of *gem*-DFCPs with alcohols and terminal alkynes, achieving modular synthesis of enol ether compounds with fully substitution.[12]



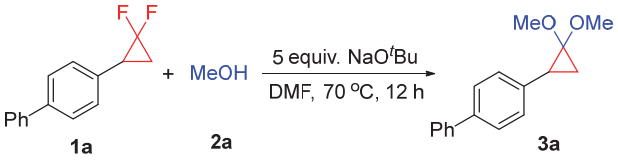

**Scheme 1** Reaction mode of *gem*-difluorinated cyclopropanes

On the other hand, the transformation of C—F bond is certain challenging owing to its high bond energy and stability over common reaction conditions. For this reason, the fluorine-containing functional groups can serve as stable handles for the late-stage modifications of complex molecules and C—F bond transformations are becoming an intriguing aspect in modern organic synthesis.[13] Due to the intrinsic high ring-strain of *gem*-DFCPs, the selective defluorination of *gem*-DFCPs with the maintaining the integrity of fragile cyclopropane core structure poses much more challenges. Considering our research interest in *gem*-DFCPs[3,9] and based on our previous study,[12] we envisioned that the selective double C—F bond transformations without the cleavage of C—C bond might be achieved under transition-metal free conditions since the transition-metal catalysts are likely to promote the ring-opening of cyclopropanes in most cases. Therefore, we chose *gem*-DFCPs and alcohols as the coupling partners and implemented the conversion of the C—F bond to the C—O bond under basic conditions, thereby constructing *gem*-dialkoxyl cyclopropanes or cyclopropanone ketals in high yields with broad substrate scope (Scheme 1d). This reaction provides a new paradigm for C—F bond transformation especially in *gem*-DFCPs and offers a new approach for the synthesis of cyclopropanone ketals. It shows higher efficiency and better practicability compared to the alkoxylation of 1-fluoro-l-bromo-cyclopropanes in solvent amount alcohols.[14]

## 2 Results and discussion

At the beginning, we carried out the investigation with 4-(2,2-difluorocyclopropyl)-1,1'-biphenyl (**1a**) and methanol (**2a**) as the model substrates (Table 1). After an extensive examination of reaction conditions, the target product **3a** was generated in 90% yield with NaO$^t$Bu as the base and *N*,*N*-dimethylformamide (DMF) as the solvent at 70 ℃ for 12 h, which was recognized as the optimized reaction conditions (Entry 1). The yields dropped significantly when NaO$^t$Bu was replaced with LiO$^t$Bu or KO$^t$Bu (Entries 2 and 3), while the reaction was shut down with $Cs_2CO_3$ as the base (Entry 4). No improvement of yields was detected upon switching the solvents to tetrahydrofuran (THF) (Entry 5) and the desired product **3a** was not formed when 1,2-dichloroethane (DCE) was utilized as the solvent (Entry 6). Next, a preliminary evaluation of temperature effect indicated that whether 60 or 80 ℃ all afforded inferior result (Entries 7 and 8). The further refinement of reaction conditions by decreasing the equivalents of methanol or NaO$^t$Bu resulted in the lower formation of expected product **3a** (Entries 9 and 10).

**Table 1** Optimization of reaction conditions[a]




**1a** **2a** **3a**

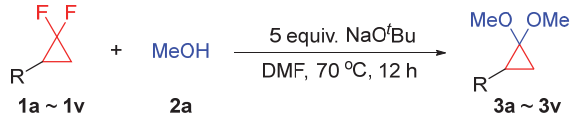
| Entry | Variation from the standard conditions | Yield[b]/% |
|---|---|---|
| 1 | None | 90 |
| 2 | LiO$^t$Bu instead of NaO$^t$Bu | 21 |
| 3 | KO$^t$Bu instead of NaO$^t$Bu | 31 |
| 4 | $Cs_2CO_3$ instead of NaO$^t$Bu | Not detected |
| 5 | THF instead of DMF | 81 |
| 6 | DCE instead of DMF | Not detected |
| 7 | 60 ℃ instead of 70 ℃ | 88 |
| 8 | 80 ℃ instead of 70 ℃ | 77 |
| 9 | 2 equiv. MeOH instead of 3 equiv. MeOH | 80 |
| 10 | 4 equiv. NaO$^t$Bu instead of 5 equiv. NaO$^t$Bu | 82 |

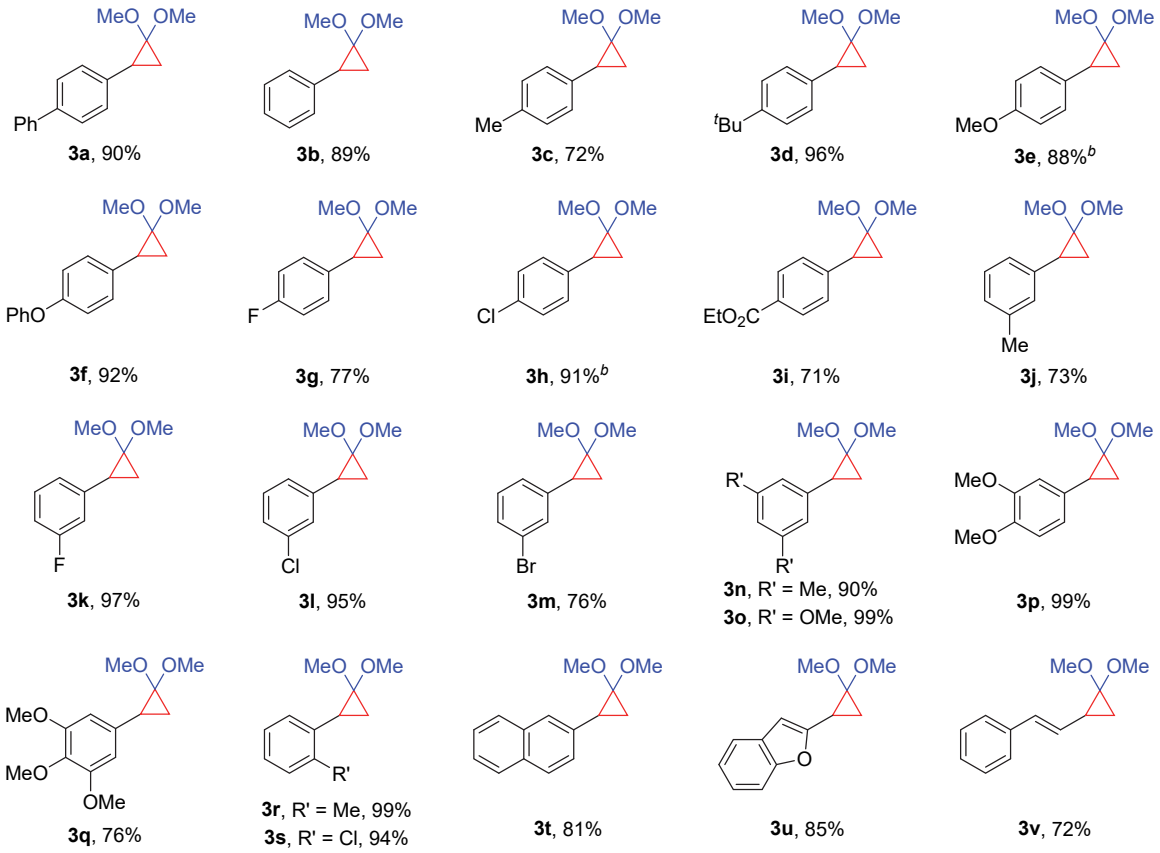
[a] Reaction conditions: **1a** (0.1 mmol), **2a** (0.3 mmol) and NaO$^t$Bu (5 equiv.) in DMF (0.2 mL) under $N_2$ atmosphere at 70 ℃ for 12 h. [b] Isolated yields.

With the optimal conditions ascertained, we turned our attention to study the generality of the current transformation. First, the substrate scope of *gem*-DFCPs was scrutinized. As outlined in Table 2, a myriad of aryl *gem*-DFCPs decorated with several functional groups could be smoothly transformed into the desired products in good to excellent yields. The unmodified phenyl *gem*-DFCP (**1b**) and its *para*-substituted counterparts bearing electron-donating substituents such as alkyl (**1c**, **1d**), alkoxyl (**1e**) and aryloxyl (**1f**) or electron-withdrawing groups represented by halogen (**1g**, **1h**) and ester (**1i**) were totally compatible

**Table 2** Substrate scope of *gem*-difluorinated cyclopropanes[a]



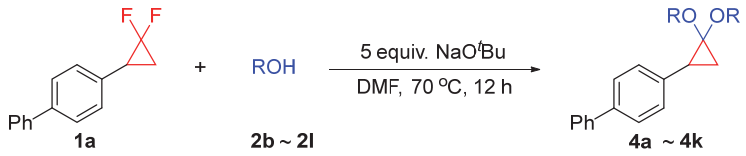

[a] Reactions were carried out on 0.1 mmol scale with isolated yields. [b] The reaction was carried out under 80 ℃.

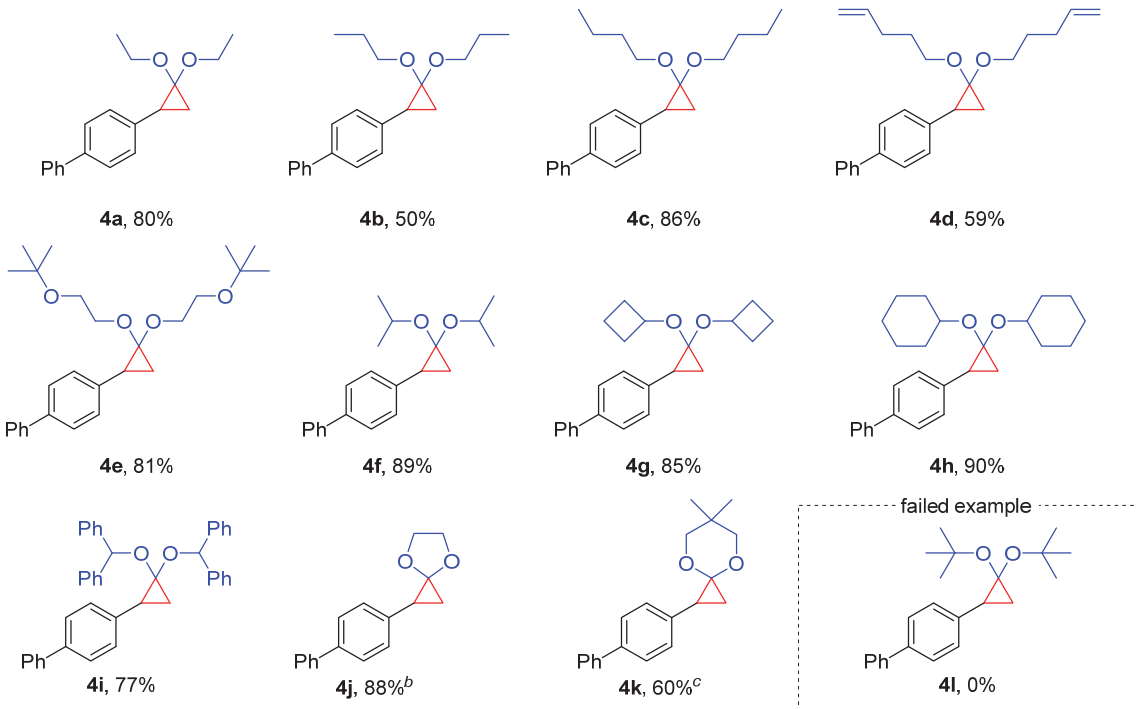
to access an assortment of cyclopropanone ketals (**3b**～**3i**) in 71%～96% yields. In addition to *para*-substituted pattern, the promising outcomes could also be upheld with mono *meta*-anchored cases, which furnished the corresponding products **3j**～**3m** in 73%～97% yields. As anticipated, the double *meta*-substituted *gem*-DFCPs **1n** and **1o** served as competent coupling partners as well, permitting the synthesis of corresponding products **3n** and **3o** in 90% and 99% yields, respectively. Furthermore, multiple methoxyls, which situated on the *meta*- and *para*-positions of phenyl ring, did not hamper the reaction and delivered the desired products **3p** and **3q** in consistently good yields. The reactions kept excellent yields when *ortho* methyl- or chloro-functionalized *gem*-DFCPs **1r** and **1s** were subjected to the present reactions. As we all know, the halogens always serve as one of the most sought-after functional entities for further synthetic operations in transition metal-catalyzed cross-coupling reactions. Hence, the retaining of chlorine and bromine in examples **3h**, **3l**, **3m** and **3s** left useful and convenient handles for downstream functional group transformations. It is not surprising that the naphthyl-modified *gem*-DFCP **1t** was amenable under optimal reaction conditions to reach the fabrication of product **3t** in 81% yield. In addition, the replacement of phenyl group with heteroaryl group had a marginal effect on the outcome (**3u**). The substituents of *gem*-DFCPs were not restricted to (hetero)aryl group, and the alkenyl-modified *gem*-DFCP **1v** was also proved to be the compatible substrate and resulted in the formation of the expected product **3v** in 72% yield. Nevertheless, alkyl-substituted *gem*-DFCPs did not work in the current reaction under standard conditions.

Next, the substrate scope of alcohols was elaborately examined. As regularly depicted in Table 3, a bunch of primary alcohols expressed good reactivity and were transformed into the anticipated products **4a**～**4e** in good to excellent yields. The functional groups such as alkene and ether attached in alcohols did not perturb the reaction outcome as exemplified in **4d** and **4e**. The secondary alcohols including isopropanol (**2g**), cyclobutanol (**2h**), cyclohexanol (**2i**) and benzhydrol (**2j**) could smoothly couple with *gem*-DFCP **1a** to provide cyclopropanone ketals **4f**～**4i** in 77%～90% yields. It should be emphasized that the fragile cyclopropane and cyclobutane scaffolds simultaneously remained intact in the case of **4g**, which is otherwise

**Table 3** Substrate scope of alcohols[a]




[a] Reactions were carried out on 0.1 mmol scale with isolated yields. [b] The reaction was carried out under 50 ℃. [c] The reaction was carried out under 80 ℃.

nevertheless difficult to be obtained via traditional manipulations. In addition, the substrate scope of alcohols could successfully expand to diols such as glycol and neopentyl glycol, which enabled the preparation of **4j** and **4k** in 88% and 60% yields, respectively. Unfortunately, tertiary alcohols, such as *tert*-butanol (**4l**), are incompatible with this transformation due to significant steric hindrance.

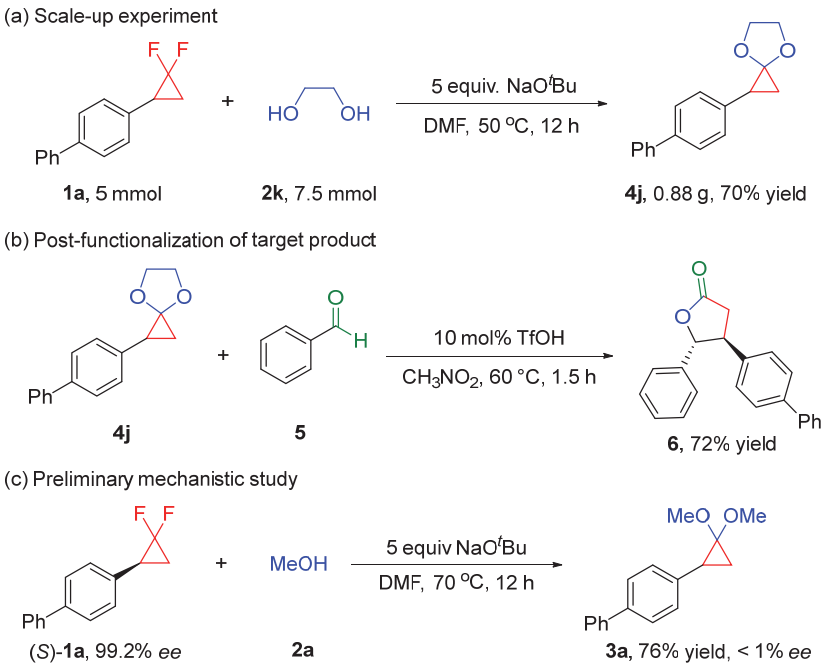
To showcase the synthetic applications of present transformation, a scale-up reaction was carried out by employing substrates **1a** and **2k** as the reactants with the desired product **4j** being isolated in 70% yield (Scheme 2a). The cyclopropanone ketal **4j** can smoothly couple with benzaldehyde **5** via a formal [3+2] cycloaddition under Brønsted acid catalysis to form five-membered lactone **6** in 72% yield (Scheme 2b).[15] To figure out the reaction process, the enanotiopure *gem*-DFCP (*S*)-**1a** and methanol **2a** were subjected to the optimal conditions, which gave rise to the product **3a** in a racemic manner (Scheme 2c). This result indicates that the chiral carbon atom in *gem*-DFCPs participates in the reaction, which provides a compelling evidence that the C—F bond cleavage may be taken place through a base-promoted elimination process.

Based on the mechanistic experiments and our previous study,[12] a mechanistic scenario is proposed in Scheme 3. First, the fluorocyclopropene **7** is formed via a base-promoted HF elimination (path a). Of note, instead of the copper-catalyzed and base-promoted HF elimination reported in our previous investigation,[12] the HF elimination of *gem*-DFCPs can also be achieved under copper free conditions by increasing the amount of base and elevating the reaction temperature. Then, the *in-situ* generated methoxide attacked the highly reactive fluorocyclopropene **7** to result in the formation of mono-substituted intermediate **8**. Next, a similar elimination and addition sequence occurs to access the cyclopropanone ketal as the final product. The alternative reaction pathway involving direct nucleophilic substitution is arguably excluded (path b).

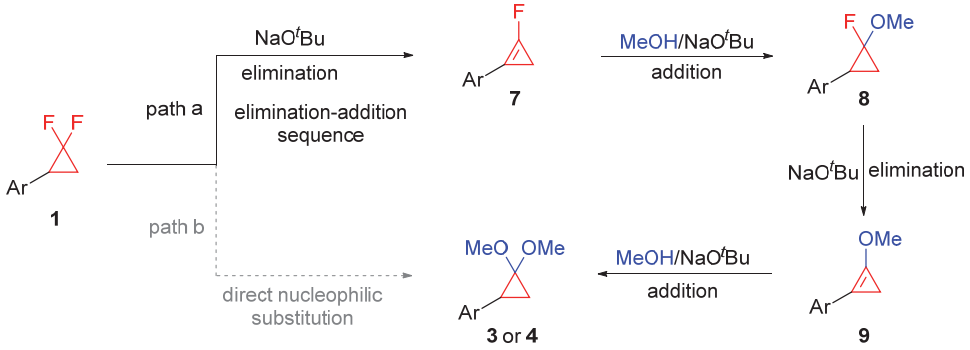
## 3 Conclusions

In conclusion, a simple and practical method has been developed for the efficient synthesis of cyclopropanone ketals from *gem*-DFCPs and alcohols. This transformation represents the first example of C—F bond functionalization in the realm of *gem*-DFCPs with avoiding the cleavage of strained cyclopropane C—C bond. A plethora of *gem*-DFCPs and alcohols can effectively couple with each other to enable the fabrication of otherwise difficult accessing cyclopropanone ketals. The mechanistic studies support the reactions that proceeds via elimination and addition sequence rather than direct nucleophilic substitution. This new reaction model provides inspiration for the conversion of C—F bonds in small rings.




**Scheme 2** Synthetic applications and mechanistic study




**Scheme 3** Proposed mechanistic scenario

## 4 Experimental section

### 4.1 General information

All air-sensitive reactions were carried out under nitrogen atmosphere. Anhydrous solvents were purchased from Energy Chemical or Adamas in AcroSeal glass bottle (extra dry over molecular sieve) and used directly. NMR spectra were recorded on a JEOL JNM-ECZ400S (400 MHz for $^1$H NMR, 100 MHz for $^{13}$C NMR, 376 MHz for $^{19}$F NMR) with $CDCl_3$ as the solvent and tetramethylsilane (TMS) as the internal standard. Unless otherwise noted, chemical shifts for $^1$H NMR are reported using tetramethylsilane (TMS, $\delta$=0) as the internal standard and using $CDCl_3$ as the solvent; Chemical shifts for $^{13}$C NMR spectra are reported with the center line of the triplet for chloroform-*d* set at $\delta$ 77.0. Enantiomeric excesses (*ee*) were determined by High Performance Liquid Chromatography (HPLC) analysis on a SHIMADZU LC-2030C with Daicel chiral columns. High-resolution mass spectra (HRMS) were recorded on a Q-Exactive Focus (Thermo Fisher Scientific) and reported for the molecular ion $[M+H]^+$ or $[M+Na]^+$. Melting points were determined using a digital melting point apparatus (JHX-4).

### 4.2 General procedure for product synthesis

In a nitrogen filled glove box, a 4 mL vial equipped with a stir bar was charged with NaO$^t$Bu (48.1 mg, 0.5 mmol, 5 equiv.), *gem*-difluorinated cyclopropane (0.1 mmol, 1 equiv.), alcohol (0.3 mmol, 3 equiv.) and DMF (0.2 mL). Then, the 4 mL vial was sealed, removed from the glove box and heated in pie-block at 70 ℃ for 12 h. The reaction mixture was cooled to room temperature and diluted with ethyl acetate, filtered through a fast column and concentrated *in vacuo*. The crude mixture was purified by silica gel column chromatography to obtain the corresponding product.

4-(2,2-Dimethoxycyclopropyl)-1,1'-biphenyl (**3a**): Yellow oil, 22.9 mg, 90% yield, $R_f$=0.65 [*V*(petroleum ether, PE)∶*V*(ethyl acetate, EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.58 (d, *J*=8.0 Hz, 2H), 7.52 (d, *J*=7.9 Hz,

2H), 7.42 (t, $J$=7.5 Hz, 2H), 7.34～7.25 (m, 3H), 3.46 (s, 3H), 3.26 (s, 3H), 2.43 (dd, $J$=10.3, 7.1 Hz, 1H), 1.49～1.45 (m, 1H), 1.33 (t, $J$=6.6 Hz, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 141.0, 138.8, 136.4, 128.7, 127.9, 127.0, 126.9, 126.8, 93.4, 53.8, 53.4, 30.3, 19.3. HRMS (ESI) calcd for $C_{17}H_{19}O_2$ $[M+H]^+$ 255.1380, found 255.1379.

(2,2-Dimethoxycyclopropyl)benzene (**3b**):[16] Colorless oil, 15.8 mg, 89% yield, $R_f$=0.45 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.30～7.26 (m, 2H), 7.21～7.17 (m, 3H), 3.44 (s, 3H), 3.21 (s, 3H), 2.40 (dd, $J$=10.3, 7.1 Hz, 1H), 1.43 (dd, $J$=10.3, 6.0 Hz, 1H), 1.31～1.28 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 137.2, 128.1, 127.5, 125.9, 93.3, 53.7, 53.4, 30.5, 19.1.

1-(2,2-Dimethoxycyclopropyl)-4-methylbenzene (**3c**): Yellow oil, 13.8 mg, 72% yield, $R_f$=0.45 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.12～7.06 (m, 4H), 3.43 (s, 3H), 3.21 (s, 3H), 2.36 (dd, $J$=10.4, 7.1 Hz, 1H), 2.31 (s, 3H), 1.39 (dd, $J$=10.3, 6.0 Hz, 1H), 1.27～1.25 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) 135.5, 134.0, 128.8, 127.4, 93.2, 53.7, 53.3, 30.1, 21.0, 18.8. HRMS (ESI) calcd for $C_{12}H_{17}O_2$ $[M+H]^+$ 193.1223, found 193.1226.

1-(*tert*-Butyl)-4-(2,2-dimethoxycyclopropyl)benzene (**3d**): Yellow oil, 22.5 mg, 96% yield, $R_f$ = 0.55 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.32～7.29 (m, 2H), 7.15～7.12 (m, 2H), 3.44 (s, 3H), 3.25 (s, 3H), 2.36 (dd, $J$=10.4, 7.1 Hz, 1H), 1.41 (dd, $J$=10.4, 5.9 Hz, 1H), 1.30 (s, 9H), 1.28～1.24 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 148.7, 134.1, 127.2, 125.0, 93.3, 53.8, 53.4, 34. 3, 31.4, 30.1, 19.1. HRMS (ESI) calcd for $C_{15}H_{23}$- $O_2$ $[M+H]^+$ 235.1693, found 235.1695.

1-(2,2-Dimethoxycyclopropyl)-4-methoxybenzene (**3e**): The reaction was carried out under 80 ℃. Colorless oil, 18.4 mg, 88% yield, $R_f$=0.55 [$V$(PE)∶$V$(EA)=5∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.12 (d, $J$=8.3 Hz, 2H), 6.83 (d, $J$=8.7 Hz, 2H), 3.79 (s, 3H), 3.43 (s, 3H), 3.21 (s, 3H), 2.35 (dd, $J$=10.4, 7.1 Hz, 1H), 1.38 (dd, $J$=10.4, 5.9 Hz, 1H), 1.21 (t, $J$=6.5 Hz, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 157.9, 129.2, 128.5, 113.6, 93.1, 55.2, 53.6, 53.3, 29.7, 18.8. HRMS (ESI) calcd for $C_{12}H_{17}O_3$ $[M+H]^+$ 209.1172, found 209.1173.

1-(2,2-Dimethoxycyclopropyl)-4-phenoxybenzene (**3f**): Yellow oil, 24.8 mg, 92% yield, $R_f$=0.55 [$V$(PE)∶$V$(EA)=5∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.34～7.29 (m, 2H), 7.18～7.15 (m, 2H), 7.10～7.06 (m, 1H), 7.01～6.97 (m, 2H), 6.96～6.92 (m, 2H), 3.44 (s, 3H), 3.24 (s, 3H), 2.38 (dd, $J$=10.4, 7.1 Hz, 1H), 1.43 (dd, $J$=10.4, 6.0 Hz, 1H), 1.26～1.22 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 134.8, 133.4, 132.1, 127.54, 127.47, 126.2, 125.89, 125.85, 125.2, 93.5, 53.7, 53.5, 30.8, 19.2. HRMS (ESI) calcd for $C_{17}H_{19}O_3$ $[M+H]^+$ 271.1329, found 271.1331.

1-(2,2-Dimethoxycyclopropyl)-4-fluorobenzene (**3g**): Yellow oil, 15.0 mg, 77% yield, $R_f$=0.35 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.19～7.11 (m, 2H), 7.00～6.94 (m, 2H), 3.43 (s, 3H), 3.21 (s, 3H), 2.37 (dd, $J$=10.4, 7.1 Hz, 1H), 1.42 (dd, $J$=10.4, 6.1 Hz, 1H), 1.24～1.21 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 161.4 (d, $J$=244.0 Hz), 132.8 (d, $J$=3.3 Hz), 128.9 (d, $J$=7.9 Hz), 114.9 (d, $J$=21.3 Hz), 93.0, 53.6, 53.4, 29.7, 19.2; $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$: −117.24 (t, $J$=7.6 Hz). HRMS (ESI) calcd for $C_{11}H_{14}FO_2$ $[M+H]^+$ 197.0972, found 197.0978.

1-Chloro-4-(2,2-dimethoxycyclopropyl)benzene (**3h**): The reaction was carried out under 80 ℃. Colorless oil, 19.3 mg, 91% yield, $R_f$=0.55 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.25～7.23 (m, 2H), 7.12 (d, $J$=8.5 Hz, 2H), 3.43 (s, 3H), 3.20 (s, 3H), 2.35 (dd, $J$=10.3, 7.1 Hz, 1H), 1.45 (dd, $J$=10.3, 6.2 Hz, 1H), 1.25～1.24 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 135.8, 131.7, 128.8, 128.2, 93.15, 53.7, 53.4, 29.9, 19.4. HRMS (ESI) calcd for $C_{11}H_{14}ClO_2$ $[M+H]^+$ 213.0677, found 213.0680.

Ethyl 4-(2,2-dimethoxycyclopropyl)benzoate (**3i**): Yellow oil, 17.8 mg, 71% yield, $R_f$=0.45 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.90～7.87 (m, 2H), 7.20～7.17 (m, 2H), 4.29 (q, $J$=7.1 Hz, 2H), 3.37 (s, 3H), 3.11 (s, 3H), 2.36 (dd, J=10.2, 7.1 Hz, 1H), 1.44 (dd, $J$=10.2, 6.1 Hz, 1H), 1.33～1.28 (m, 4H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 166.6, 142.9, 129.3, 128.1, 127.3, 93.5, 60.8, 53.7, 53.5, 30.7, 19.9, 14.3. HRMS (ESI) calcd for $C_{14}H_{19}O_4$ $[M+H]^+$ 251.1278, found 251.1281.

1-(2,2-Dimethoxycyclopropyl)-3-methylbenzene (**3j**): Yellow oil, 14.0 mg, 73% yield, $R_f$=0.45 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.19～7.15 (m, 1H), 7.02～6.99 (m, 3H), 3.44 (s, 3H), 3.22 (s, 3H), 2.36 (dd, $J$=10.4, 7.3 Hz, 1H), 2.33 (s, 3H), 1.41 (dd, $J$=10.3, 6.0 Hz, 1H), 1.30～1.28 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) 137.6, 137.0, 128.4, 128.0, 126.8, 124.5, 93.3, 53.7, 53.4, 30.5, 21.4, 18.9. HRMS (ESI) calcd for $C_{12}H_{17}$-$O_2$ $[M+H]^+$ 193.1223, found 193.1225.

1-(2,2-Dimethoxycyclopropyl)-3-fluorobenzene (**3k**): Yellow oil, 19.0 mg, 97% yield, $R_f$ = 0.45 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.24～7.20 (m, 1H), 7.00～6.98 (m, 1H), 6.90～6.87 (m, 2H), 3.43 (s, 3H), 3.22 (s, 3H), 2.37 (dd, $J$=10.3, 7.1 Hz, 1H), 1.46 (dd, $J$=10.3, 6.1 Hz, 1H), 1.28～1.25 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 162.8 (d, $J$=244.0 Hz), 140.1 (d, $J$=7.9 Hz), 129.4 (d, $J$=8.6 Hz), 123.5 (d, $J$=2.8 Hz), 114.2 (d, $J$=22.0 Hz), 112.8 (d, $J$=21.2 Hz), 93.2, 53.7, 53.4, 30.2 (d, $J$=1.9 Hz), 19.6; $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$: −113.90. HRMS (ESI) calcd for $C_{11}H_{14}FO_2$ $[M+H]^+$ 197.0972, found 197.0974.

1-Chloro-3-(2,2-dimethoxycyclopropyl)benzene (**3l**): Yellow oil, 20.1 mg, 95% yield, $R_f$ = 0.55 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.22～7.15 (m, 3H), 7.09～7.07 (m, 1H), 3.43 (s, 3H), 3.23 (s, 3H), 2.35 (dd, $J$=10.3, 7.1 Hz, 1H), 1.46 (dd, $J$=10.3, 6.1 Hz, 1H), 1.29～1.26 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$: 139.5, 133.9, 129.2, 127.6, 126.1, 125.8, 93.2, 53.7, 53.5, 30.1, 19.5. HRMS (ESI) calcd for $C_{11}H_{14}ClO_2$ $[M+H]^+$ 213.0677, found 213.0676.

1-Bromo-3-(2,2-dimethoxycyclopropyl)benzene (**3m**): Yellow oil, 19.5 mg, 76% yield, $R_f$ = 0.45 [$V$(PE)∶$V$(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.35～

7.31 (m, 2H), 7.17～7.11 (m, 2H), 3.43 (s, 3H), 3.23 (s, 3H), 2.34 (dd, *J*=10.3, 7.0 Hz, 1H), 1.46 (dd, *J*=10.3, 6.1 Hz, 1H), 1.29～1.27 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 139.8, 130.6, 129.5, 129.0, 126.2, 122.2, 93.2, 53.8, 53.5, 30.1, 19.5. HRMS (ESI) calcd for $C_{11}H_{14}BrO_2$ $[M+H]^+$ 257.0172, found 257.0171.

1-(2,2-Dimethoxycyclopropyl)-3,5-dimethylbenzene (**3n**):Colorless oil, 18.5 mg, 90% yield, $R_f$ = 0.55 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) 6.83～6.81 (m, 3H), 3.43 (s, 3H), 3.24 (s, 3H), 2.35～2.30 (m, 1H), 2.29 (s, 6H), 1.40～1.36 (m, 1H), 1.29～1.26 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 137.5, 136.9, 127.8, 125.4, 93.3, 53.7, 53.3, 30.4, 21.3, 18.8. HRMS (ESI) calcd for $C_{13}H_{19}O_2$ $[M+H]^+$ 207.1380, found 207.1384.

1-(2,2-Dimethoxycyclopropyl)-3,5-dimethoxybenzene (**3o**): Yellow oil, 23.6 mg, 99% yield, $R_f$ = 0.55 [*V*(PE)∶*V*(EA)=5∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 6.38 (d, *J*=2.3 Hz, 2H), 6.32 (t, *J*=2.3 Hz, 1H), 3.78 (s, 6H), 3.43 (s, 3H), 3.24 (s, 3H), 2.33 (dd, *J*=10.3, 7.1 Hz, 1H), 1.42 (dd, *J*=10.3, 6.1 Hz, 1H), 1.29～1.26 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 160.5, 139.7, 105.8, 98.0, 93.3, 55.2, 53.8, 53.4, 30.8 19.3. HRMS (ESI) calcd for $C_{13}H_{19}O_4$ $[M+H]^+$ 239.1278, found 239.1282.

4-(2,2-Difluorocyclopropyl)-1,2-dimethoxybenzene (**3p**): Yellow oil, 23.6 mg, 99% yield, $R_f$ = 0.55 [*V*(PE)∶*V*(EA)=5∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 6.81～6.74 (m, 3H), 3.87 (s, 3H), 3.86 (s, 3H), 3.44 (s, 3H), 3.22 (s, 3H), 2.35 (dd, *J*=10.4, 7.1 Hz, 1H), 1.41 (dd, *J*=10.3, 6.0 Hz, 1H), 1.24～1.21 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 148.6, 147.4, 129.7, 119.6, 110.92, 110.85, 93.1, 55.83, 55.75, 53.6, 53.3, 30.1, 19.0. HRMS (ESI) calcd for $C_{13}H_{19}O_4$ $[M+H]^+$ 239.1278, found 239.1285.

5-(2,2-Dimethoxycyclopropyl)-1,2,3-trimethoxybenzene (**3q**): Yellow oil, 20.4 mg, 76% yield, $R_f$=0.35 [*V*(PE)∶*V*(EA)=2∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 6.44 (s, 2H), 3.85 (s, 6H), 3.83 (s, 3H), 3.44 (s, 3H), 3.25 (s, 3H), 2.33 (dd, *J*=10.3, 7.1 Hz, 1H), 1.44 (dd, *J*=10.4, 6.1 Hz, 1H), 1.25～1.22 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 152.9, 136.4, 133.0, 104.5, 93.2, 60.8, 56.0, 53.7, 53.4, 30.8, 19.5. HRMS (ESI) calcd for $C_{14}H_{21}O_5$ $[M+H]^+$ 269.1384, found 269.1389.

1-(2,2-Dimethoxycyclopropyl)-2-methylbenzene (**3r**): Colorless oil, 19.0 mg, 99% yield, $R_f$ = 0.60 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.17～7.06 (m, 4H), 3.47 (s, 3H), 3.18 (s, 3H), 2.44～2.40 (m, 1H), 2.43 (s, 3H), 1.39 (dd, *J*=10.3, 5.9 Hz, 1H), 1.35～1.32 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) 137.5, 135.0, 129.7, 126.5, 126.1, 125.7, 93.6, 53.42, 53.38, 28.2, 20.2, 17.8. HRMS (ESI) calcd for $C_{12}H_{17}O_2$ $[M+H]^+$ 193.1223, found 193.1223.

1-Chloro-2-(2,2-dimethoxycyclopropyl)benzene (**3s**): Yellow oil, 19.9 mg, 94% yield, $R_f$=0.55 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.36 (dd, *J*=7.7, 1.6 Hz, 1H), 7.22～7.13 (m, 2H), 7.09 (dd, *J*=7.6, 2.0 Hz, 1H), 3.51 (s, 3H), 3.23 (s, 3H), 2.72 (dd, *J*=10.2, 7.4 Hz, 1H), 1.45 (dd, *J*=10.2, 6.1 Hz, 1H), 1.40～1.36 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 135.3, 134.5, 129.1, 127.8, 127.3, 126.4, 93.4, 53.8, 53.7, 28.4, 17.8. HRMS (ESI) calcd for $C_{11}H_{14}ClO_2$ $[M+H]^+$ 213.0677, found 213.0679.

2-(2,2-Dimethoxycyclopropyl)naphthalene (**3t**): White solid, m.p. 85.5～87.2 ℃; 18.5 mg, 81% yield, $R_f$=0.45 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.81～7.75 (m, 3H), 7.64 (s, 1H), 7.46～7.39 (m, 2H), 7.36 (dd, *J*=8.5, 1.8 Hz, 1H), 3.48 (s, 3H), 3.19 (s, 3H), 2.56 (dd, J=10.2, 7.1 Hz, 1H), 1.51 (dd, J=10.3, 6.0 Hz, 1H), 1.44 (dd, J=7.2, 6.1 Hz, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) 134.8, 133.4, 132.1, 127.53, 127.46, 126.2, 125.9, 125.8, 125.2, 93.5, 53.7, 53.4, 30.7, 19.2. HRMS (ESI) calcd for $C_{15}H_{17}O_2$ $[M+H]^+$ 229.1223, found 229.1225.

2-(2,2-Dimethoxycyclopropyl)benzofuran (**3u**): Yellow oil, 18.5 mg, 85% yield, $R_f$=0.35 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.48～7.41 (m, 2H), 7.22～7.15 (m, 2H), 6.42 (t, *J*=0.9 Hz, 1H), 3.47 (s, 3H), 3.30 (s, 3H), 2.49 (ddd, J=9.9, 6.8, 0.6 Hz, 1H), 1.54 (dd, J=10.3, 5.9 Hz, 1H), 1.46 (dd, J=7.0, 5.9 Hz, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 155.2, 154.5, 128.9, 123.2, 122.5, 120.2, 110.8, 102.3, 92.9, 53.9, 53.7, 23.8, 18.9. HRMS (ESI) calcd for $C_{13}H_{15}O_3$ $[M+H]^+$ 219.1016, found 219.1020.

(*E*)-(2-(2,2-dimethoxycyclopropyl)vinyl)benzene (**3v**): Following the general procedure, product **3v** was isolated as yellow oil, 14.7 mg, 72% yield, $R_f$ = 0.35 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.35～7.26 (m, 4H), 7.20～7.16 (m, 1H), 6.52 (d, *J*=16.0 Hz, 1H), 5.93 (dd, *J*=16.0, 9.4 Hz, 1H), 3.41 (s, 3H), 3.40 (s, 3H), 2.09～2.03 (m, 1H), 1.35～1.31 (m, 1H), 0.99 (t, *J*=6.0 Hz, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 137.5, 129.7, 128.5, 128.1, 126.8, 125.8, 93.7, 53.8, 53.3, 29.6, 20.5. HRMS (ESI) calcd for $C_{13}H_{17}O_2$ $[M+H]^+$ 205.1223, found 205.1227.

4-(2,2-Diethoxycyclopropyl)-1,1'-biphenyl (**4a**): Colorless oil, 22.5 mg, 80% yield, $R_f$=0.65 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) 7.60～7.57 (m, 2H), 7.53～7.50 (m, 2H), 7.44～7.40 (m, 2H), 7.34～7.26 (m, 3H), 3.82～3.62 (m, 3H), 3.38～3.30 (m, 1H), 2.43 (dd, *J*=10.3, 7.1 Hz, 1H), 1.49 (dd, *J*=10.3, 6.0 Hz, 1H), 1.37～1.34 (m, 1H), 1.27 (t, *J*=7.1 Hz, 3H), 1.05 (t, *J*=7.1 Hz, 3H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.0, 138.6, 136.9, 128.7, 127.7, 127.0, 126.9, 126.6, 92.3, 62.2, 61.7, 30.4, 20.0, 15.3, 15.1. HRMS (ESI) calcd for $C_{19}H_{23}O_2$ $[M+H]^+$ 283.1693, found 283.1699.

4-(2,2-Dipropoxycyclopropyl)-1,1'-biphenyl (**4b**): Colorless oil, 15.5 mg, 50% yield, $R_f$=0.65 [*V*(PE)∶*V*(EA)=40∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.58 (d, *J*=7.7 Hz, 2H), 7.51 (d, *J*=7.9 Hz, 2H), 7.42 (t, *J*=7.5 Hz, 2H), 7.33～7.25 (m, 3H), 3.69～3.60 (m, 2H), 3.57～3.51 (m, 1H), 3.30～3.25 (m, 1H), 2.43 (dd, *J*=10.2, 7.1 Hz, 1H), 1.69～1.60 (m, 2H), 1.50～1.42 (m, 3H), 1.36～1.33 (m, 1H), 0.97 (t, *J*=7.4 Hz, 3H), 0.79 (t, *J*=7.4 Hz, 3H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.1, 138.6, 136.9, 128.7, 127.9, 126.9, 126.6, 92.2, 68.1, 68.0, 30.5, 23.0, 22.8, 19.9, 10.8, 10.7. HRMS (ESI) calcd for $C_{21}H_{27}O_2$ $[M+H]^+$

311.2006, found 311.2012.

4-(2-Butoxy-2-(pentyloxy)cyclopropyl)-1,1'-biphenyl (**4c**): Colorless oil, 29.1 mg, 86% yield, $R_f$ = 0.55 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.58 (d, *J*=7.7 Hz, 2H), 7.50 (d, *J*=6.6 Hz, 2H), 7.42 (t, *J*=7.5 Hz, 2H), 7.33～7.26 (m, 3H), 3.73～3.63 (m, 2H), 3.58 (q, *J*=7.1 Hz, 1H), 3.32～3.26 (m, 1H), 2.42 (dd, *J*=10.3, 7.1 Hz, 1H), 1.64～1.56 (m, 2H), 1.49～1.33 (m, 6H), 1.25～1.20 (m, 2H), 0.95 (t, *J*=7.3 Hz, 3H), 0.79 (t, *J*=7.3 Hz, 3H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.1, 138.6, 136.9, 128.7, 127.8, 127.0, 126.9, 126.6, 92.2, 66.14, 66.05, 31.8, 31.7, 30.5, 19.8, 19.5, 19.3, 13.9, 13.8. HRMS (ESI) calcd for $C_{23}H_{31}O_2$ $[M+H]^+$ 339.2319, found 339.2320.

4-(2,2-Bis(pent-4-en-1-yloxy)cyclopropyl)-1,1'-biphenyl (**4d**): Colorless oil, 21.4 mg, 59% yield, $R_f$ = 0.30 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.60～7.57 (m, 2H), 7.52～7.50 (m, 2H), 7.44～7.41 (m, 2H), 7.34～7.30 (m, 1H), 7.28～7.26 (m, 2H), 5.84 (ddt, *J*=16.9, 10.2, 6.6 Hz, 1H), 5.68 (ddt, *J*=16.9, 10.2, 6.6 Hz, 1H), 5.06 (dq, *J*=17.1, 1.7 Hz, 1H), 5.00 (dq, *J*=10.2, 1.4 Hz, 1H), 4.95～4.87 (m, 2H), 3.74～3.68 (m, 2H), 3.59 (dt, *J*=9.4, 6.7 Hz, 1H), 3.32 (dt, *J*=9.4, 6.4 Hz, 1H), 2.44 (dd, *J*=10.3, 7.0 Hz, 1H), 2.19～2.14 (m, 2H), 2.00～1.93 (m, 2H) , 1.76～1.69 (m, 2H), 1.57～1.46 (m, 3H), 1.37～1.34 (m, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.0, 138.7, 138.14, 138.09, 136.7, 128.7, 127.9, 127.0, 126.9, 126.7, 114.9, 114.6, 92.2, 65.8, 65.6, 30.4, 30.2, 28.8, 28.7, 19.7. HRMS (ESI) calcd for $C_{25}H_{31}O_2$ $[M+H]^+$ 363.2319, found 363.2321.

4-(2,2-Bis(2-(*tert*-butoxy)ethoxy)cyclopropyl)-1,1'-biphenyl (**4e**): Colorless oil, 34.5 mg, 81% yield, $R_f$=0.65 [*V*(PE)∶*V*(EA)=40∶1]. $^1$H NMR (400 MHz, $CDCl_3$) 7.57 (d, *J*=7.6 Hz, 2H), 7.49 (d, *J*=8.0 Hz, 2H), 7.42 (t, *J*=7.5 Hz, 2H), 7.33～7.30 (m, 3H), 3.87～3.78 (m, 2H), 3.75～3.70 (m, 1H), 3.56～3.50 (m, 3H), 3.40～3.31 (m, 2H), 2.48 (dd, *J*=10.3, 7.2 Hz, 1H), 1.55 (dd, *J*=10.4, 5.9 Hz, 1H), 1.39 (t, *J*=6.7 Hz, 1H), 1.21 (s, 9H), 1.13 (s, 9H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.1, 138.6, 136.9, 128.7, 127.9, 126.9, 126.6, 92.2, 68.1, 68.0, 30.5, 23.0, 22.8, 19.9, 10.8, 10.7. HRMS (ESI) calcd for $C_{27}H_{39}O_4$ $[M+H]^+$ 427.2843, found 427.2845.

4-(2,2-Diisopropoxycyclopropyl)-1,1'-biphenyl (**4f**): Yellow oil, 27.6 mg, 89% yield, $R_f$ = 0.65 [*V*(PE)∶*V*(EA)=40∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.58 (d, *J*=7.7 Hz, 2H), 7.51 (d, *J*=7.9 Hz, 2H), 7.42 (t, *J*=7.6 Hz, 2H), 7.31 (t, *J*=7.4 Hz, 1H), 7.25 (d, *J*=9.9 Hz, 2H), 4.18～4.27 (m, 1H), 3.99～4.09 (m, 1H), 2.42 (dd, *J*=10.3, 7.2 Hz, 1H), 1.50 (dd, *J*=10.4, 6.0 Hz, 1H), 1.39～1.36 (m, 1H), 1.28～1.24 (m, 6H), 1.20 (d, *J*=6.3 Hz, 3H), 1.09 (d, *J*=6.2 Hz, 3H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.0, 138.6, 136.9, 128.7, 127.7, 127.0, 126.9, 126.6, 92.3, 62.2, 61.7, 30.4, 20.0, 15.4, 15.1. HRMS (ESI) calcd for $C_{21}H_{26}NaO_2$ $[M+Na]^+$ 333.1825, found 333.1823.

4-(2,2-Dicyclobutoxycyclopropyl)-1,1'-biphenyl (**4g**): Yellow oil, 28.4 mg, 85% yield, $R_f$ = 0.65 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.58 (d, *J*=7.7 Hz, 2H), 7.50 (d, *J*=8.0 Hz, 2H), 7.42 (t, *J*=7.5 Hz, 2H), 7.32 (t, *J*=7.4 Hz, 1H), 7.22 (d, *J*=7.9 Hz, 2H), 4.41 (p, *J*=7.7 Hz, 1H), 4.09 (p, *J*=7.7 Hz, 1H), 2.38 (dd, *J*=10.3, 7.1 Hz, 1H), 2.30～2.18 (m, 3H), 2.10～1.91 (m, 3H), 1.82～1.65 (m, 3H), 1.52～1.43 (m, 3H), 1.35～1.29 (m, 2H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.0, 138.6, 136.7, 128.7, 127.9, 127.0, 126.9, 126.6, 91.5, 71.8, 70.3, 32.2, 32.0, 31.7, 31.4, 29.7, 19.4, 13.2, 12.8. HRMS (ESI) calcd for $C_{23}H_{27}O_2$ $[M+H]^+$ 335.2006, found 335.2008.

4-(2,2-Bis(cyclohexyloxy)cyclopropyl)-1,1'-biphenyl (**4h**): Colorless oil, 35.1 mg, 90% yield, $R_f$=0.65 [*V*(PE)∶*V*(EA)=40∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.57 (d, *J*=7.6 Hz, 2H), 7.50 (d, *J*=7.9 Hz, 2H), 7.42 (t, *J*=7.6 Hz, 2H), 7.33～7.24 (m, 3H), 3.91～3.86 (m, 1H), 3.75～3.69 (m, 1H), 2.43 (dd, *J*=10.3, 7.2 Hz, 1H), 2.09～1.97 (m, 3H), 1.86～1.63 (m, 5H), 1.50 (dd, *J*=10.5, 5.8 Hz, 2H), 1.39～1.08 (m, 12H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.2, 138.6, 137.1, 128.7, 128.0, 127.0, 126.9, 126.6, 90.5, 74.9, 33.7, 33.3, 33.2, 31.0, 25.7, 25.5, 24.62, 24.59, 24.5, 19.6. HRMS (ESI) calcd for $C_{27}H_{34}NaO_2$ $[M+H]^+$ 413.2451, found 413.2458.

4-(2,2-Bis(benzhydryloxy)cyclopropyl)-1,1'-biphenyl (**4i**): Yellow oil, 43.0 mg, 77% yield, $R_f$=0.45 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.60～7.58 (m, 2H), 7.49～7.39 (m, 5H), 7.37～7.31 (m, 7H), 7.21～7.18 (m, 4H), 7.16～7.11 (m, 7H), 7.08～7.06 (m, 2H), 6.81 (d, *J*=8.3 Hz, 2H), 5.86 (s, 2H), 2.15～2.10 (m, 1H), 1.32 (dd, *J*=10.3, 6.2 Hz, 1H), 0.98 (dd, *J*=7.4, 6.1 Hz, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 142.7, 142.52, 142.50, 142.4, 141.1, 138.5, 136.1, 130.1, 128.72, 128.69, 128.5, 128.4, 128.1, 128.03, 127.97, 127.7, 127.5, 127.4, 127.1, 126.9, 126.8, 126.7, 126.5, 126.2, 91.7, 80.9, 79.4, 29.6, 18.0. HRMS (ESI) calcd for $C_{41}H_{34}NaO_2$ $[M+H]^+$ 581.2451, found 581.2455.

1-([1,1'-Biphenyl]-4-yl)-4,7-dioxaspiro[2.4]heptane (**4j**): The reaction was carried out under 50 ℃. Yellow solid, m.p. 88.1～90.3 ℃; 22.4 mg, 89% yield, $R_f$ = 0.55 [*V*(PE)∶*V*(EA)=20∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.59～7.56 (m, 2H), 7.54～7.50 (m, 2H), 7.44～7.39 (m, 2H), 7.34～7.30 (m, 1H), 7.28～7.25 (m, 2H), 4.12～4.02 (m, 3H), 3.92～3.83 (m, 1H), 2.38 (dd, *J*=11.0, 7.6 Hz, 1H), 1.63 (dd, *J*=10.9, 7.2 Hz, 1H), 1.45 (t, *J*=7.4 Hz, 1H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 141.0, 138.7, 136.6, 128.7, 127.8, 126.99, 126.95, 126.9, 96.6, 65.3, 64.9, 26.6, 15.0. HRMS (ESI) calcd for $C_{17}H_{17}O_2$ $[M+H]^+$ 253.1223, found 253.1226.

1-([1,1'-Biphenyl]-4-yl)-6,6-dimethyl-4,8-dioxaspiro-[2.5]octane (**4k**): The reaction was carried out under 80 ℃. White solid, m.p. 91.2～92.8 ℃; 17.6 mg, 60% yield, $R_f$=0.65 [*V*(PE)∶*V*(EA)=40∶1]. $^1$H NMR (400 MHz, $CDCl_3$) *δ*: 7.60～7.58 (m, 2H), 7.53～7.51 (m, 2H), 7.44～7.40 (m, 2H), 7.34～7.28 (m, 3H), 3.63～3.62 (m, 2H), 3.37 (d, *J*=10.7 Hz, 1H), 3.18 (d, *J*=10.8 Hz, 1H), 2.41 (dd, *J*=10.4, 7.2 Hz, 1H), 1.56～1.53 (m, 1H), 1.40 (t, *J*=6.8 Hz, 1H), 1.14 (s, 3H), 0.83 (s, 3H); $^{13}$C NMR (101 MHz, $CDCl_3$) *δ*: 140.9, 138.6, 136.7, 128.7, 127.6, 127.0, 126.9, 126.8, 90.8, 76.3, 76.0, 30.6, 29.7, 22.5, 22.1,

19.8. HRMS (ESI) calcd for $C_{20}H_{23}O_2$ $[M+H]^+$ 295.1693, found 295.1699.

**Supporting Information** Synthetic applications, mechanistic studies, gas chromatography (GC) and nuclear magnetic resonance (NMR) spectra. The NMR spectra of products **3a**～**3v**, **4a**～**4k**, **6**. The Supporting Information is available free of charge via the Internet at http://sioc-journal.cn/.

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