Acid-Promoted sp^2 C–F Bond Activation and Its Application toward the Synthesis of Polycyclic Aromatic Hydrocarbons

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CHAPTER 1

General Introduction

1-1. C–F Bond Activation

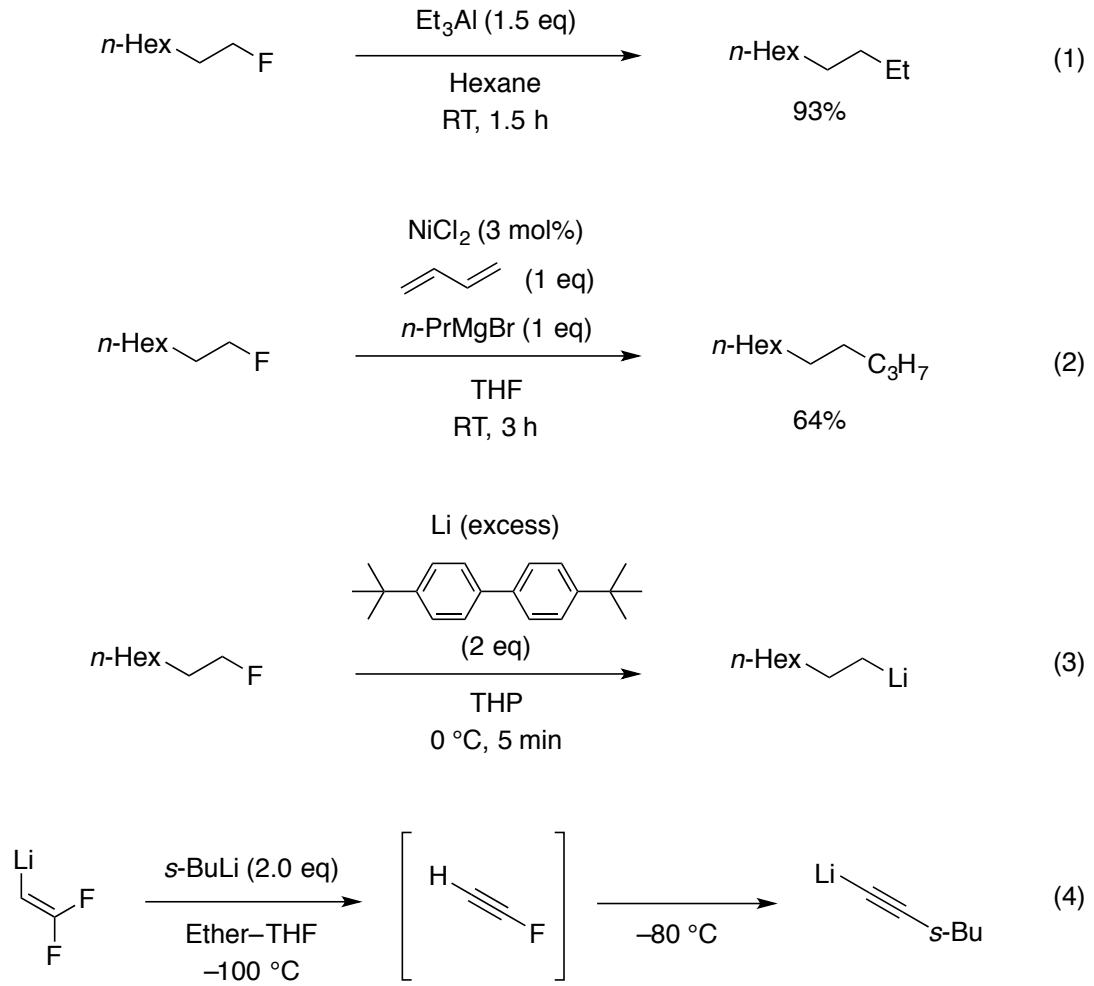
Chemical transformations of carbon–halogen (C–X) bonds are widely utilized in pharmaceutical, agrochemical, and materials sciences, especially for construction of new C–C bonds in (i) nucleophilic substitution, (ii) radical reactions, and (iii) transition metal-catalyzed cross coupling, etc. Among these transformations, reactions involving carbon–fluorine (C–F) bond cleavage still remain difficult, thus requiring harsh conditions, because its bond energy is highest in those of single covalent bonds with a carbon atom, including C–H, C–C, C–O, C–N, C–Cl, C–Br, and C–I bonds (Table 1).[1]

Table 1. Bond energies

C–X	Bond Energy (kJ/mol)
C–H	413
C–C	346
C–O	358
C–N	304
C–Cl	327
C–Br	285
C–I	213
C–F	**485**

Several methods for activation of C–F bonds were reported depending on the hybridization modes of carbons.[2] Activation of sp^3 C–F bonds has been achieved via (i) Lewis acid-mediated nucleophilic substitution (eq 1),[3] (ii) transition metal-catalyzed cross coupling (eq 2),[4] (iii)

reduction with low-valent metals, such as magnesium or lithium (eq 3).[5] Second, sp^2 C–F bond activation is conducted by (i) nucleophilic substitution via addition–elimination process with strong nucleophiles, such as Grignard or organolithium reagents, (ii) oxidative addition with highly-reductive transition metal complexes with directing groups or with Lewis acids, (iii) strong acid-mediated reaction under harsh conditions (vide infra). Last, sp C–F bond activation is done by nucleophilic substitution under exceptionally mild conditions (eq 4).[6]

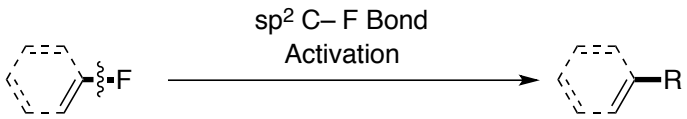


At the methods for C–F bond activation mentioned above show sp^2 C–F bond activation seems especially difficult. In terms of transition metal-catalyzed cross coupling, sp^3 C–F bond activation proceeds at room temperature (eq 2), whereas sp^2 C–F bond activation requires appropriate directing groups, special ligands, or harsh conditions.

Therefore I focused on sp^2 C–F bond activation and envisioned that the problems should be solved by taking full advantages of chemical properties of fluorine, because alternative facile methods for sp^2 C–F bond activation was highly desirable. I turned my attention to the α-carbocation stabilizing effect of fluorine. Fluorine has cation stabilizing effect by conjugation of its unshared electron pair into the vacant p orbital of cationic carbon atoms. Due to this effect, when a fluorine-containing unsaturated system is treated with Brønsted or Lewis acids, the carbon β to the fluorine is selectively protonated or metalated, which thus generates stabilized α-carbocation. Considering some reports from the Ichikawa group, nucleophilic attack to the stabilized α-fluorocarbocations and subsequent HF elimination would afford the substitution products via C–C bond formation and sp^2 C–F bond cleavage. Thus, I started my project on developing new methodologies for vinylic and aromatic sp^2 C–F bond activation by utilizing α-fluorocarbocations as key intermediates.

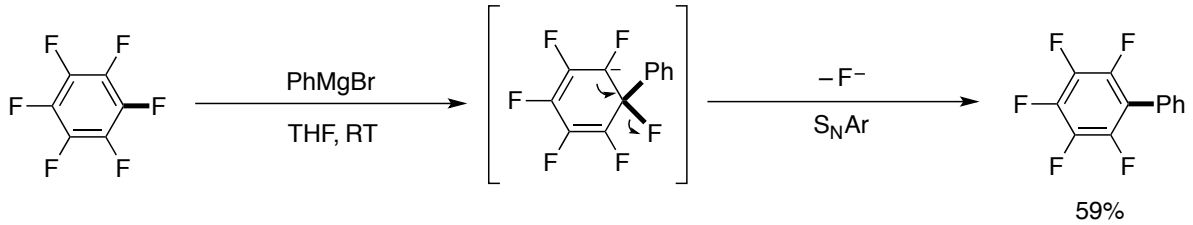
In the next section, the overview of conventional methods for activation of vinylic and aromatic sp^2 C–F bonds is shown (Scheme 1).

Scheme 1. sp^2 C–F bond activation



1-2. Conventional Methods for sp^2 C–F Bond Activation

Nucleophilic substitution via addition–elimination processes is known as a classic method for sp^2 C–F bond activation.[7] On treatment with phenylmagnesium bromide, for example, hexafluorobenzene underwent nucleophilic addition to the carbons α to the fluorine substituents. Subsequent fluorine elimination gave the pentafluorobiphenyl. Aromatic nucleophilic substitution (S_NAr) enables C–F bond activation of fluoroarenes (eq 5). In a similar manner, vinylic nucleophilic substitution (S_NV) has been conducted to allow sp^2 C–F bond activation in difluoroalkenes (eq 6). Thus, nucleophilic substitution of fluoroarenes bearing electron-withdrawing groups and difluoroalkenes has been achieved by using strong nucleophiles such as organomagnesium and organolithium reagents.



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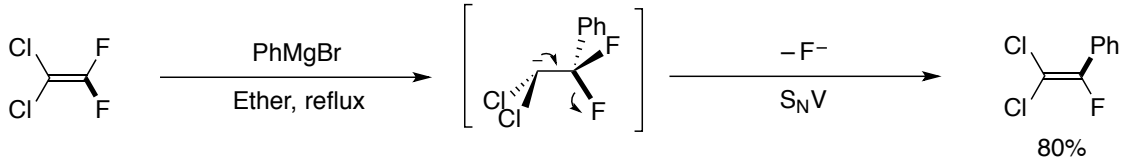
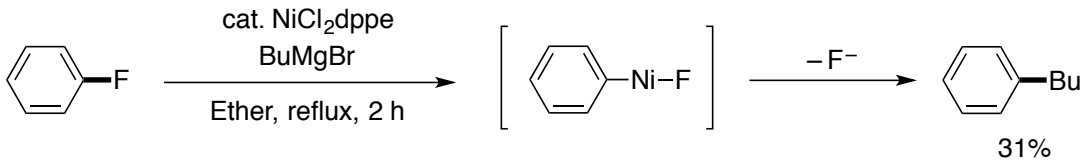


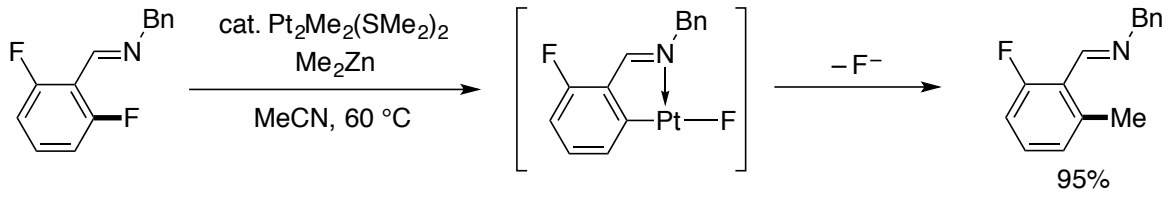
(6)

On the other hand, sp^2 C–F bond activation by transition metal-catalyzed oxidative addition has been recently brought into the spotlight over the decade,[8] after Kumada and Tamao developed nickel-catalyzed coupling reactions of fluoroarenes with organomagnesium reagents in 1973.[9] This protocol involves (i) oxidative addition of C–F bonds to the low-valent metal center followed by (ii) transmetalation with organometallic reagents and (iii) subsequent reductive elimination (eq 7).



(7)

During the last decade, several types of aromatic sp^2 C–F bond activation reactions via oxidative addition has been reported. On treatment with dimethylzinc in the presence of platinum catalyst, *ortho*-methylation of arylimines bearing fluorine substituents on the *ortho* positions proceeded by the aid of the directing effect of the imine part (eq 8).[10] Hydroxy-group-containing phosphine ligand was effective for C–F bond activation of fluoroarenes under mild conditions (eq 9).[8d] In addition, the nickel-catalyzed Suzuki–Miyaura coupling of fluoroarenes with arylboronates to give biaryl compounds (eq 10).[8a] However, aromatic sp^2 C–F bond activation via oxidative addition generally requires appropriate directing groups, special ligands, or harsh conditions.



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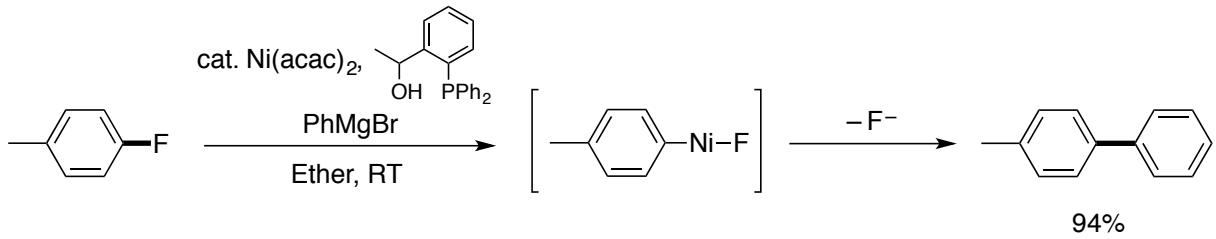

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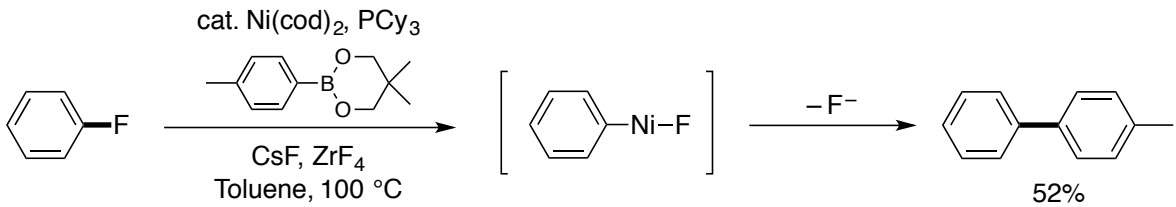
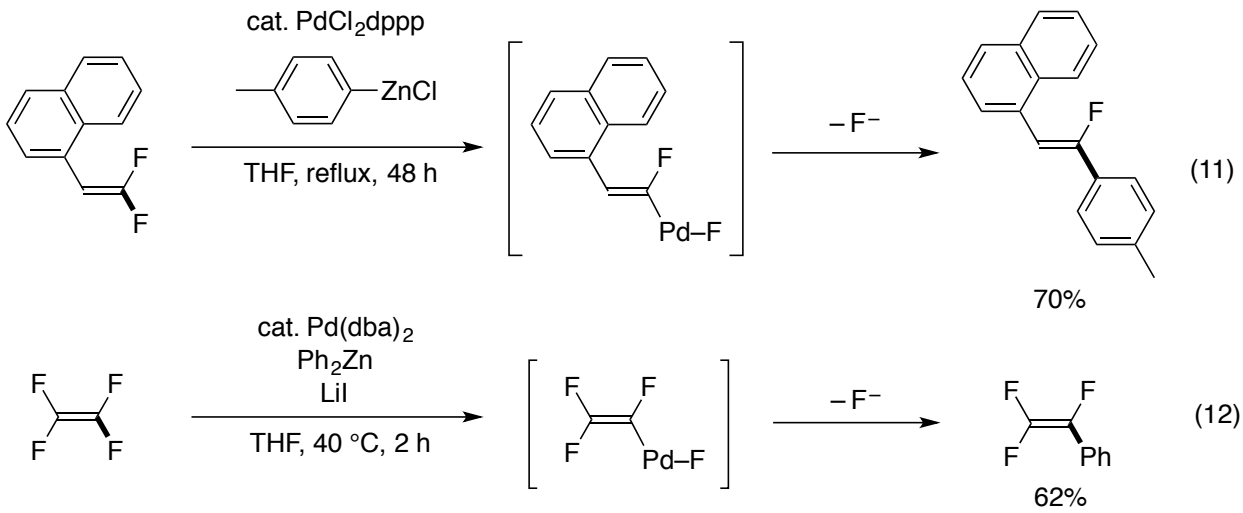


(10)

Recently vinylic sp^2 C–F bond activation in fluoroalkenes has been achieved via oxidative addition as well as aromatic C–F bond activation.[11] In the presence of $PdCl_2$dppp catalyst, for example, treatment of β,β-diflurostyrenes with arylzinc reagents afforded fluorostilbenes via an intermediary vinyl palladium fluoride (eq 11).[11a] Similarly, coupling of tetrafluoroethylene with diarylzinc reagents was catalyzed by $Pd(dba)_2$, leading to the synthesis of trifluorostyrenes (eq 12).[11b] However, only a few examples of vinylic sp^2 C–F bond activation have been reported to date.



1-3. sp^2 C–F Bond Activation under Acidic Conditions

Friedel–Crafts-type cyclizations of α-fluorocarbocations generated from fluoroalkenes can produce carbocyclic compounds (eq 13). The carbocations generated at the position α to fluorine substituents are stabilized by lone pairs of fluorine atoms. Due to this effect, when *gem*-difluoroalkenes are treated with Brønsted or Lewis acids, the carbon β to fluorine is selectively protonated or metalated to generate the stabilized α-fluorocarbocations (Figure 1). Although fluoroalkenes are electron-deficient alkenes because of strong electronegativity of fluorine, their electrophilic activation is achieved by addition of appropriate acids. Since cyclization reactions via

such α-fluorocarbocations are followed by the elimination of hydrogen fluoride (HF) or metal fluoride, vinylic sp^2 C–F bond activation is accomplished as a result.

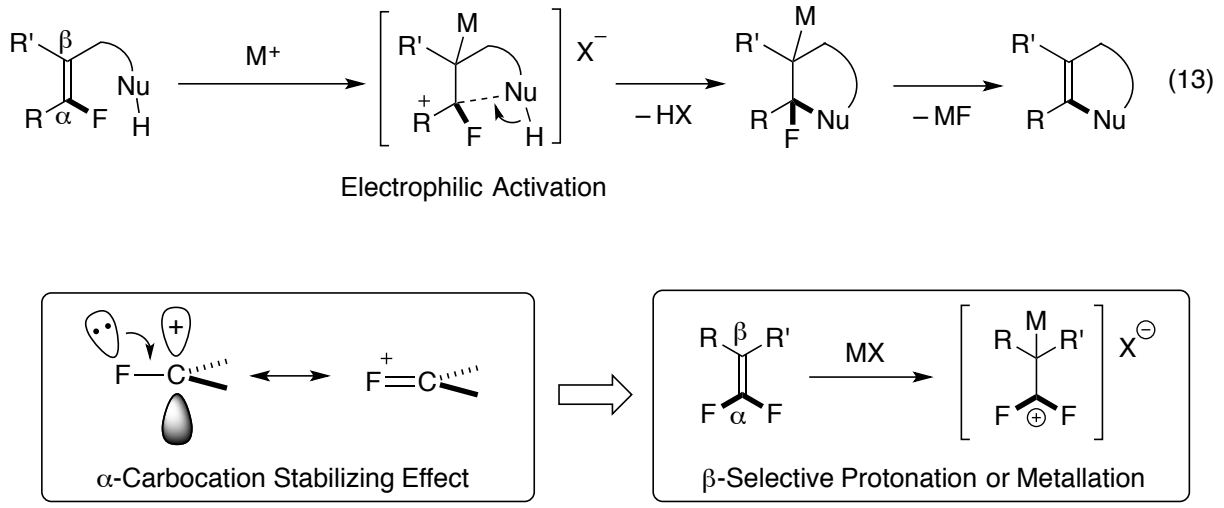
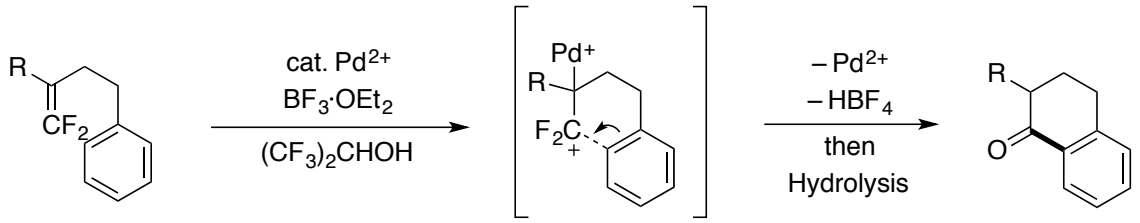


Figure 1. Generation of α-Fluorocarbocation

By utilizing these characteristics of fluorine atom, the Ichikawa group has reported Friedel–Crafts-type cyclizations via vinylic sp^2 C–F bond activation under acidic conditions.[12] In the presence of a catalytic amount of a cationic palladium complex in 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP), Friedel–Crafts-type cyclizations of 1,1-difluoro-1-alkenes bearing phenethyl or biphenyl-2-yl groups readily proceeded to afford tetralones or phenacenes, respectively (eqs 14, 15).[12d,h] Magic acid ($FSO_3H{\cdot}SbF_5$) also mediated similar reactions with phenethyl-substituted difluoroalkenes (eq 16).[12b] Furthermore, the domino Friedel–Crafts-type cyclization of 1,1-difluoro-1-alkenes bearing two phenethyl groups proceeded by addition of magic acid in HFIP to afford helical compounds (eq 17).[12e,g] Therefore, an acid-mediated cyclization–HF elimination sequence is quite effective for vinylic sp^2 C–F bond activation. It is noted that taking full advantage of chemical properties of fluorine, such as α-carbocation stabilizing effect and serving as a leaving group, enables regioselective C–C bond formation by weak nucleophiles.



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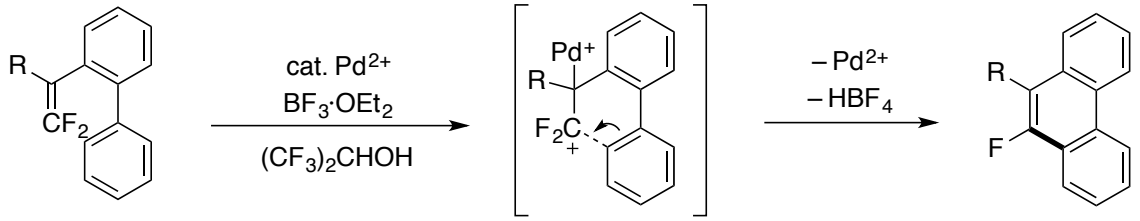

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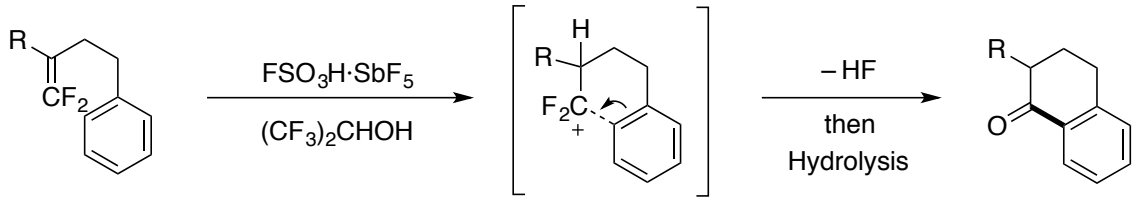

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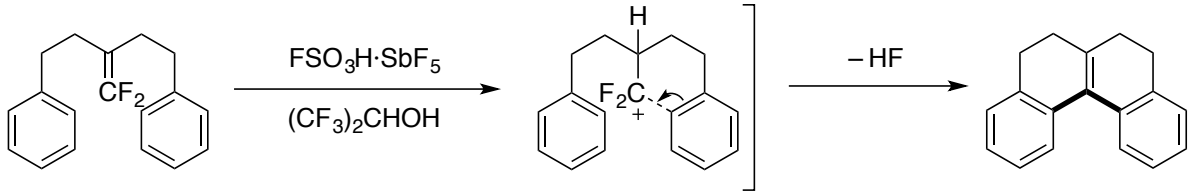
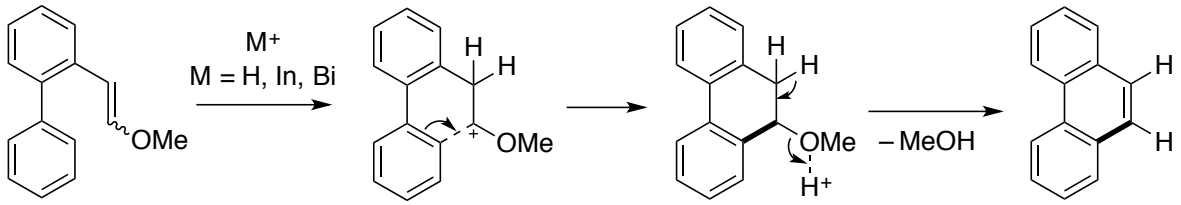


(17)

Similarly, when a methoxy or phenyl group was substituted at the terminal position of 2-phenylstyrenes, phenanthrene frameworks were formed via cycloaromatization (eqs 18, 19).[13] In these cases, intermediary carbocations stabilized by the methoxy or phenyl group are generated at the β positions of styrenes. Friedel–Crafts-type cyclizations and subsequent elimination of methanol or benzene afforded phenanthrenes.



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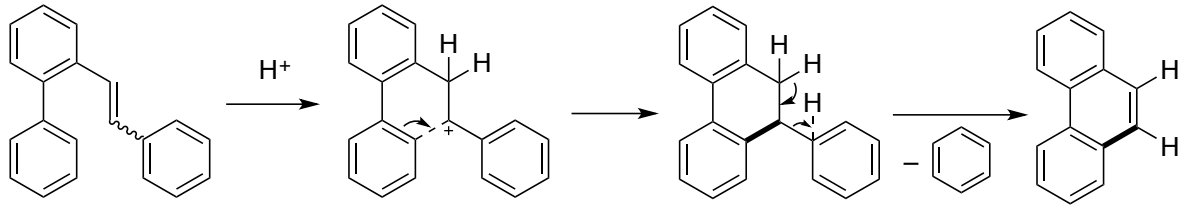
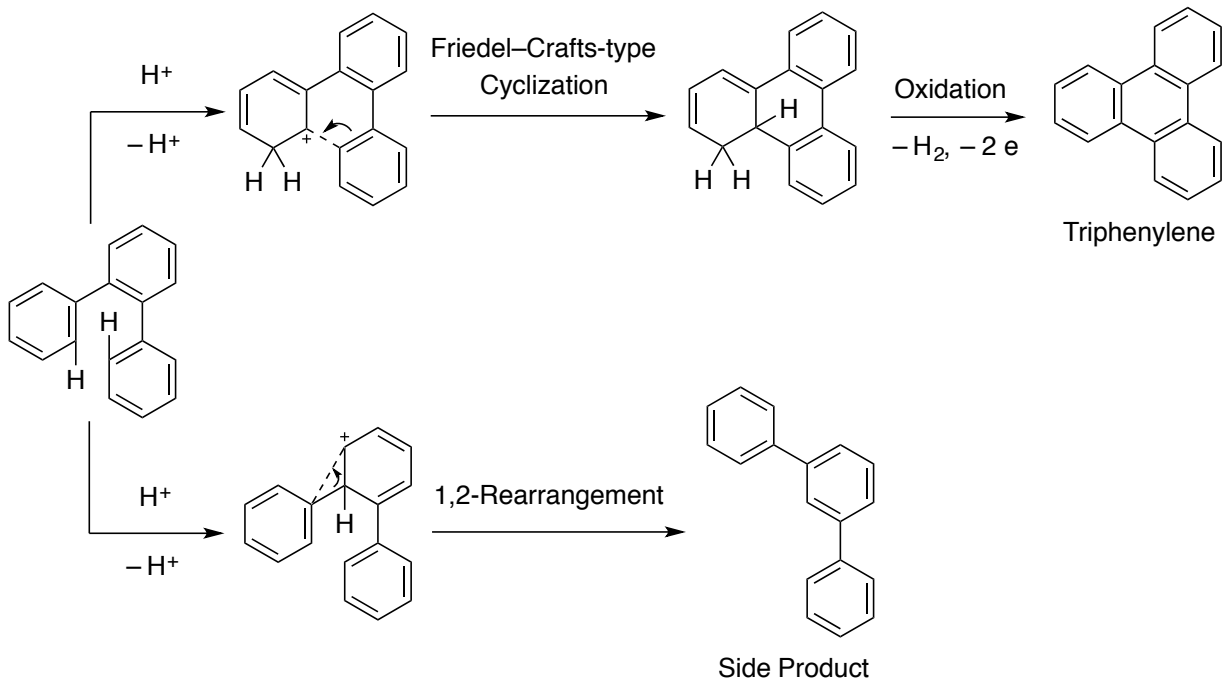


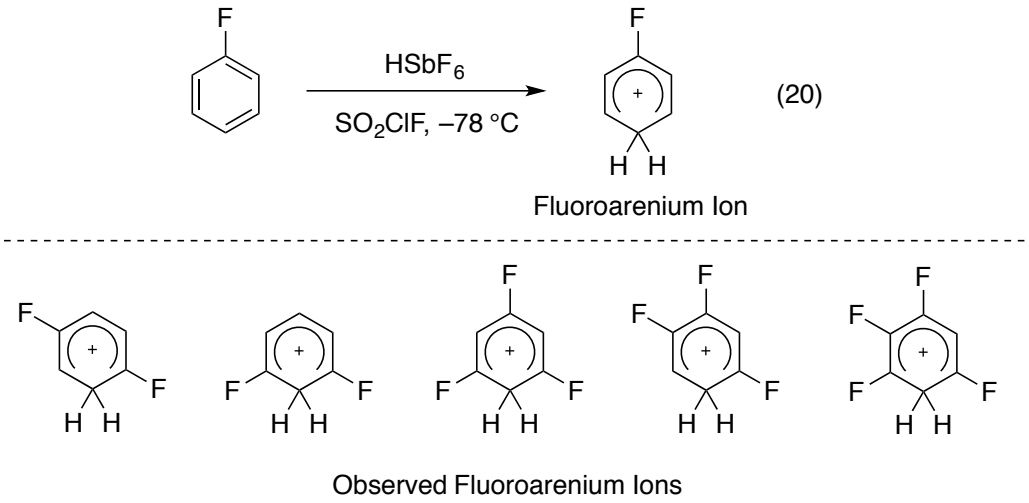
(19)

Contrary to reactions of alkenes mentioned above, reactions of arenes with nucleophiles under acidic conditions are much more difficult because of remarkable stability of aromatic rings. The Scholl reaction, which is cycloaromatization via intramolecular oxidative aromatic C–H/C–H coupling, is one of a few examples (Scheme 2).[14] In this reaction, initial protonation of an aromatic ring generates the corresponding arenium ion. This intermediate undergoes a Friedel–Crafts-type cyclization and subsequent oxidation gives the corresponding benzenoid compound. However, the problem of this reaction is potential side reactions, such as rearrangement, caused by an arenium ion generated from a different aromatic ring,which is due to the difficulty in selective protonation of the appropriate ring (Scheme 2). Thus, reactions of arenium ions with nucleophiles appear troublesome because of uncontrollable protonation.

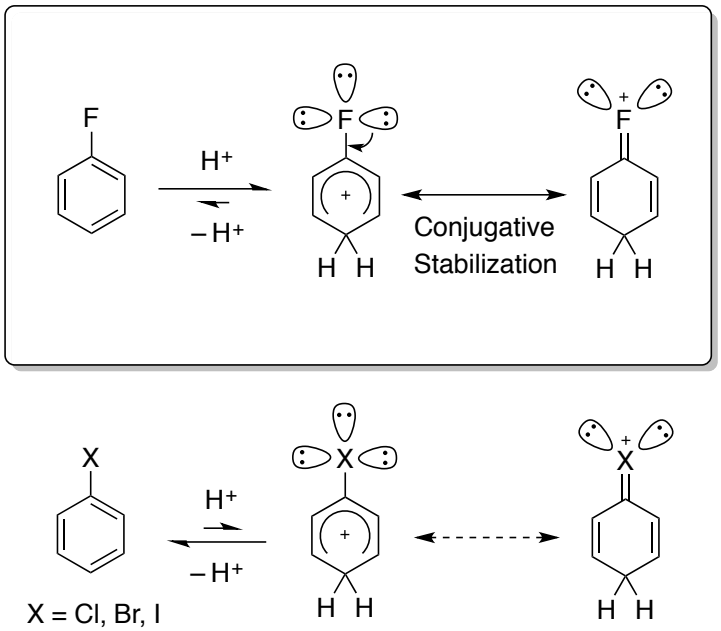
Scheme 2. Reaction Mechanism of Acid-Mediated Scholl Reaction



Olah reported generation of fluoroarenium ions by protonation of fluoroarenes.[15] Under cryogenic conditions, treatment of fluoroarenes with FSO_3H in SO_2ClF afforded fluoroarenium ions (eq 20). In these cases, both *para*- and *ortho*-protonated arenium ions were observed by NMR measurement. Fluoroarenium ions thus obtained are stabilized by the conjugative effect of the fluorine atoms (Scheme 3). Olah noted that the availability of the fluoroarenium ions is mainly attributed not to high π-basicity of fluoroarenes but to conjugation by the lone pairs of fluorine atoms. In contrast to fluoroarenium ions, the other haloarenium ions, such as chloro-, bromo-, and iodoarenium ions have never been observed in NMR measurements, which is due to the lack of stabilizing effect by conjugation. These facts indicated that fluoroarenium ions would serve as useful intermediates for aromatic C–F bond activation. However, their practical use in synthetic organic chemistry remained unprecedented.



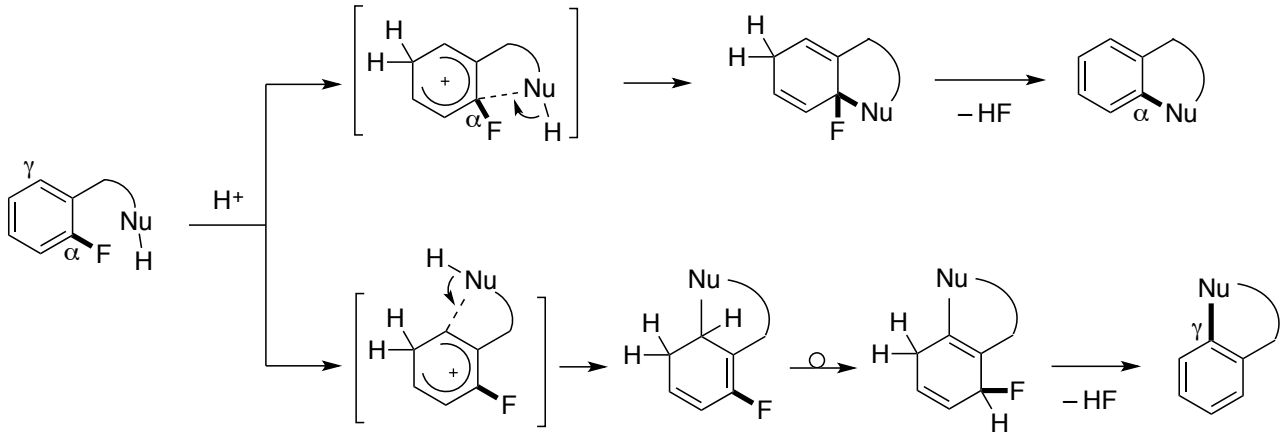
Scheme 3. Stabilized Fluoroarenium Ion



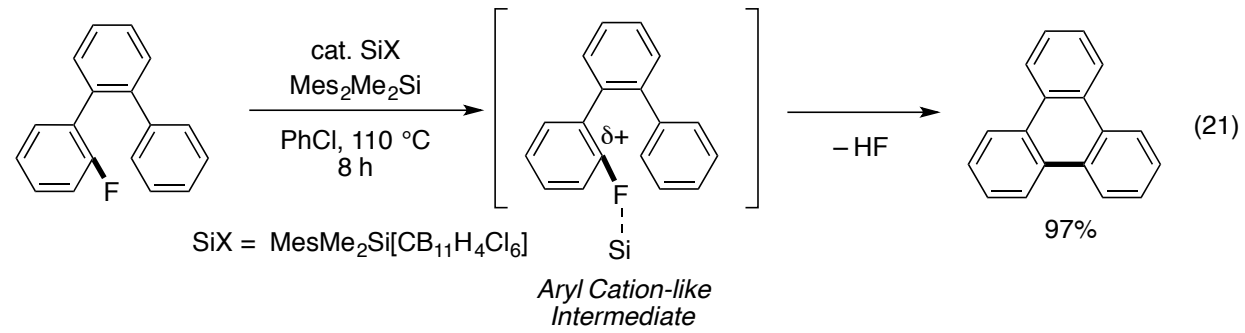
To apply the fluoroarenium ions to synthetic organic chemistry, the intramolecular C–C bond formation seemed to be an appropriate model. In this case, nucleophilic addition of another aromatic ring to the fluorine-stabilized, selectively generated arenium ion would afford the desired cyclic compounds via rearomatization by HF elimination, not requiring oxidation like an acid mediated Scholl reaction. Thus, this protocol would be an alternative and powerful method for aromatic sp^2 C–F bond activation. Activation under mild condition would be possible because

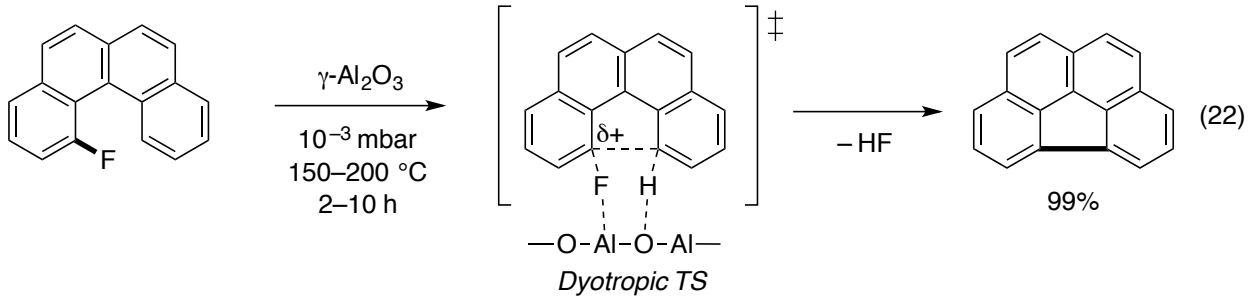
fluoroarenium ions could be generated under cryogenic conditions. Furthermore, the cationic charge density in fluoroarenium intermediates would be distributed not only on the position α to fluorine but also on the position γ to fluorine. Therefore, I assumed that the position γ to fluorine also might serve as a reaction site (Scheme 4).

Scheme 4. Aromatic C–F Bond Activation Utilizing Fluoroarenium Ion



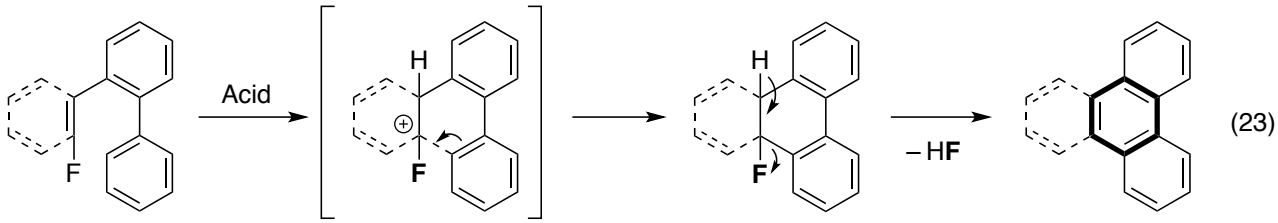
Quite recently, two different methodologies for acid-promoted aromatic sp^2 C–F bond activation were independently reported by Siegel[16] and Amsharov.[17] In 2010, Siegel et al. reported aromatic C–F bond activation by extremely unstable silyl cation species (eq 21). In this reaction, defluorinative cycloaromatization of a fluorinated *o*-terphenyl compounds might proceed via the aryl cation-like intermediate. On the other hand, in 2012 Amsharov et al. reported defluorinative cycloaromatization mediated by γ-Al_2O_3 at high temperatures (eq 22). They insisted that the reaction might proceed via dyotropic transition state. As illustrated by these examples, activation of aromatic sp^2 C–F bonds under acidic conditions has required extremely unstable silylcation species or harsh conditions to date.



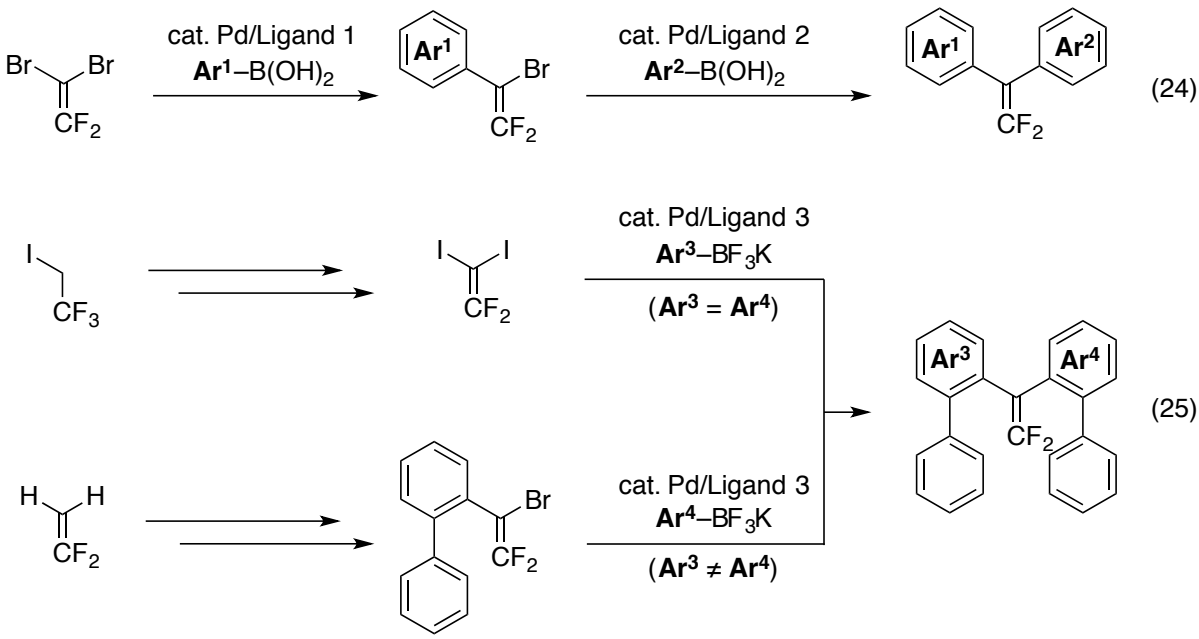


1-3. Survey of This Thesis

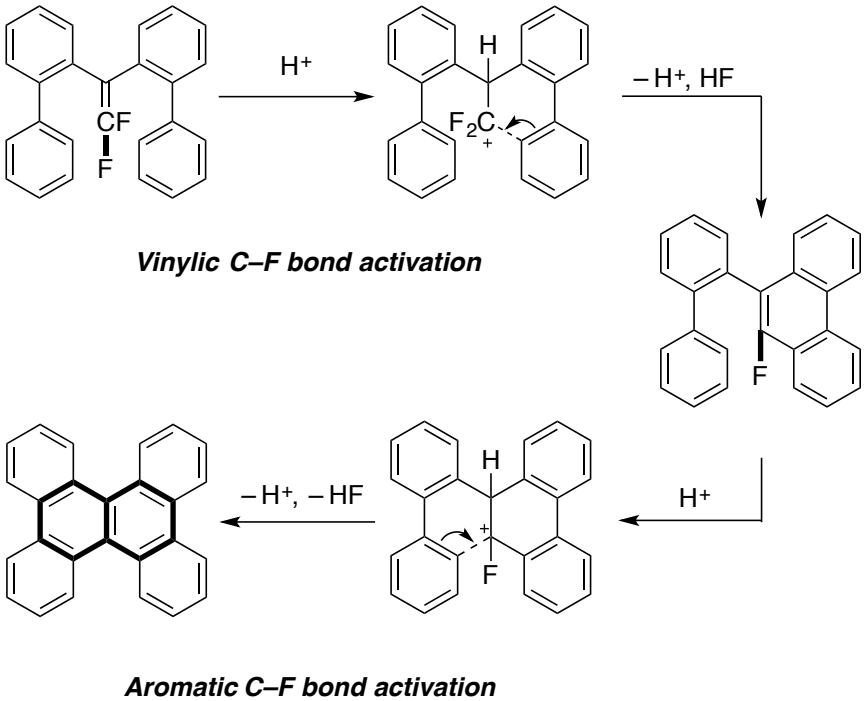
Utilizing α-fluorocarbocations as reaction intermediates, I developed new methodologies for vinylic and aromatic sp^2 C–F bond activation, which consisted of C–C bond formation via Friedel–Crafts-type cyclizations and C–F bond cleavage via HF elimination (eq 23). Thus, I achieved syntheses of polycyclic aromatic hydrocarbons (PAHs), which are expected to be used as materials such as liquid crystals and/or organic semiconductors.[18]



In Chapters 2 and 3, I developed the synthetic method for 1,1-diaryl-2,2-difluoroethenes and their domino Friedel−Crafts-type cyclization via double C–F bond activation, respectively. 1,1-Diaryl-2,2-difluoroethenes were prepared from easily accessible difluoroethylene derivatives by using palladium-catalyzed cross coupling reactions (eqs 24, 25). I also devised a method for the synthesis of dibenzo[*g*,*p*]chrysenes via the domino Friedel−Crafts-type cyclization of 1,1-difluoroethenes bearing two biaryl groups, which was mediated by appropriate acids. In this approach, both vinylic and aromatic sp^2 C−F bond activations were successfully effected to achieve direct construction of two aromatic rings (Scheme 5).

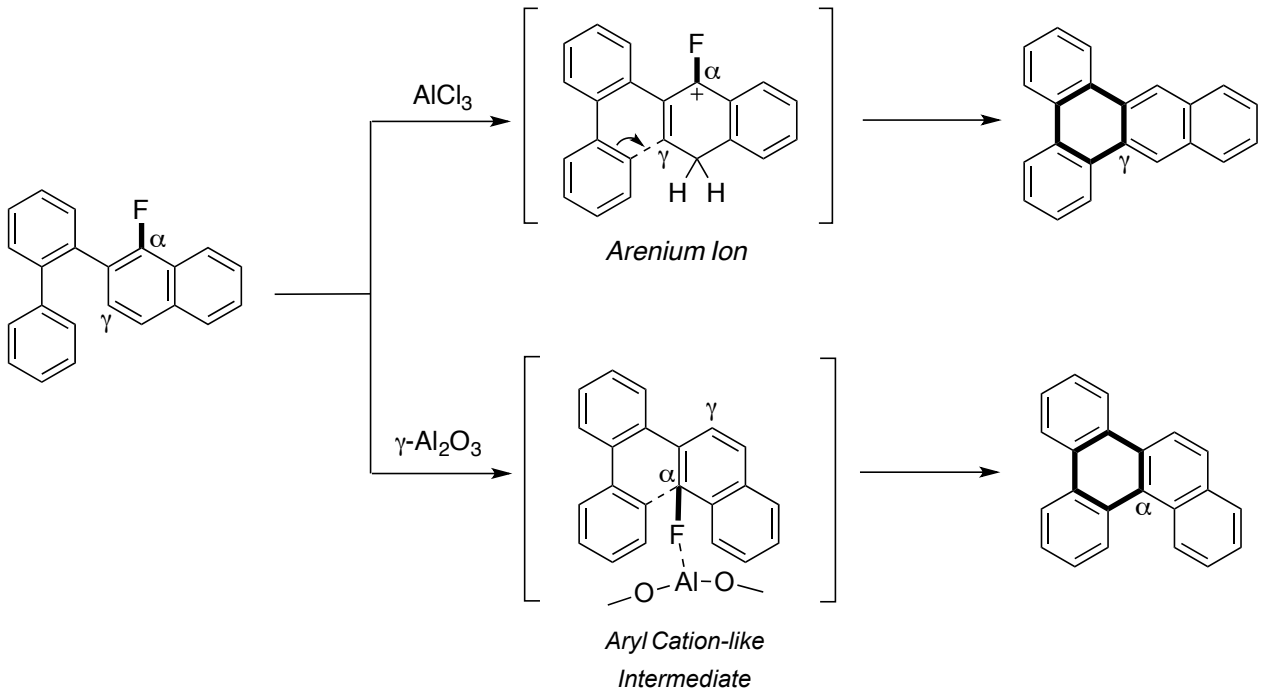


Scheme 5. Vinylic and Aromatic C–F Bond Activation



In Chapter 4, I succeeded in aromatic sp^2 C–F bond activation of fluoronaphthalene derivatives. The complete switching of the regioselectivity in defluorinative intramolecular cyclizations of fluoronaphthalenes was achieved by using different aluminium reagents, which gave rise to the synthesis of differently benzene-fused triphenylenes (Scheme 6). When aluminium chloride was used, fluoronaphthalenes bearing a biaryl group underwent intramolecular cyclization via selective C–C bond formation on the carbon atom γ to the original position of the fluorine substituent and C–F bond cleavage. This reaction proceeded properly via fluoroarenium intermediates. On the other hand, treatment of the fluoronaphthalenes with γ-Al_2O_3 selectively afforded benzo[*g*]chrysenes via C–C bond formation on the α-carbon atom and C–F bond cleavage.

Scheme 6. Regioswitchable Aromatic C–F Bond Activation



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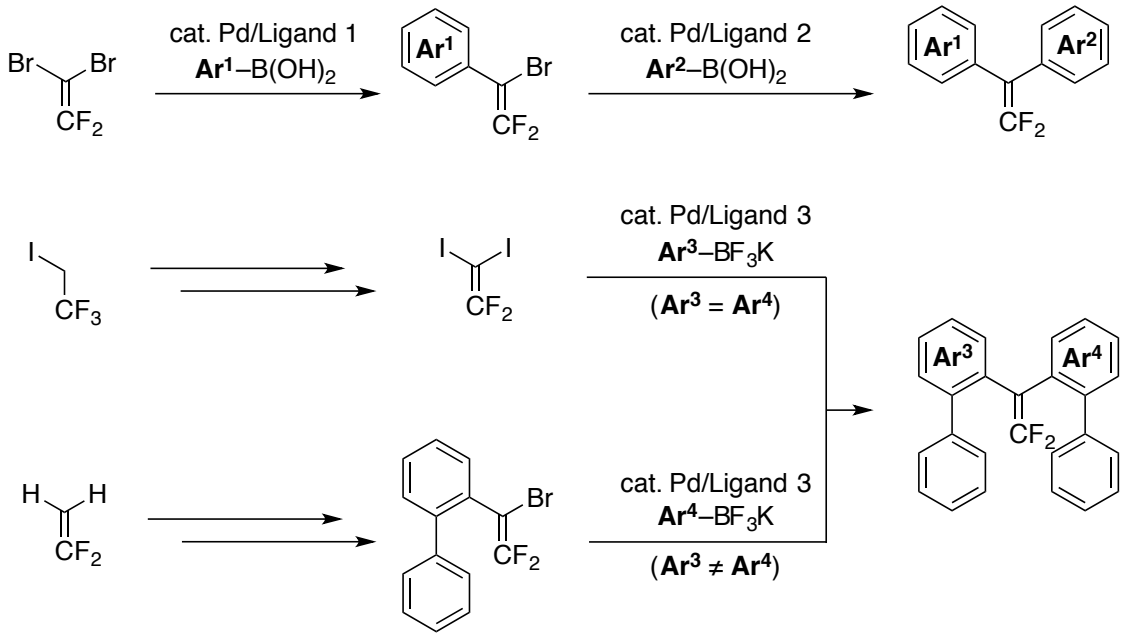
CHAPTER 2

Facile Synthesis of 1,1-Diaryl-2,2-difluoroethenes via Stepwise Coupling of 1,1-Difluoroethene Derivatives

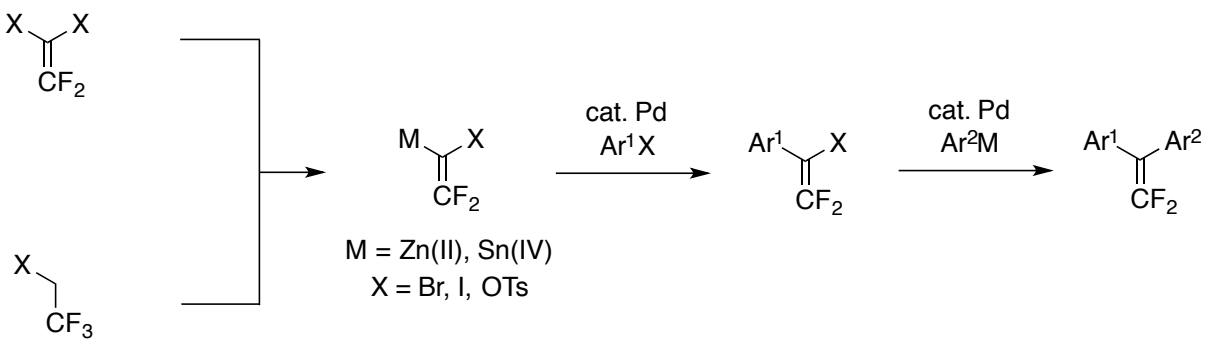
Abstract

1,1-Diaryl-2,2-difluoroethenes were synthesized from 1,1-dibromo-2,2-difluoroethene, 1,1-difluoro-2,2-diiodoethene, and 1,1-difluoroethene via stepwise palladium-catalyzed coupling reactions. The choice of ligands for each coupling process was important to achieve selective synthesis of diaryldifluoroethenes.



2-1. Introduction

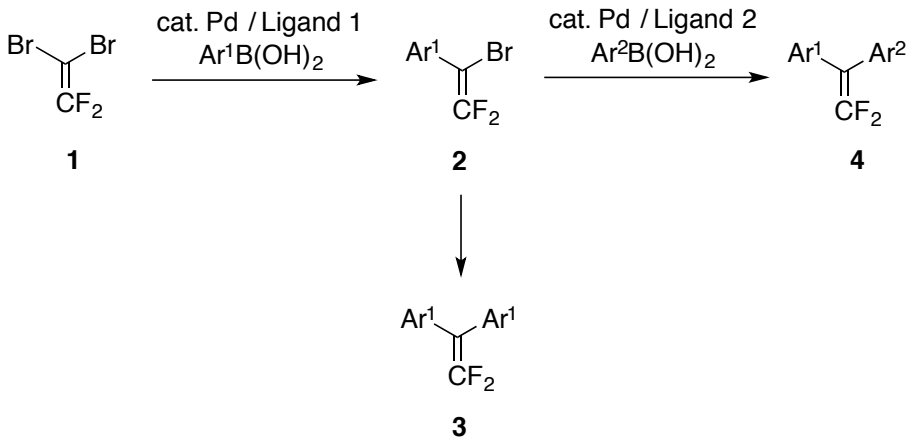
1,1-Diaryl-2,2-difluoroethenes are an important class of fluoroalkenes, because they have the potential to be used for a wide range of purposes, including functional materials and medicines such as photoreceptors,[1] anticancer drugs,[2] and dermatological agents.[3] These compounds are also expected to be bioisosteres of biologically active diarylketones.[4] Additionally, as mentioned in Chapter 1, 1,1-difluoroethenes bearing two biaryl groups might serve as a cyclization precursor via sp^2 C–F bond activation by treatment with acids. Despite their versatility, the supply of 1,1-diaryl-2,2-difluoroethenes has been limited because of difficulties involved in their synthesis (Scheme 1).[5,6] Conventional methods, especially for unsymmetrically disubstituted 1,1-diaryl-2,2-difluoroethenes, mostly required difluorovinylidene species as key intermediates, bearing both a metal functional group and a halogen (or pseudohalogen) substituent at the carbon β to the fluorine substituents.[6] This is due to selective introduction of two different aryl groups. The preparation of such intermediates is unsymmetrical troublesome and requires extra synthetic steps.



Scheme 1. Conventional synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes.

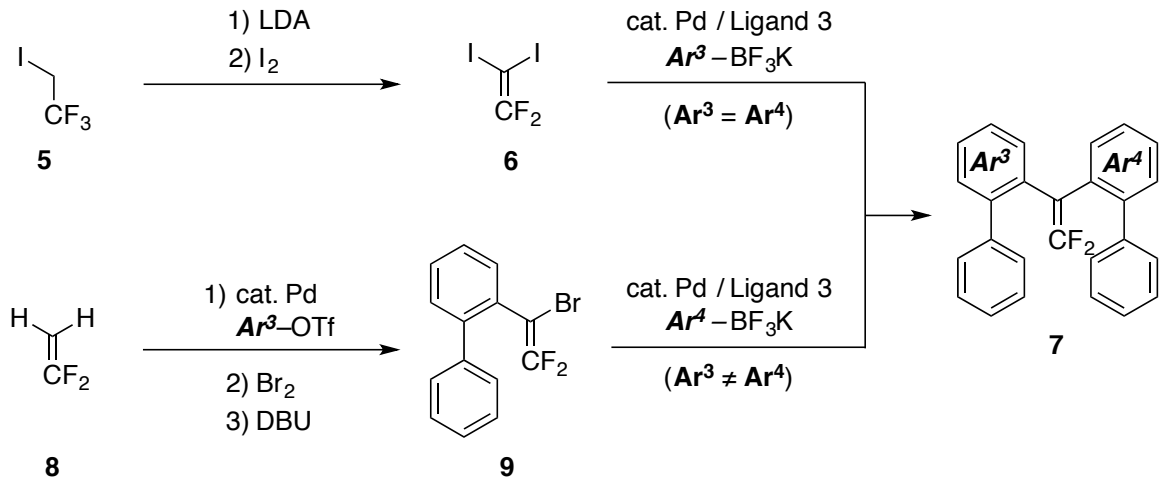
A straightforward synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes might be achieved simply with two reactivity-controlled coupling reactions, starting from 1,1-difluoro-2,2-dihaloethenes. However, there are only few examples of the monoarylation of symmetric 1,1-dihaloethenes,[7] because this type of selective reaction requires steric and/or electronic effects of vinylic substituents.[8] Although the monoarylation of symmetric 1,1-dichloroethenes has been reported, the low reactivities of their chlorine substituents might prevent a second arylation toward diarylated ethenes. Using highly reactive coupling partners of the arylating agents and/or vinyl halides (or pseudohalides) would induce double arylation, leading to undesirable symmetrical byproducts. Therefore, the selective synthesis of unsymmetrically disubstituted 1,1-diaryl-2,2-difluoroethenes is a significant challenge.

To solve these synthetic problems, I sought to find an appropriate ligand for each coupling step, preventing the formation of symmetrical 1,1-diaryl-2,2-difluoroethenes **3**. Eventually, the selective synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes **4** was achieved by choosing ligands to control the reactivities in the first and second arylations of 1,1-dibromo-2,2-difluoroethene (**1**), which was commercially available (Scheme 2).[9]



Scheme 2. Strategy for the synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes **4** via stepwise coupling of 1,1-dibromo-2,2-difluoroethene (**1**).

On the other hand, synthesis of 1,1-diaryl-2,2-difluoroethenes bearing *ortho*-substituted aryl groups was unprecedented probably due to their steric hindrance. To solve this problem, I used the following strategies: (i) the tandem Suzuki–Miyaura coupling of highly reactive 1,1-difluoro-2,2-diiodoethene (**6**) readily prepared from 1,1,1-trifluoro-2-iodoethane (**5**) and (ii) stepwise installation of sterically hindered aryl groups via a sequence of the Negishi/Suzuki–Miyaura couplings starting from 1,1-difluoroethene (**8**). Thus, I achieved the synthesis of symmetrical 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes **7** via the former protocol, while unsymmetrical 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes **7** were successfully synthesized by the latter one (Scheme 3).

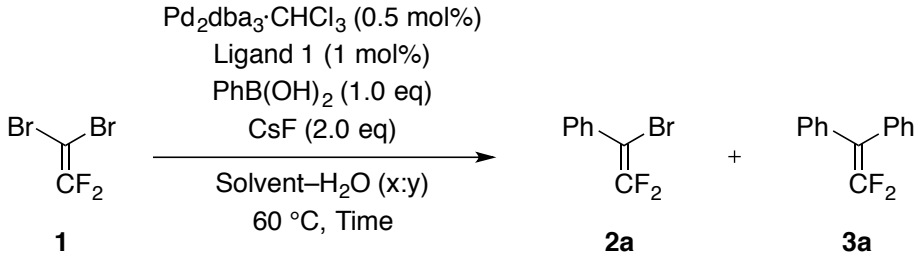


Scheme 3. Strategy for the synthesis of symmetrical and unsymmetrical 1,1-diaryl-2,2-difluoroethenes bearing two biaryl-2-yl groups **7** via coupling of 1,1-difluoroethene derivatives.

2-2. Synthesis of Unsymmetrically Disubstituted 1,1-Diaryl-2,2-difluoroethenes

To synthesize unsymmetrically disubstituted 1,1-diaryl-2,2-difluoroethenes **4**, I first sought suitable conditions for selective monoarylation in the Suzuki–Miyaura coupling between 1,1-dibromo-2,2-difluoroethene (**1**) and phenylboronic acid, using cesium fluoride as a base (Table 1). The choice of ligands used with $Pd_2dba_3 \cdot CHCl_3$ (dba = dibenzylideneacetone) was found to be critical for the yield of the monoarylated product, 1-bromo-1-phenyl-2,2-difluoroethene (**2a**, Entries 1–8). Among the ligands that were screened, 1,1-bis(diphenylphosphino)methane (dppm) gave the highest yield of **2a** (Entry 8), suppressing the formation of the diarylated product **3a**. Co-solvents used with water (Entries 9–14) at different ratios (entries 15–16) were subsequently examined. Ether-solvents typically gave good yields and selectivities of **2a** (Entries 9–11), and dioxane gave the highest yield of **2a** in a short reaction time (Entry 11). Finally, we found that the optimum dioxane/water ratio was 2:1 (Entry 16), which almost exclusively gave bromodifluorostyrene **2a** in 80% yield.

Table 1. Effects of the ligands and solvents used in the first Suzuki–Miyaura coupling

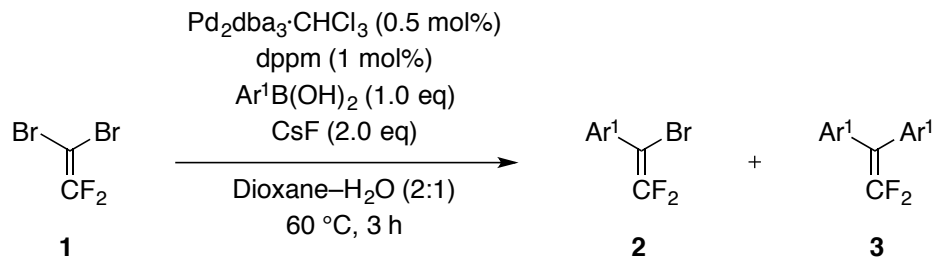


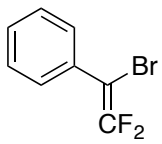
entry	Ligand 1	Solvent (x:y)	Time / h	**2a** / %[a]	**3a** / %[a]
1	PPh_3[b]	THF (4:1)	6	51	Trace
2	P(*t*-Bu)$_3$[b]	THF (4:1)	6	–	–
3	Cy-JohnPhos	THF (4:1)	6	–	–
4	$AsPh_3$[b]	THF (4:1)	6	24	Trace
5	Xantphos	THF (4:1)	6	8	12
6	dppf	THF (4:1)	6	40	1
7	dppb	THF (4:1)	6	14	Trace
8	dppm	THF (4:1)	6	54	Trace
9	dppm	THF (4:1)	3	36	2
10	dppm	DME (4:1)	3	49	1
11	dppm	Dioxane (4:1)	3	70	4
12	dppm	DMF (4:1)	3	10	4
13	dppm	MeCN (4:1)	3	36	4
14	dppm	Toluene (4:1)	3	23	Trace
15	dppm	Dioxane (8:1)	3	53	2
16	dppm	Dioxane (2:1)	3	80	3

[a] ^{19}F NMR yield based on $PhCF_3$. [b] 2 mol%.

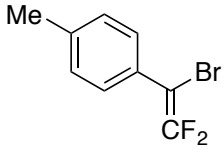
Having the optimal conditions in hand, I investigated the scope of the substrates (Table 2). Monoarylation with several para-functionalized (Me, Ph, OMe, and F) phenylboronic acids was successfully achieved, providing bromodifluorostyrenes **2a**–**2e**. To the best of my knowledge, this is the first example of the selective monoarylation of symmetrical 1,1-dibromoalkenes.

Table 2. Monoarylation of 1,1-dibromo-2,2-difluoroethene (**1**)[a]

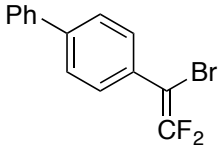




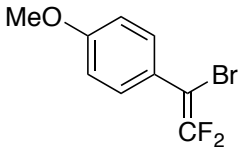
2a 86% (**3a** 3%)



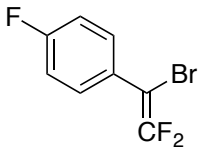
2b 69% (**3b** 3%)



2c 83% (**3c** 4%)



2d 59% (**3d** 5%)

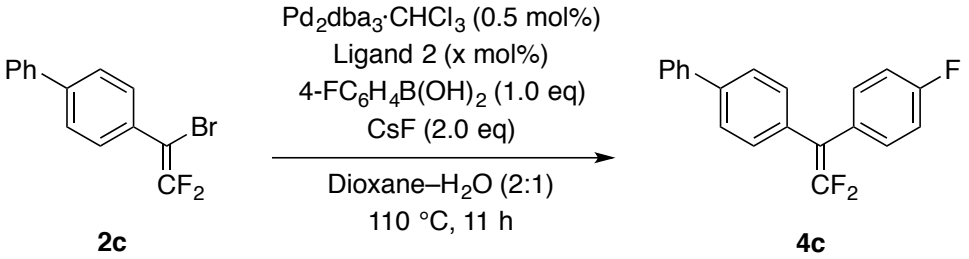


2e, 68% (**3e** 5%)

[a] Isolated yield (^{19}F NMR yield of **3** based on $PhCF_3$ is shown in parentheses).

Next, the ligand used for the second coupling in the synthesis of unsymmetrically disubstituted 1,1-diaryl-2,2-difluoroethenes **4** was examined. The ligands were screened in the Suzuki– Miyaura coupling of monoarylated bromodifluorostyrene **2c** with 4-fluorophenylboronic acid at higher temperatures than in the first step (Table 3). The second coupling proceeded most effectively by using triphenylphosphine, yielding 1,1-diaryl-2,2-difluoroethenes **4c** in 72% yield (Entry 1). The low yield obtained by using dppm indicated that dppm, although highly suitable for the first coupling, significantly suppressed the second coupling (Entry 4).

Table 3. Effects of the ligand in the second Suzuki–Miyaura coupling

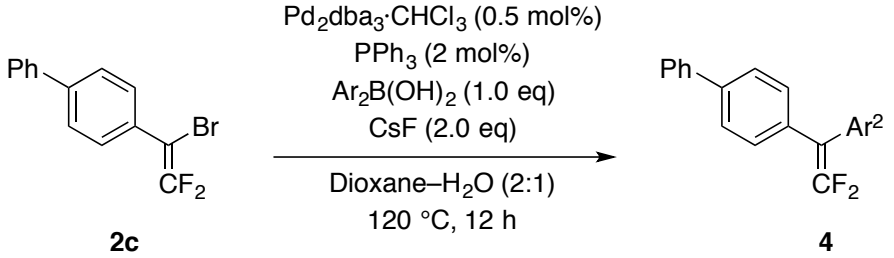


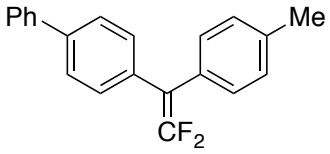
entry	Ligand 2	x / mol%	**4c** / %[a]
1	PPh_3	2	72
2	$AsPh_3$	2	50
3	dppf	1	70
4	dppm	1	27

[a] ^{19}F NMR yield based on $PhCF_3$.

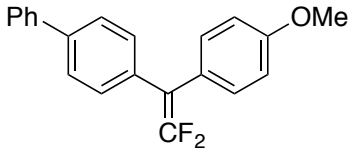
The synthesis of several unsymmetrically disubstituted 1,1-diaryl-2,2-difluoroethenes **4** was examined under the conditions described above (Table 4). Both *para*-substituted (Me, OMe, and F) and *ortho*-substituted (Me) phenylboronic acids readily participated in the reaction to afford the desired difluoroethenes **4a**–**d** in high yields.

Table 4. Synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes **4**[a]

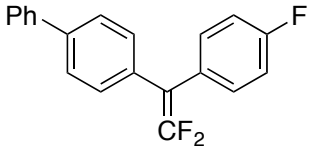




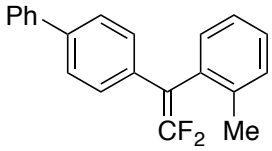
4a 93%



4b 92%



4c 72%

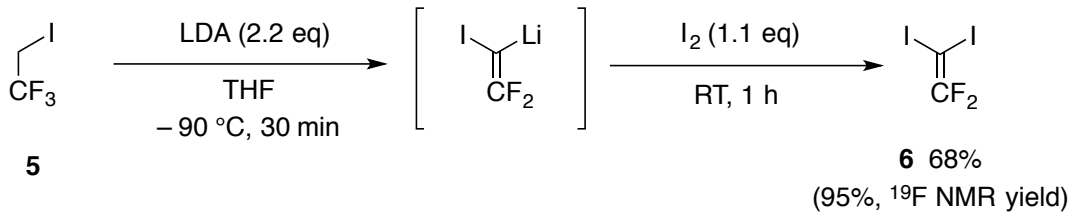


4d 88%

[a] Isolated yield.

2-3. Synthesis of 1,1-Diaryl-2,2-difluoroethenes Bearing Two Sterically-hindered Biaryl-2-yl Groups

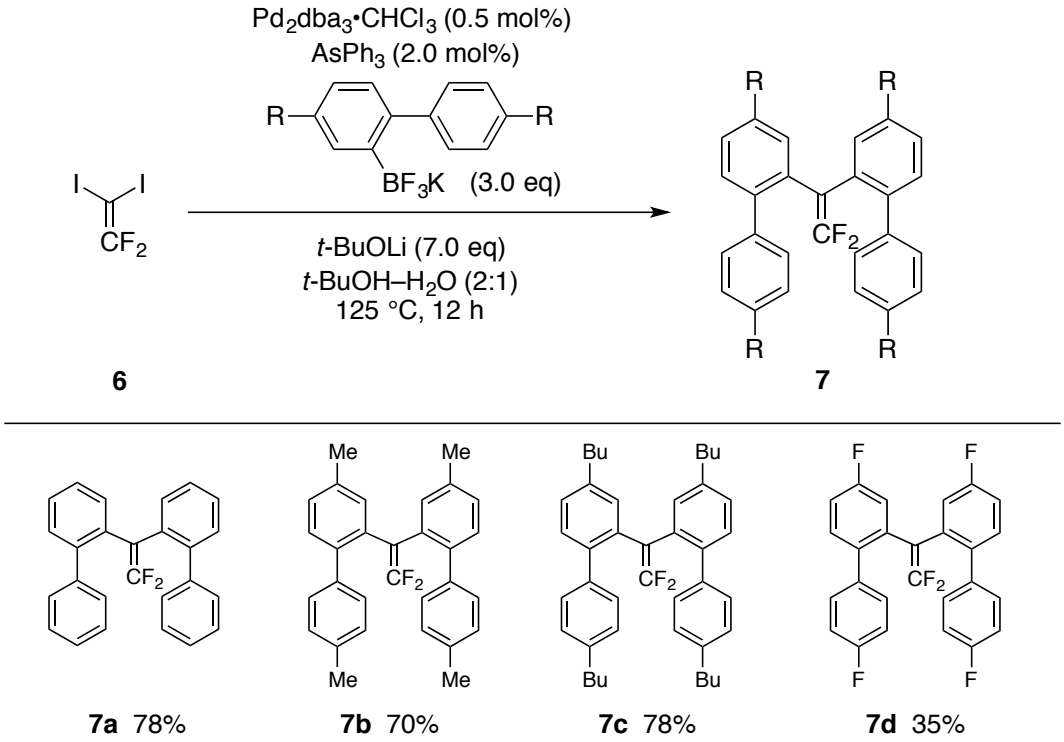
First, I attempted several conditions to synthesize symmetrical 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes **7** from 1,1-dibromo-2,2-difluoroethene (**1**), but the yield of **7** was quite low. Thus, **7** were synthesized via a reactive intermediate, 1,1-difluoro-2,2-diiodoethene (**6**), prepared from 1,1,1-trifluoro-2-iodoethane (**5**) to enhance the reactivity for coupling. Treatment of **5** with 2.2 equiv. of lithium diisopropylamide (LDA) afforded difluoroiodovinylithium through a deprotonation/fluoride elimination/deprotonation sequence. The reaction of the vinylithium with iodine gave the desired 1,1-difluoro-2,2-diiodoethene (**6**) in 68% isolated yield (eq 1).



(1)

Then, I sought optimized condition to synthesize 1,1-bis(biphenyl-2-yl)-2,2-difluoroethene **7a** as a model compound. Finally, in the presence of a catalytic amount of $Pd_2dba_3{\cdot}CHCl_3$ and $AsPh_3$, treatment of **6** obtained above with potassium (biphenyl-2-yl)trifluoroborate afforded **7a** in 78% yield. In this case, triphenylarsine was found to be an effective ligand presumably because of its less electron-donating character whitch might promote the transmetallation step suppressing the hydrolysis of the C–B bond of the potassium aryltrifluoroborate as a result. Similarly, methyl-, butyl-, and fluorine-substituted 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes **7b**–**7d** were obtained in good yields (Table 5).

Table 5. Synthesis of symmetrical 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes **7**[a]



[a] Isolated yield.

In contrast, unsymmetrical 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes were prepared via the Suzuki–Miyaura coupling between (biaryl-2-yl)trifluoroborates and 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**), which was obtained via the Negishi coupling of the 2,2-difluorovinylzinc–TMEDA complex derived from difluoroethene (**8**)[13] and a subsequent dibromination/dehydrobromination sequence of the intermediary difluoroalkene (eq 3).[14] In the presence of a catalytic amount of $Pd_2dba_3{\cdot}CHCl_3$ and $AsPh_3$, treatment of **9** with (biaryl-2-yl)trifluoroborates successfully afforded mono- and disubstituted unsymmetrical 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes **7e–7m** (Table 6).

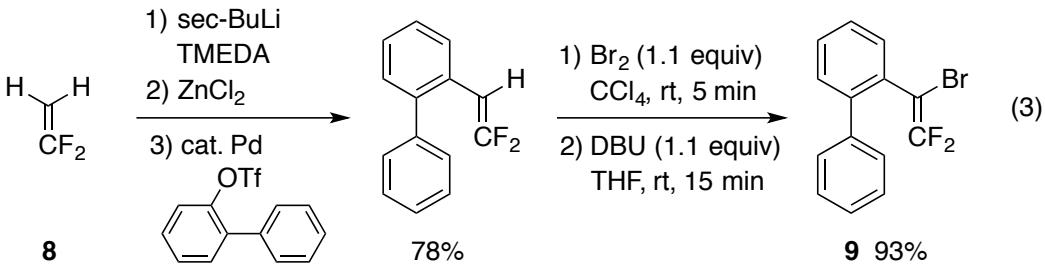
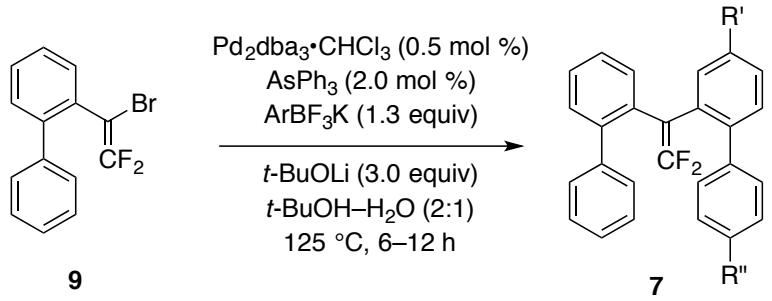
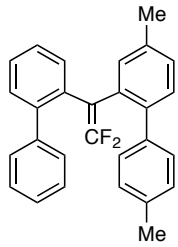
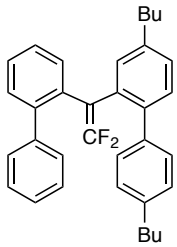


Table 6. Synthesis of unsymmetrical 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes **7**[a]

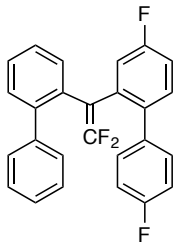




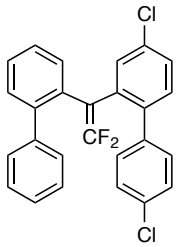
7e 87%



7f 93%



7g 83%



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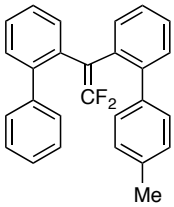
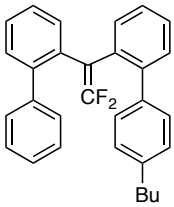
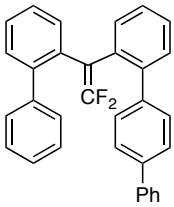


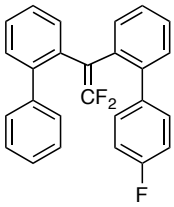
7i 86%



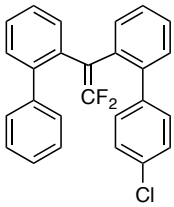
7j 93%



7k 62%



7l 58%



7m 51%

[a] Isolated yield.

2-4. Summary

I synthesized unsymmetrically and symmetrically disubstituted 1,1-diaryl-2,2-difluoroethenes **4** and **7** via stepwise coupling reactions, starting from 1,1-difluoroethene derivatives, such as 1,1-dibromo-2,2-difluoroethene (**1**), 1,1-difluoro-2,2-diiodoethene (**6**) and 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**). The key to success was using the appropriate ligand in each coupling step. These protocols provide versatile methods for synthesizing 1,1-diaryl-2,2-difluoroethenes. It is expected that 1,1-diaryl-2,2-difluoroethenes formed by these methods will act as biologically active compounds and important intermediates for further chemical transformations. In fact, I applied a series of 1,1-bis(biaryl-2-yl)-2,2-difluoroethenes to acid-mediated defluorinative cyclization, leading to material candidates, dibenzo[*g*,*p*]chrysenes in Chapter 3.

2-5. References and Notes

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(9) Although synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes had been reported once by the Suzuki–Miyaura coupling of 1,1-dichloro-2,2-difluoroethene using a water-soluble phosphine ligand, the paper was retracted later, see: Pschierer, J.; Perschek, N.; Plenio, H. *Green Chem.* **2010**, *12*, 636–642. Retraction was endorsed by Sarah Ruthven, Editor, and published on 15th September 2010.

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2-6. Experimental section

General statements

^{1}H NMR, ^{13}C NMR, and ^{19}F NMR spectra were recorded on a Bruker Avance 500 or a JEOL ECS-400 spectrometer. Chemical shift values are given in ppm relative to internal Me_4Si (for ^{1}H NMR: d = 0.00 ppm), $CDCl_3$ (for ^{13}C NMR: d = 77.0 ppm), and C_6F_6 (for ^{19}F NMR: d = 0.00 ppm). IR spectra were recorded on a Horiba FT-300S spectrometer by the attenuated total reflectance (ATR) method. Mass spectra were measured on a JEOL JMS-T100GCV or a JMS-T100CS spectrometer. Elemental analyses were carried out at the Elemental Analysis Laboratory, Division of Chemistry, Faculty of Pure and Applied Sciences, University of Tsukuba.

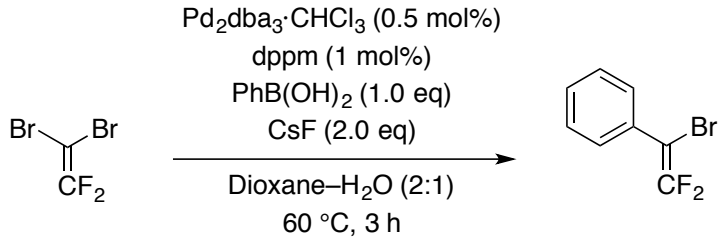
Column chromatography and preparative thin-layer chromatography (PTLC) were conducted on silica gel (Silica Gel 60 N, Kanto Chemical Co., Inc. for column chromatography and Wakogel B-5F, Wako Pure Chemical Industries for PTLC, respectively). All the reactions were conducted under nitrogen. Diethyl ether, tetrahydrofuran (THF) and dichloromethane were purified by a solvent-purification system (GlassContour) equipped with columns of activated alumina and supported-copper catalyst (Q-5) before use. 1,1,1-Trifluoro-2-iodoethane was distilled from CaH_2. 1,1-Dibromo-2,2-difluoroethene, purchased from SynQuest Labs, Inc., was used without further purification. Unless otherwise noted, materials were obtained from commercial sources and used directly without further purification. 2-Bromo-4,4'-dimethylbiphenyl,[1] 2-(2,2-difluorovinyl)biphenyl,[2] 2-bromo-4'-methylbiphenyl,[1] 2-bromo-4'-fluorobiphenyl,[1] and 2-bromo-4'-chlorobiphenyl[1] were prepared according to the literature procedures. Unless otherwise noted, materials were obtained from commercial sources and used directly without further purifications.

Spectral data for compounds **2a**[3,4], **2b**[5], **2d**[5], and **2e**[4] showed good agreement with the literature data. As for compounds **2a**, **2b**, **2d**, and **2e**, we present only NMR data in this section.

Procedure and spectrum

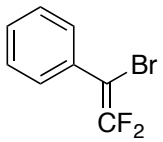
Synthesis of 1-aryl-1-bromo-2,2-difluoroethenes 2

Typical procedure for the synthesis of 1-aryl-1-bromo-2,2-difluoroethenes 2



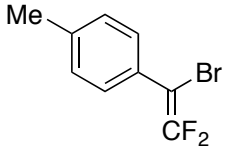
In a pyrex-glass tube were placed phenylboronic acid (61 mg, 0.50 mmol), CsF (152 mg, 1.0 mmol), $Pd_2dba_3{\cdot}CHCl_3$ (2.6 mg, 2.5 mmol), and dppm (1.9 mg, 4.9 mmol). After the tube was purged with nitrogen, a pre-degassed mixed solvent (2.5 mL, 1,4-dioxane/water = 2:1) and 1,1-dibromo-2,2-difluoroethylene (**1**, 48 mL, 0.50 mmol) was added to the tube. After stirring for 3 h at 60 °C, the mixuture was quenched with NH_4Cl aq., and organic materials were extracted with ether three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of solvent under reduced pressure, the residue was purified by column chromatography on silica gel (pentane) to give 2a (95 mg, 86%) as a colorless oil.

1-Bromo-1-phenyl-2,2-difluoroethene (2a)



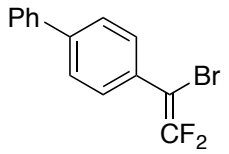
Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.33 (tt, J = 7.3, 1.3 Hz, 1H), 7.39 (dd, J = 7.4, 7.3 Hz, 2H), 7.48–7.51 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 79.9 (dd, J_{CF} = 35, 26 Hz), 128.5, 128.80, 128.84 (d, J_{CF} = 4 Hz) 131.6 (d, J_{CF} = 3 Hz), 153.1 (dd, J_{CF} = 295, 287 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 77.1 (d, J_{FF} = 28 Hz), 83.3 (d, J_{FF} = 28 Hz).

1-Bromo-1-(4-methylphenyl)-2,2-difluoroethene (2b)



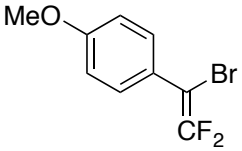
Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ 2.37 (s, 3H), 7.19 (d, J = 7.8 Hz, 2H), 7.37 (d, J = 7.8 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.2, 79.9 (dd, J_{CF} = 35, 26 Hz), 128.7 (dd, J_{CF} = 4, 4 Hz), 129.2, 130.8 (dd, J_{CF} = 4, 4 Hz), 139.0, 153.0 (dd, J_{CF} = 294, 286 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 76.5 (d, J_{FF} = 32 Hz), 82.6 (d, J_{FF} = 32 Hz).

1-(Biphenyl-4-yl)-1-bromo-2,2-difluoroethene (2c)



White solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.30 (tt, J = 7.3, 1.3 Hz, 1H), 7.38 (dd, J = 7.7, 7.7 Hz, 2H), 7.49–7.55 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 79.8 (dd, J_{CF} = 34, 26 Hz), 127.1, 127.2, 127.8, 128.9, 129.2 (dd, J_{CF} = 4, 4 Hz), 130.5 (d, J_{CF} = 4 Hz), 140.1, 141.7, 153.2 (dd, J_{CF} = 295, 287 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 77.5 (d, J_{FF} = 30 Hz), 83.8 (d, J_{FF} = 30 Hz). IR (neat): $\tilde{n}$ = 1709, 1290, 984, 841, 764, 692 cm^{-1}. HRMS (EI): m/z calcd. for $C_{14}H_9{}^{79}BrF_2$ $[M]^+$: 293.9856; Found: 293.9863.

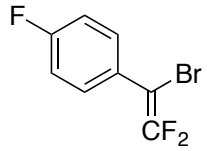
1-Bromo-2,2-difluoro-1-(4-methoxyphenyl)ethene (2d)



Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) : δ 3.83 (s, 3H), 6.90 (d, J = 9.0 Hz, 2H), 7.41 (d, J = 9.0 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 55.5, 79.6 (dd, J_{CF} = 35, 26 Hz), 113.9, 123.8 (d, J_{CF} = 3 Hz), 130.2 (dd, J_{CF} = 3, 3 Hz), 152.8 (dd, J_{CF} = 293, 286 Hz), 159.9. ^{19}F NMR (470 MHz, $CDCl_3$):

δ 75.7 (d, J_{FF} = 36 Hz), 81.9 (d, J_{FF} = 36 Hz).

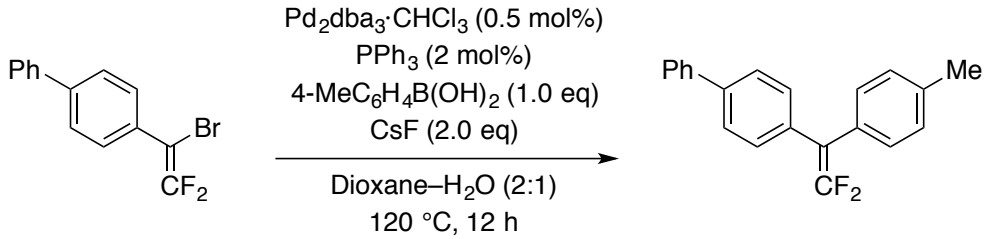
1-Bromo-2,2-difluoro-1-(4-fluorophenyl)ethene (2e)



Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.08 (dd, J = 8.7, 8.7 Hz, 2H), 7.45–7.49 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 78.8 (dd, J_{CF} = 35, 27 Hz), 115.6 (d, J_{CF} = 22 Hz), 127.7 (dd, J_{CF} = 3 Hz), 130.8 (ddd, J = 9, 3, 3 Hz), 153.1 (dd, J_{CF} = 294, 287 Hz), 162.7 (d, J_{CF} = 250 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 49.9–50.0 (m), 76.9 (d, J_{FF} = 31 Hz), 83.2 (d, J_{FF} = 31 Hz).

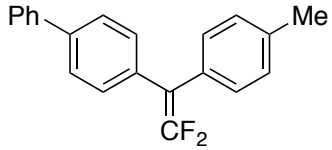
Synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes 4

Typical procedure for the synthesis of 1,1-diaryl-2,2-difluoroethenes 4



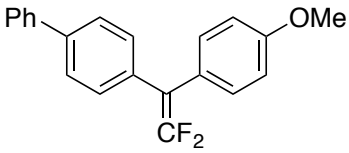
In a pyrex-glass tube were placed 1-bromo-1-(biphenyl-4-yl)-2,2-difluoroethene (**2c**, 89 mg, 0.30 mmol), 4-methylphenylboronic acid (45 mg, 0.33 mmol), CsF (91 mg, 0.60 mmol), $Pd_2dba_3{\cdot}CHCl_3$ (1.6 mg, 1.5 mmol), and PPh_3 (1.6 mg, 6.1 mmol). After the tube was purged with nitrogen, a pre-degassed mixed solvent (3.0 mL, 1,4-dioxane/water = 2:1) was added to the tube. After stirring for 12 h at 120 °C, the mixuture was quenched with NH_4Cl aq., and organic materials were extracted with ether three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of solvent under reduced pressure, the residue was purified by column chromatography on silica gel (hexane/EtOAc = 50:1) to give **4a** (86 mg, 93%) as a colorless oil.

1-(Biphenyl-4-yl)-2,2-difluoro-1-(4-methylphenyl)ethene (4a)



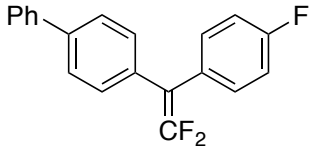
White solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ 2.40 (s, 3H), 7.19 (s, 4H), 7.33–7.37 (m, 3H), 7.44 (dd, J = 7.7, 7.7 Hz, 2H), 7.57 (d, J = 8.4 Hz, 2H), 7.60 (d, J = 7.1 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.4, 96.0 (dd, J_{CF} = 18, 18 Hz), 127.20, 127.20, 127.6, 129.0, 129.3, 129.8 (dd, J_{CF} = 3, 3 Hz), 130.1 (dd, J_{CF} = 3, 3 Hz), 131.4 (dd, J_{CF} = 3, 3 Hz), 133.7 (dd, J_{CF} = 4, 4 Hz), 137.6, 140.4, 140.7, 153.9 (dd, J_{CF} = 294, 294 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.7 (d, J_{FF} = 33 Hz), 74.1 (d, J_{FF} = 33 Hz). IR (neat): ν 2924, 1699, 1242, 982, 820, 766, 692 cm^{-1}. HRMS (EI): *m*/*z* calcd. for $C_{21}H_{16}F_2$ [M]$^{+}$: 306.1220; Found: 306.1217.

1-(Bipnenyl-4-yl)-2,2-difluoro-1-(4-methoxyphenyl)ethene (4b)



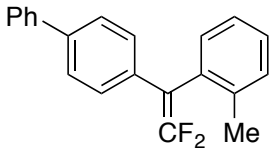
White solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ 3.83 (s, 3H), 6.91 (d, J = 9.1 Hz, 2H), 7.23 (d, J = 9.1 Hz, 2H), 7.33–7.39 (m, 3H), 7.45 (dd, J = 7.6, 7.6 Hz, 2H), 7.57 (d, J = 8.4 Hz, 2H), 7.60 (d, J = 8.4 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 55.4, 95.6 (dd, J_{CF} = 19, 19 Hz), 114.0, 126.5 (dd, J_{CF} = 4, 4 Hz), 127.16, 127.16, 127.6, 128.9, 130.0 (dd, J_{CF} = 3, 3 Hz), 131.0 (dd, J_{CF} = 3, 3 Hz), 133.7 (dd, J_{CF} = 4, 4 Hz), 140.4, 140.7, 153.8 (dd, J_{CF} = 293, 293 Hz), 159.1. ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.2 (d, J_{FF} = 33 Hz), 73.6 (d, J_{FF} = 33 Hz). IR (neat): ν 2960, 1699, 1512, 1246, 1178, 984, 835, 766 cm^{-1}. HRMS (EI): *m*/*z* calcd. for $C_{21}H_{16}F_2O$ [M]$^{+}$: 322.1169; Found: 322.1169.

1-(Bipnenyl-4-yl)-2,2-difluoro-1-(4-fluorophenyl)ethene (4c)



White solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.07 (dd, J = 8.7, 8.7 Hz, 2H), 7.28, (dd, J = 8.9, 1.0 Hz, 2H), 7.32 (dd, J = 8.5, 1.2 Hz, 2H), 7.36 (tt, J = 7.4, 1.2 Hz, 1H), 7.45 (dd, J = 7.6, 7.6 Hz, 2H), 7.57–7.61 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 95.2 (dd, J_{CF} = 19, 19 Hz), 115.5 (d, J = 22 Hz), 127.0, 127.1, 127.5, 128.8, 129.8 (dd, J_{CF} = 3, 3 Hz), 130.1 (dd, J_{CF} = 3, 3 Hz), 131.4 (ddd, J_{CF} = 8, 8, 3 Hz), 133.1 (dd, J_{CF} = 3, 3 Hz), 140.4, 140.5, 153.8 (dd, J_{CF} = 294, 294 Hz), 162.1 (d, J_{CF} = 248 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 47.7–47.6 (m), 74.2 (d, J_{FF} = 32 Hz), 74.3 (d, J_{FF} = 32 Hz). IR (neat): ν 1707, 1508, 1247, 987, 835 cm^{-1}. HRMS (EI): m/z calcd. for $C_{20}H_{13}F_3$ [M]$^+$: 310.0969; Found: 310.0965.

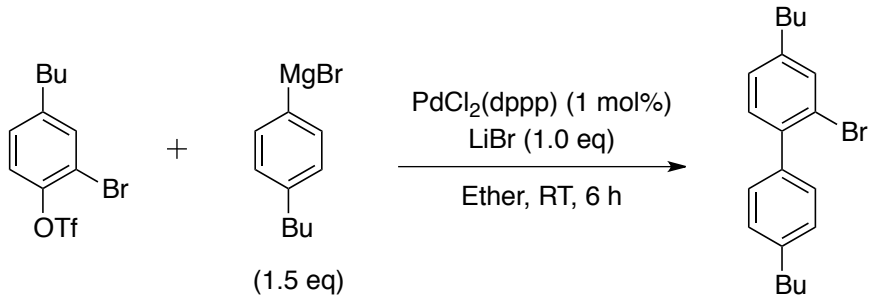
1-(Bipnenyl-4-yl)-2,2-difluoro-1-(2-methylphenyl)ethene (4d)



White solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ 2.19 (s, 3H), 7.25–7.29 (m, 6H), 7.34 (t, J = 7.4 Hz, 1H), 7.43 (dd, J = 7.7, 7.7 Hz, 2H), 7.54 (d, J = 8.4 Hz, 2H), 7.57 (d, J = 8.2 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 19.6, 94.5 (dd, J_{CF} = 23, 15 Hz), 126.1, 127.0, 127.1, 127.4, 128.4, 128.5 (dd, J_{CF} = 6, 3 Hz), 128.8, 130.5, 131.0 (dd, J_{CF} = 2, 2 Hz), 132.8 (d, J_{CF} = 4 Hz), 132.9 (d, J_{CF} = 4 Hz), 137.7 (d, J_{CF} = 3 Hz), 139.8, 140.5, 153.4 (dd, J_{CF} = 299, 288 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.1 (d, J_{FF} = 31 Hz), 78.2 (d, J_{FF} = 31 Hz). IR (neat): ν 1705, 1487, 1244, 984, 841, 764, 696 cm^{-1}. HRMS (EI): m/z calcd. for $C_{21}H_{16}F_2$ [M]$^+$: 306.1220; Found: 306.1207.

Preparation of 2-bromobiaryl compounds

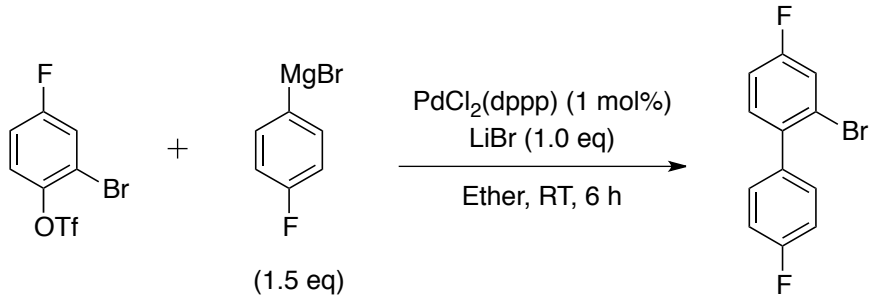
2-Bromo-4,4'-dibutylbiphenyl



To a diethyl ether (5.0 mL) solution of $PdCl_2$(dppp) (59 mg, 0.10 mmol), LiBr (869 mg, 10.0 mmol), and 2-bromo-4-butylphenyl trifluoromethanesulfonate (3.61 g, 10.0 mmol) was added 4-butylphenylmagnesium bromide in diethyl ether [prepared from 1-bromo-4-butylbenzene (2.57 mL, 15.0 mmol) and magnesium (383 mg, 15.8 mmol)]. After stirring for 6 h, the reaction was quenched with aqueous HCl (2 M) at 0 °C, and organic materials were extracted with ether three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane) to give 2-bromo-4,4'-dibutylbiphenyl (2.70 g, 78%) as a colorless liquid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.93–0.97 (m, 6H), 1.35–1.44 (m, 4H), 1.60–1.68 (m, 4H), 2.62 (t, *J* = 7.8 Hz, 2H), 2.66 (t, *J* = 7.9 Hz, 2H), 7.15 (d, *J* = 7.8 Hz, 1H), 7.22–7.23 (m, 3H), 7.32 (*J* = 8.1 Hz, 2H), 7.48 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 13.9, 14.0, 22.3, 22.5, 33.4, 33.5, 34.9, 35.4, 122.4, 127.5, 127.9, 129.3, 131.1, 132.9, 138.3, 139.7, 142.1, 143.7. IR (neat): ν 2956, 2929, 2871, 2858, 1481, 1213, 1144, 825 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{20}H_{25}{}^{79}Br$ $[M]^+$: 344.1140; Found: 344.1125.

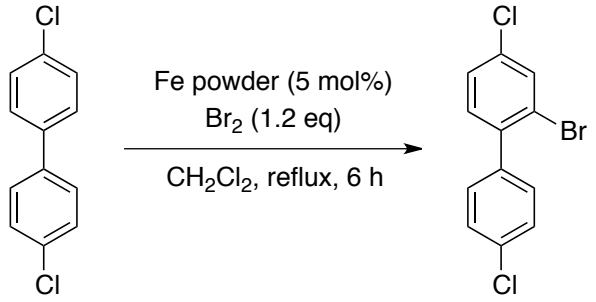
2-Bromo-4,4'-difluorobiphenyl



2-Bromo-4,4'-difluorobiphenyl was prepared by the method described for 2-bromo-4,4'-dibutylbiphenyl using $PdCl_2$(dppp) (156 mg, 0.26 mmol), LiBr (2.29 g, 26.4 mmol), 2-bromo-4-fluorophenyl trifluoromethanesulfonate (8.53 g, 26.4 mmol), 4-fluorophenylmagnesium bromide in diethyl ether, [prepared from 1-bromo-4-fluorobenzene (4.32 mL, 39.5 mmol) and magnesium (1.01 g, 41.6 mmol)], and diethyl ether (15 mL). Purification by silica gel column chromatography (hexane) gave 2-bromo-4,4'-difluorobiphenyl (4.41 g, 62%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.06–7.14 (m, 3H), 7.28 (dd, J_{HF} = 8.5 Hz, J = 6.1 Hz, 1H), 7.34 (dd, J = 8.8 Hz, J_{HF} = 5.3 Hz, 2H), 7.41 (dd, J_{HF} = 8.5 Hz, J = 2.6 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 114.6 (d, J_{CF} = 21 Hz), 115.0 (d, J_{CF} = 22 Hz), 120.2 (d, J_{CF} = 24 Hz), 122.8 (d, J_{CF} = 10 Hz), 131.1 (d, J_{CF} = 8 Hz), 132.0 (d, J_{CF} = 8 Hz), 136.1 (d, J_{CF} = 3 Hz), 137.8 (d, J_{CF} = 4 Hz), 161.6 (d, J_{CF} = 251 Hz), 162.4 (d, J_{CF} = 248 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 47.4 (tt, J_{FH} = 9, 5 Hz, 1F), 48.5–48.6 (m, 1F). IR (neat): ν 3043, 2924, 2846, 1599, 1498, 1479, 1236, 1159, 822, 764 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{12}H_7{}^{79}BrF_2$ $[M]^+$: 267.9699; Found: 267.9699.

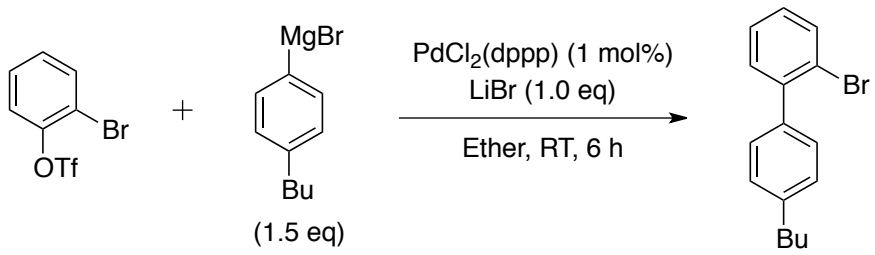
2-Bromo-4,4'-dichlorobiphenyl



To a dichloromethane (100 mL) solution of 4,4'-dichlorobiphenyl (2.23 g, 10.0 mmol) and $FeCl_3$ (81 mg, 0.50 mmol) was added bromine (615 mL, 12.0 mmol). After the reaction mixture was refluxed for 6 h, the reaction was quenched with saturated aqueous $Na_2S_2O_3$, and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane) to give 2-bromo-4,4'-dichlorobiphenyl (2.98 g, 99%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.23 (d, J = 8.2 Hz, 1H), 7.31 (d, J = 8.5 Hz, 2H), 7.35 (dd, J = 8.2, 2.1 Hz, 1H), 7.41 (d, J = 8.5 Hz, 2H), 7.69 (d, J = 2.1 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 122.9, 127.8, 128.4, 130.6, 131.7, 132.8, 134.07, 134.14, 138.3, 139.9. IR (neat): ν 3059, 3030, 1464, 1092, 1005, 814 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{12}H_7{}^{79}BrCl_2$ $[M]^+$: 299.9108; Found: 299.9098.

2-Bromo-4'-butylbiphenyl

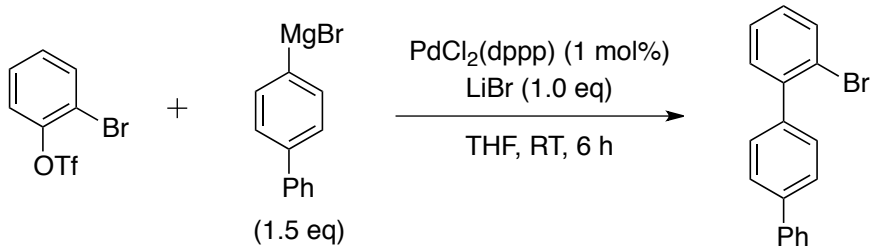


2-Bromo-4,4'-difluorobiphenyl was prepared by the method described for

2-bromo-4,4'-dibutylbiphenyl using $PdCl_2$(dppp) (59 mg, 0.10 mmol), LiBr (869 mg, 10.0 mmol), 2-bromophenyl trifluoromethanesulfonate (3.05 g, 10.0 mmol), 4-butylphenylmagnesium bromide in diethyl ether [prepared from 1-bromo-4-butylbenzene (2.57 mL, 15.0 mmol) and magnesium (383 mg, 15.8 mmol)], and diethyl ether (5 mL). Purification by silica gel column chromatography (hexane) gave 2-bromo-4'-butylbiphenyl (2.37 g, 82%) as a colorless liquid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.96 (t, J = 7.4 Hz, 3H), 1.37–1.44 (m, 2H), 1.62–1.69 (m, 2H), 2.67 (t, J = 7.8 Hz, 2H), 7.18 (ddd, J = 8.0, 6.6, 2.5 Hz, 1H), 7.24 (d, J = 8.1 Hz, 2H), 7.32–7.36 (m, 4H), 7.66 (d, J = 7.6 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 14.0, 22.5, 33.5, 35.4, 122.7, 127.3, 128.0, 128.5, 129.2, 132.3, 133.1, 138.3, 142.3, 142.6. IR (neat): ν 2954, 2927, 2870, 2856, 1466, 1435, 1024, 1005, 835, 756 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{16}H_{17}{}^{79}Br$ $[M]^+$: 288.0514; Found: 288.0503.

2-Bromo-1,1':4',1''-terphenyl



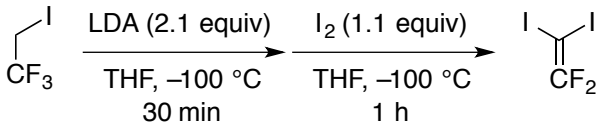
2-Bromo-1,1':4',1''-terphenyl was prepared by the method described for 2-bromo-4,4'-dibutylbiphenyl using $PdCl_2$(dppp) (30 mg, 0.050 mmol), LiBr (434 mg, 5.00 mmol), 2-bromophenyl trifluoromethanesulfonate (1.53 g, 5.02 mmol), biphenyl-4-ylmagnesium bromide in THF [prepared from 4-bromobiphenyl (1.75 g, 7.51 mmol) and magnesium (191 mg, 7.9 mmol)], and THF (15 mL). Purification by silica gel column chromatography (hexane/EtOAc = 30:1) gave 2-bromo-1,1':4',1''-terphenyl (1.05 g, 68%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.20–7.24 (m, 1H), 7.35–7.38 (m, 3H), 7.45–7.48 (m, 3H), 7.50 (d,

J = 7.9 Hz, 2H), 7.64–7.70 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 122.5, 126.6, 127.1, 127.3, 127.4, 128.70, 128.73, 129.8, 131.3, 133.1, 139.9, 140.3, 140.6, 142.1. IR (neat): ν 3059, 3030, 1464, 1026, 1003, 839, 768, 752, 733, 696 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{18}H_{13}{}^{79}Br$ $[M]^+$: 308.0201; Found: 308.0191.

Preparation of symmetrically substituted difluoroethenes 7a–7d

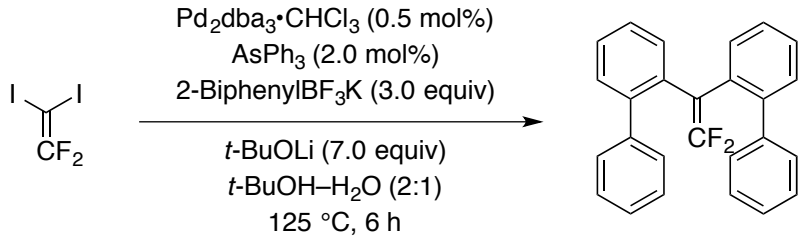
1,1-Difluoro-2,2-diiodoethene (6)[6]



To a THF (20 mL) solution of CF_3CH_2I (**5**, 1.97 mL, 20.0 mmol) was added lithium diisopropylamide (42.0 mL, 1.0 M in THF/hexane, 42 mmol) at –100 °C. After stirring at the same temperature for 30 min, a THF (10 mL) solution of I_2 (5.33 g, 21.0 mmol) was added to the reaction mixture. The mixture was stirred at –100 °C for another 1 h, and then warmed to room temperature. The reaction was quenched with saturated aqueous NH_4Cl, and organic materials were extracted with ether three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure (> 150 hPa), the residue was purified by silica gel column chromatography (pentane) to give **6** (4.63 g, 73%) as a pale yellow liquid.

^{13}C NMR (126 MHz, $CDCl_3$): δ –39.0 (t, J_{CF} = 25 Hz), 151.7 (t, J_{CF} = 293 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 97.8 (s, 2F). IR (neat): ν 2958, 2926, 2856, 1730, 1482, 1288, 1122, 1074 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_2F_2I_2$ $[M]^+$: 315.8057; Found: 315.8048.

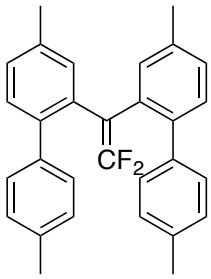
1,1-Bis(biphenyl-2-yl)-2,2-difluoroethene (7a)



Potassium (biphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromobiphenyl and was used without further purification. In a Schlenk tube were placed 1,1-difluoro-2,2-diiodoethene (**6**, 63 mg, 0.20 mmol), potassium (biphenyl-2-yl)trifluoroborate (156 mg, 0.60 mmol), *t*-BuOLi (112 mg, 1.4 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.0 mg, 0.97 mmol), and $AsPh_3$ (1.2 mg, 3.9 mmol). To the mixture was added a degassed mixture of *t*-BuOH (0.67 mL) and water (0.33 mL). After stirring at 125 °C for 6 h, saturated aqueous NH_4Cl was added to the reaction mixture, and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 40:1) to give **7a** (58 mg, 78%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.57 (d, J = 7.7 Hz, 2H), 6.90 (dddd, J = 7.7, 7.7, 3.5, 1.6 Hz, 2H), 7.00–7.03 (m, 4H), 7.07 (ddd, J = 7.4, 3.2, 1.3 Hz, 2H), 7.13 (dddd, J = 7.7, 7.7, 3.5, 1.3 Hz, 2H), 7.20–7.22 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 95.0 (t, J_{CF} = 21 Hz), 126.5, 126.8, 127.2, 127.8, 128.6, 129.8, 131.4, 132.4, 141.6, 142.1, 153.5 (t, J_{CF} = 292 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.4 (s, 2F). IR (neat): ν 3734, 1716, 1684, 1219, 771, 669 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{26}H_{18}F_2$ $[M]^+$: 368.1377; Found: 368.1386.

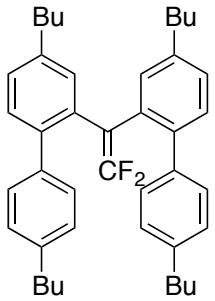
1,1-Bis(4,4'-dimethylbiphenyl-2-yl)-2,2-difluoroethene (7b)



Potassium (4,4'-dimethylbiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4,4'-dimethylbiphenyl and was used without further purification. Difluoroethene **7b** was prepared by the method described for **7a** using 1,1-difluoro-2,2-diiodoethene (**6**, 316 mg, 1.00 mmol), potassium (4,4'-dimethylbiphenyl-2-yl)trifluoroborate (864 mg, 3.00 mmol), *t*-BuOLi (560 mg, 7.00 mmol), $Pd_2dba_3 \cdot CHCl_3$ (5.2 mg, 5.0 mmol), and $AsPh_3$ (6.2 mg, 20 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 25:1) gave difluoroethene **7b** (297 mg, 70%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.06 (s, 6H), 2.36 (s, 6H), 6.21 (s, 2H), 6.86–6.94 (m, 8H), 7.03 (d, J = 7.7 Hz, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 20.6, 21.1, 95.2 (t, J_{CF} = 21 Hz), 127.7, 128.3, 128.8, 129.4, 132.1, 132.2, 135.7, 136.0, 138.7, 139.2, 153.6 (t, J_{CF} = 288 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 72.1 (s, 2F). IR (neat): ν 3022, 2922, 1718, 1487, 1244, 810 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{30}H_{26}F_2$ $[M]^+$: 424.2003; Found: 424.2001.

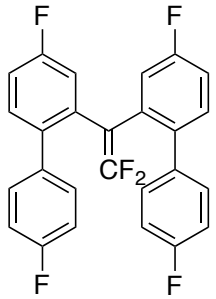
1,1-Bis(4,4'-dibutylbiphenyl-2-yl)-2,2-difluoroethene (7c)



Potassium (4,4'-dibutylbiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4,4'-dibutylbiphenyl and was used without further purification. Difluoroethene **7c** was prepared by the method described for **7a** using 1,1-difluoro-2,2-diiodoethene (**6**, 63 mg, 0.20 mmol), potassium (4,4'-dibutylbiphenyl-2-yl)trifluoroborate (224 mg, 0.602 mmol), *t*-BuOLi (114 mg, 1.4 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.0 mg, 0.97 mmol), and $AsPh_3$ (1.2 mg, 3.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 40:1) gave difluoroethene **7c** (93 mg, 78%) as a yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.93 (t, J = 7.5 Hz, 6H), 0.97 (t, J = 7.5 Hz, 6H), 1.28–1.35 (m, 4H), 1.38–1.45 (m, 8H), 1.62–1.68 (m, 4H), 2.31 (t, J = 7.7 Hz, 4H), 2.63 (t, J = 7.8 Hz, 4H), 6.19 (s, 2H), 6.95 (dd, J = 7.8, 1.8 Hz, 2H), 6.99–7.03 (m, 6H), 7.10 (d, J = 8.1 Hz, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 13.96, 13.99, 22.55, 22.58, 33.2, 33.6, 35.0, 35.4, 94.7 (t, J_{CF} = 21 Hz), 127.2, 127.8, 128.8, 129.8, 131.2, 132.0, 139.0, 139.4, 140.9, 141.2, 153.5 (t, J_{CF} = 290 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.2 (s, 2F). IR (neat): ν 2956, 2927, 2858, 1716, 1485, 1246, 1001, 823 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{42}H_{51}F_2$ $[M+H]^+$: 593.3959; Found: 593.3943.

1,1-Bis(4,4'-difluorobiphenyl-2-yl)-2,2-difluoroethene (7d)

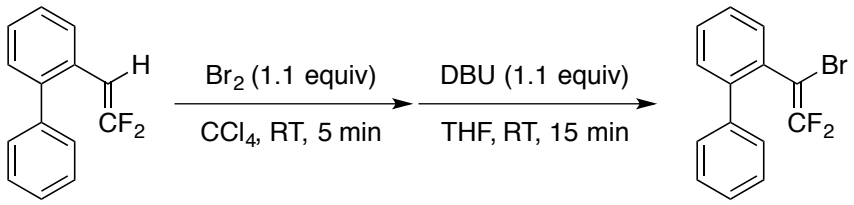


Potassium (4,4'-difluorobiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4,4'-difluorobiphenyl and was used without further purification. Difluoroethene **7d** was prepared by the method described for **7a** using 1,1-difluoro-2,2-diiodoethene (**6**, 158 mg, 0.50 mmol), potassium (4,4'-difluorobiphenyl-2-yl)trifluoroborate (444 mg, 1.50 mmol), *t*-BuOLi (280 mg, 3.50 mmol), $Pd_2dba_3 \cdot CHCl_3$ (2.6 mg, 2.5 mmol), and $AsPh_3$ (3.1 mg, 10 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 30:1) gave difluoroethene **7d** (76 mg, 35%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.26 (dd, J_{HF} = 9.7 Hz, J = 3.0 Hz, 2H), 6.83–6.88 (m, 6H), 6.91–6.94 (m, 4H), 6.99 (dd, J = 8.5 Hz, J_{HF} = 6.0 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 94.3 (t, J_{CF} = 21 Hz), 114.6 (d, J_{CF} = 21 Hz), 114.9 (d, J_{CF} = 22 Hz), 118.2 (ddd, J_{CF} = 23, 3, 3 Hz), 130.2 (d, J_{CF} = 8 Hz), 131.3 (d, J_{CF} = 8 Hz), 133.8 (d, J_{CF} = 8 Hz), 136.3 (d, J_{CF} = 3 Hz), 137.0, 154.2 (t, J_{CF} = 294 Hz), 161.3 (d, J_{CF} = 248 Hz), 162.2 (d, J_{CF} = 248 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 45.3–45.4 (m, 2F), 46.58–46.64 (m, 2F), 74.9 (s, 2F). IR (neat): ν 3041, 1716, 1602, 1483, 1255, 1225, 1157, 1003, 824, 669, 521 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{26}H_{14}F_6$ $[M]^+$: 440.1000; Found: 440.0984.

Preparation of unsymmetrically substituted difluoroethenes 7e–7m

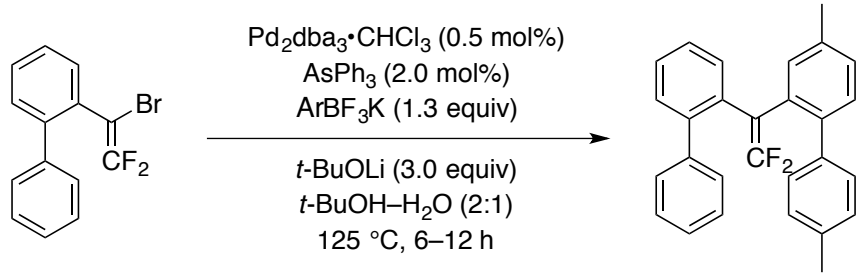
1-(Biphenyl-2-yl)-1-bromo-2,2-difluoroethene (9)[8]



To a CCl_4 (45 mL) solution of 2-(2,2-difluorovinyl)biphenyl[2] (4.83 g, 22.3 mmol) was added bromine (1.21 mL, 23.6 mmol) at room temperature. After stirring for 5 min, the solvent was removed under reduced pressure. To the residue were added THF (45 mL) and DBU (3.71 mL, 24.8 mmol) at room temperature. After stirring for 15 min, the reaction was quenched with water, and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane) to give **9** (6.18 g, 93%) as a colorless liquid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.35–7.39 (m, 5H), 7.40–7.41 (m, 1H), 7.42–7.46 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 77.6 (dd, J_{CF} = 40, 27 Hz), 127.5, 127.6, 128.2, 128.5, 129.9, 130.1, 130.4, 131.2 (dd, J_{CF} = 4, 2 Hz), 140.2, 142.7, 152.5 (dd, J_{CF} = 291, 288 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 78.1 (d, J_{FF} = 30 Hz, 1F), 79.4 (d, J_{FF} = 30 Hz, 1F). IR (neat): ν 3059, 3026, 1732, 1477, 1281, 1227, 987, 916, 758, 700 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{14}H_9{}^{79}BrF_2$ $[M]^+$: 293.9856; Found: 293.9856.

1-(Biphenyl-2-yl)-1-(4,4'-dimethylbiphenyl-2-yl)-2,2-difluoroethene (7e)

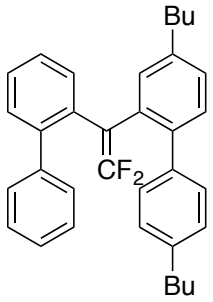


Ar = 4,4'-dimethylbiphenyl-2-yl

Potassium (4,4'-dimethylbiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[6] starting from 2-bromo-4,4'-dimehylbiphenyl and was used without further purification. In a Schlenk tube were placed 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (4,4'-dimethylbiphenyl-2-yl)trifluoroborate (112 mg, 0.39 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). To the mixture was added a degassed mixture of *t*-BuOH (1.0 mL) and water (0.50 mL). After stirring at 125 °C for 6 h, saturated aqueous NH_4Cl was added to the reaction mixture at room temperature, and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 50:1) to give **7e** (104 mg, 87%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.08 (s, 3H), 2.35 (s, 3H), 6.29 (s, 1H), 6.56 (d, J = 7.8 Hz, 1H), 6.89–6.96 (m, 5H), 7.01–7.03 (m, 4H), 7.07 (dd, J = 7.4, 1.1 Hz, 1H), 7.13 (ddd, J = 7.6, 7.6, 1.4 Hz, 1H), 7.21–7.24 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 20.6, 21.1, 95.0 (dd, J_{CF} = 21, 21 Hz), 126.3, 126.6, 127.1, 127.7, 128.0, 128.43, 128.44, 128.6, 128.7, 129.7, 131.3 (dd, J_{CF} = 2, 2 Hz), 132.15, 132.15, 132.5 (dd, J_{CF} = 3 Hz), 135.8, 136.2, 138.7, 139.3 (d, J_{CF} = 3 Hz), 141.7, 142.1 (d, J = 3 Hz), 153.5 (dd, J_{CF} = 291, 291 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 72.9 (d, J_{FF} = 32 Hz, 1F), 73.2 (d, J_{FF} = 32 Hz, 1F). IR (neat): ν 3059, 3022, 2922, 1718, 1485, 1477, 1244, 1221, 812, 760, 748, 700 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{28}H_{22}F_2$ $[M]^+$: 396.1690; Found: 396.1705.

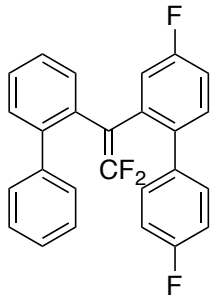
1-(Biphenyl-2-yl)-1-(4,4'-dibutylbiphenyl-2-yl)-2,2-difluoroethene (7f)



Difluoroethene **7f** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (4,4'-dibutylbiphenyl-2-yl)trifluoroborate (145 mg, 0.39 mmol), *t*-BuOLi (72.0 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 40:1) gave difluoroethene **7f** (133 mg, 93%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.94 (t, J = 7.3 Hz, 3H), 0.98 (t, J = 7.4 Hz, 3H), 1.30–1.34 (m, 2H), 1.38–1.46 (m, 4H), 1.59–1.65 (m, 2H), 2.32 (t, J = 7.8 Hz, 2H), 2.60 (t, J = 7.6 Hz, 2H), 6.30 (s, 1H), 6.50 (d, J = 7.5 Hz, 1H), 6.85 (dd, J = 7.4, 7.4 Hz, 1H), 6.91–6.97 (m, 4H), 7.01–7.06 (m, 5H), 7.11 (dd, J = 7.4, 7.4 Hz, 1H), 7.22–7.24 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 13.9, 14.0, 22.3, 22.5, 33.1, 33.8, 34.9, 35.3, 95.2 (dd, J_{CF} = 20 Hz), 126.3, 126.8, 127.0, 127.2, 127.7, 127.8, 128.7, 128.8, 129.7, 129.8, 131.4 (d, J_{CF} = 2 Hz), 131.5 (d, J_{CF} = 2 Hz), 132.0, 132.5, 139.0, 139.6, 140.8, 141.3, 141.8, 142.1, 153.7 (dd, J_{CF} = 292, 292 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 72.9 (brs, 2F). IR (neat): ν 2956, 2929, 2858, 1716, 1244, 748, 700 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{34}H_{34}F_2$ $[M]^+$: 480.2629; Found: 480.2649.

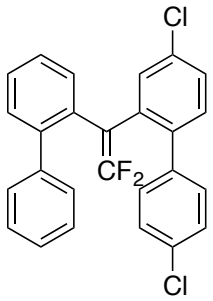
1-(Biphenyl-2-yl)-1-(4,4'-difluorobiphenyl-2-yl)-2,2-difluoroethene (7g)



Difluoroethene **7g** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (4,4'-difluorobiphenyl-2-yl)trifluoroborate (112 mg, 0.38 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 30:1) gave difluoroethene **7g** (101 mg, 83%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.23 (ddd, J_{HF} = 9.9, J = 2.7, 1.5 Hz, 1H), 6.57 (ddd, J = 7.8, 1.5, 1.5 Hz, 1H), 6.81 (ddd, J = 8.3, 8.3, 2.7 Hz, 1H), 6.88–6.89 (m, 4H), 6.93–6.99 (m, 4H), 7.08 (dd, J = 7.6, 1.4 Hz, 1H), 7.15 (ddd, J = 7.6, 7.6, 1.3 Hz, 1H), 7.22–7.30 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 94.8 (dd, J_{CF} = 20, 20 Hz), 114.2 (d, J_{CF} = 21 Hz), 114.7 (d, J_{CF} = 21 Hz), 118.3 (ddd, J_{CF} = 23, 2, 2 Hz), 126.5, 127.1, 127.4, 127.9, 128.5, 129.8, 130.2 (d, J_{CF} = 8 Hz), 131.1 (d, J_{CF} = 8 Hz), 131.3, 131.7 (dd, J_{CF} = 3, 3 Hz), 134.4 (ddd, J_{CF} = 8, 3, 3 Hz), 136.6 (d, J_{CF} = 3 Hz), 137.0 (dd, J_{CF} = 3,3 Hz), 141.4, 142.1 (d, J_{CF} = 3 Hz), 154.0 (dd, J_{CF} = 293, 293 Hz), 161.2 (d, J_{CF} = 247 Hz), 162.1 (d, J_{CF} = 247 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 44.76–44.81 (m, 1F), 45.8–45.9 (m, 1F), 73.7 (d, J_{FF} = 31 Hz, 1F), 73.9 (d, J_{FF} = 31 Hz, 1F). IR (neat): ν 3068, 3059, 1716, 1604, 1481, 1250, 1219, 1165, 1157 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{26}H_{16}F_4$ $[M]^+$: 404.1188; Found: 404.1182.

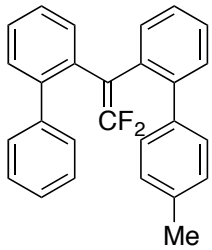
1-(Biphenyl-2-yl)-1-(4,4'-dichlorobiphenyl-2-yl)-2,2-difluoroethene (7h)



Potassium (4,4'-dichlorobiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4,4'-dichlorobiphenyl and was used without further purification. Difluoroethene **7h** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 88.5 mg, 0.30 mmol), potassium (4,4'-dichlorobiphenyl-2-yl)trifluoroborate (128 mg, 0.39 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 30:1) gave difluoroethene **7h** (45.9 mg, 35%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.47 (s, 1H), 6.55 (d, J = 7.8 Hz, 1H), 6.83 (d, J = 8.3 Hz, 2H), 6.90 (d, J = 8.3 Hz, 1H), 6.93–6.96 (m, 3H), 7.06 (dd, J = 7.8, 1.8 Hz, 2H), 7.13–7.16 (m, 3H), 7.23 (dd, J = 7.8, 7.1 Hz, 2H), 7.29 (t, J = 7.1 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 94.7 (dd, J_{CF} = 21, 21 Hz), 126.5, 127.2, 127.3, 127.5, 127.8, 128.0, 128.5, 129.7, 129.8, 130.6, 131.4 (dd, J_{CF} = 2, 2 Hz), 131.56 (dd, J_{CF} = 4, 4 Hz), 131.65 (dd, J_{CF} = 2, 2 Hz), 132.6, 133.2, 134.0 (dd, J_{CF} = 3, 3 Hz), 138.9, 139.1 (d, J_{CF} = 3 Hz), 141.1, 142.1 (d, J_{CF} = 3 Hz), 154.1 (dd, J_{CF} = 293, 293 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.7 (d, J_{FF} = 30 Hz, 1F), 74.0 (d, J_{FF} = 30 Hz, 1F). IR (neat): ν 3061, 3024, 1716, 1471, 1219, 793, 758, 748 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{26}H_{16}Cl_2F_2$ $[M]^+$: 436.0597; Found: 436.0617.

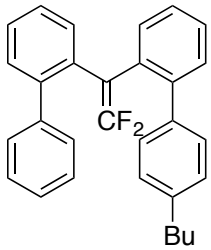
1-(Biphenyl-2-yl)-2,2-difluoro-1-(4'-methylbiphenyl-2-yl)ethene (7i)



Potassium (4'-methylbiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4'-methylbiphenyl and was used without further purification. Difluoroethene **7i** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (4'-methylbiphenyl-2-yl)trifluoroborate (107 mg, 0.39 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification purified by silica gel column chromatography (hexane/EtOAc = 50:1) gave difluoroethene **7i** (99 mg, 86%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.35 (s, 3H), 6.58 (d, J = 7.8 Hz, 1H), 6.62 (d, J = 7.9 Hz, 1H), 6.89–6.94 (m, 4H), 7.02–7.04 (m, 4H), 7.07–7.09 (m, 2H), 7.11–7.16 (m, 2H), 7.21–7.24 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.1, 94.8 (dd, J_{CF} = 20, 20 Hz), 126.3, 126.4, 126.7, 127.2, 127.8, 128.43, 128.43, 128.5, 128.6, 129.8, 129.9, 131.3 (dd, J_{CF} = 3, 3 Hz), 131.4 (dd, J_{CF} = 4, 4 Hz), 132.46, 132.46, 136.4, 138.7, 141.7, 142.08, 142.08, 153.3 (dd, J_{CF} = 291, 291 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.5 (d, J_{FF} = 30 Hz, 1F), 73.6 (d, J_{FF} = 30 Hz, 1F). IR (neat): ν 3057, 3022, 2923, 1711, 1477, 1242, 1200, 984, 758, 700 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{27}H_{20}F_2$ $[M]^+$: 382.1533; Found: 382.1534.

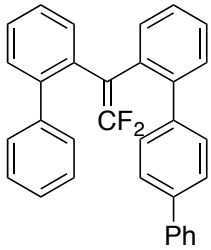
1-(Biphenyl-2-yl)-1-(4'-butylbiphenyl-2-yl)-2,2-difluoroethene (7j)



Potassium (4'-butylbiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4'-butylbiphenyl and was used without further purification. Difluoroethene **7j** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (4'-butylbiphenyl-2-yl)trifluoroborate (123 mg, 0.39 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 50:1) gave difluoroethene **7j** (118 mg, 93%) as a colorless liquid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.98 (t, J = 7.4 Hz, 3H), 1.36–1.44 (m, 2H), 1.59–1.65 (m, 2H), 2.60 (t, J = 7.7 Hz, 2H), 6.54 (d, J = 7.8 Hz, 1H), 6.57 (d, J = 7.8 Hz, 1H), 6.87 (dd, J = 7.5, 7.5 Hz, 2H), 6.92 (d, J = 7.9 Hz, 2H), 7.00–7.03 (m, 4H), 7.06 (d, J = 7.6 Hz, 2H), 7.09–7.14 (m, 2H), 7.19–7.23 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 14.0, 22.3, 33.8, 35.3, 95.1 (dd, J_{CF} = 20, 20 Hz), 126.2, 126.3, 126.7, 127.06, 127.10, 127.8, 127.9 128.5, 128.6, 129.8, 129.9, 131.3, 131.4, 132.38, 132.38, 138.9, 141.5, 141.7, 142.06, 142.12, 153.6 (dd, J_{CF} = 293, 293 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.1 (brs, 2F). IR (neat): ν 2956, 2929, 2858, 1713, 1479, 1242, 984, 758, 748 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{30}H_{26}F_2$ $[M]^+$: 424.2003; Found:424.1997.

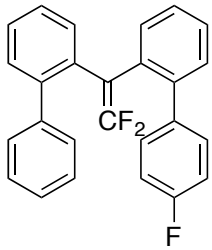
1-(Biphenyl-2-yl)-2,2-difluoro-1-(1,1':4',1''-terphenyl-2-yl)ethene (7k)



Potassium (1,1':4',1''-terphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-1,1':4',1''-terphenyl and was used without further purification. Difluoroethene **7k** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (1,1':4',1''-terphenyl-2-yl)trifluoroborate (131 mg, 0.39 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 25:1) gave difluoroethene **7k** (83 mg, 62%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.60 (d, J = 7.7 Hz, 1H), 6.64 (d, J = 7.6 Hz, 1H), 6.86 (ddd, J = 7.5, 7.5, 1.5 Hz, 1H), 6.90 (ddd, J = 7.7, 7.7, 1.8 Hz, 1H), 7.00–7.03 (m, 2H), 7.04–7.08 (m, 3H), 7.10–7.16 (m, 3H), 7.19–7.22 (m, 3H), 7.37 (tt, J = 7.2, 1.4 Hz, 1H), 7.41–7.44 (m, 2H), 7.45–7.49 (m, 2H), 7.58–7.61 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 95.1 (dd, J_{CF} = 20, 20 Hz), 126.4, 126.5, 126.6, 126.7, 127.06, 127.14, 127.14, 127.2, 127.8, 128.6, 128.8, 129.0, 129.7, 129.8, 131.46 (dd, J_{CF} = 2, 2 Hz), 131.54 (dd, J_{CF} = 2, 2 Hz), 132.4 (dd, J_{CF} = 2 Hz), 132.5 (dd, J_{CF} = 2, 2 Hz), 139.7, 140.7, 141.1, 141.64, 141.64, 142.1 (d, J_{CF} = 2 Hz), 153.7 (dd, J_{CF} = 292, 292 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.2 (d, J_{FF} = 33 Hz, 1F), 73.3 (d, J_{FF} = 33 Hz, 1F). IR (neat): ν 3057, 3026, 2925, 1716, 1477, 1242, 984, 754, 698 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{32}H_{22}F_2$ $[M]^+$: 444.1690; Found: 444.1707.

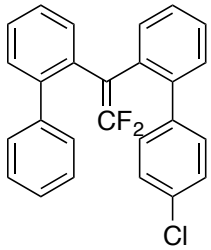
1-(Biphenyl-2-yl)-2,2-difluoro-1-(4'-fluorobiphenyl-2-yl)ethene (7l)



Potassium (4'-fluorobiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4'-fluorobiphenyl and was used without further purification. Difluoroethene **7l** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (4'-fluorobiphenyl-2-yl)trifluoroborate (109 mg, 0.39 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 50:1) gave difluoroethene **7l** (67 mg, 58%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.58 (d, J = 7.8 Hz, 1H), 6.62 (d, J = 7.8 Hz, 1H), 6.87–6.91 (m, 4H), 6.92–6.96 (m, 3H), 6.98–7.00 (m, 2H), 7.02 (dd, J = 7.6, 1.2 Hz, 1H), 7.07 (dd, J = 7.6, 1.3 Hz, 1H), 7.11 (ddd, J = 7.5, 7.5, 1.2 Hz, 1H), 7.15 (ddd, J = 7.5, 7.5, 1.2 Hz, 1H), 7.18–7.23 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 95.0 (dd, J_{CF} = 22, 22 Hz), 114.6 (d, J_{CF} = 21 Hz), 126.4, 126.5, 126.7, 127.1, 127.2, 127.8, 128.5, 129.8, 129.9, 130.0 (d, J_{CF} = 8 Hz), 131.3, 131.4, 132.3, 132.4, 137.6 (d, J = 3 Hz), 140.9, 141.5, 142.0, 153.6 (dd, J_{CF} = 292, 292 Hz), 161.9 (d, J_{CF} = 246 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 45.55–45.61 (m, 1F), 73.4 (d, J_{FF} = 31 Hz, 1F), 73.5 (d, J_{FF} = 31 Hz, 1F). IR (neat): ν 3064, 2918, 1716, 1516, 1244, 1223, 984, 760 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{26}H_{17}F_3$ $[M]^+$: 386.1282; Found: 386.1278.

1-(Biphenyl-2-yl)-1-(4'-chlorobiphenyl-2-yl)-2,2-difluoroethene (7m)



Potassium (4'-chlorobiphenyl-2-yl)trifluoroborate was prepared according to literature procedures[7] starting from 2-bromo-4'-chlorobiphenyl and was used without further purification. Difluoroethene **7m** was prepared by the method described for **7e** using 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene (**9**, 89 mg, 0.30 mmol), potassium (4'-chlorobiphenyl-2-yl)trifluoroborate (115 mg, 0.39 mmol), *t*-BuOLi (72 mg, 0.90 mmol), $Pd_2dba_3 \cdot CHCl_3$ (1.6 mg, 1.5 mmol), and $AsPh_3$ (1.8 mg, 5.9 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 40:1) gave difluoroethene **7m** (62 mg, 51%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.60 (d, J = 7.8 Hz, 1H), 6.64 (d, J = 7.8 Hz, 1H), 6.89–6.91 (m, 3H), 6.96–7.02 (m, 4H), 7.07 (d, J = 7.7 Hz, 1H), 7.11 (dd, J = 7.5, 7.5 Hz, 1H), 7.15–7.24 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 95.0 (dd, J_{CF} = 35, 35 Hz), 126.5, 126.77, 126.80, 127.2, 127.3, 127.8, 127.9, 128.5, 129.6, 129.8, 129.9, 131.45, 131.52, 132.3, 132.4, 132.8, 140.1, 140.7 (d, J_{CF} = 2 Hz), 141.5, 142.1 (d, J_{CF} = 2 Hz), 153.6 (dd, J_{CF} = 293, 293 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 73.6 (d, J_{FF} = 30 Hz), 73.7 (d, J_{FF} = 30 Hz). IR (neat): ν 3059, 3022, 1714, 1475, 1244, 1090, 984, 829, 758, 698 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{26}H_{17}ClF_2$ $[M]^+$: 402.0987; Found: 402.0990.

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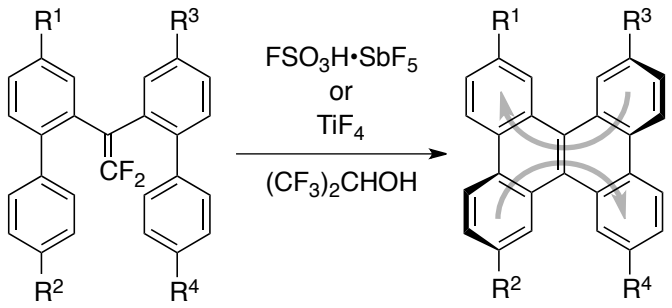
CHAPTER 3

Acid-Promoted Vinylic and Aromatic C–F Bond Activation: Synthesis of Dibenzo[*g*,*p*]chrysenes

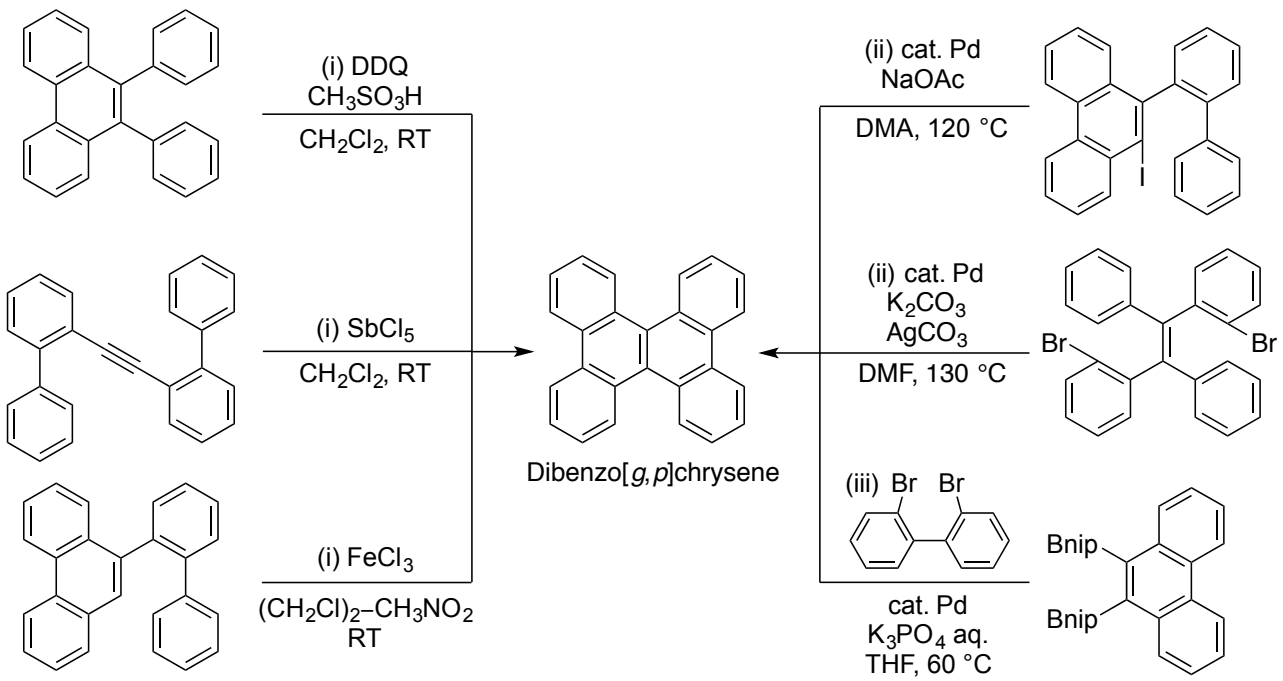
Abstract

Dibenzo[*g*,*p*]chrysenes were readily synthesized via the superacid- or TiF_4-mediated domino Friedel–Crafts-type cyclization of 1,1-difluoroethenes bearing two biaryl groups, which were easily prepared via the Suzuki–Miyaura coupling of 1,1-difluoro-2,2-diiodoethene or 1-(biphenyl-2-yl)-1-bromo-2,2-difluoroethene with potassium (biaryl-2-yl)trifluoroborates as described in Chapter 2. In this approach, the activation of both vinylic and aromatic C–F bonds was successfully achieved to make two new C–C bonds.



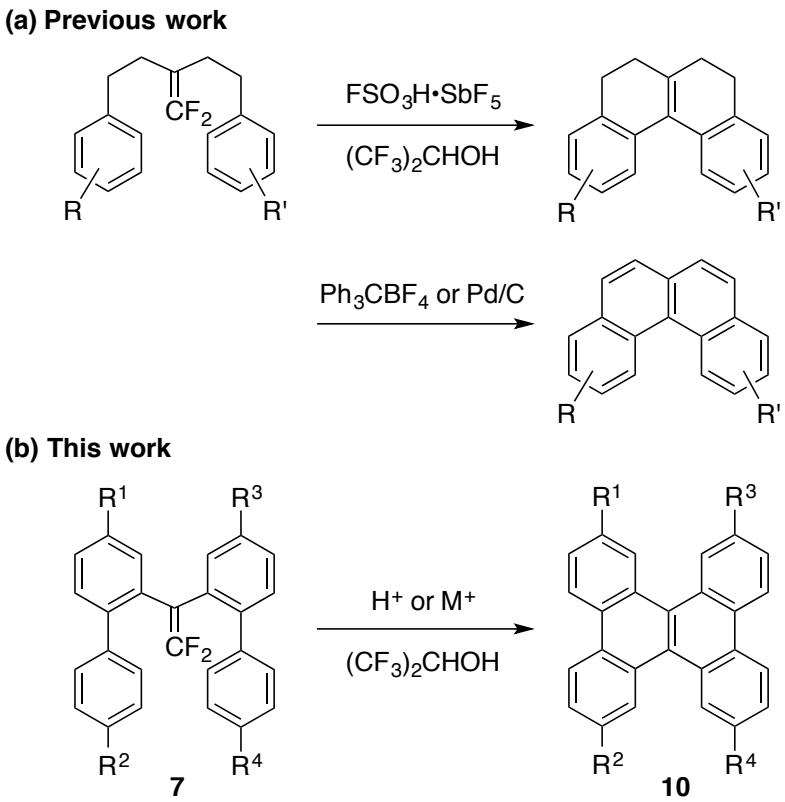
3-1. Introduction

Dibenzo[*g*,*p*]chrysenes constitute a unique class of polycyclic aromatic hydrocarbons (PAHs) because of their characteristic double helical structure.[1] Their twisted π-systems are expected to be suitable for organic semiconductors directed toward electronic devices such as thin-film transistors and organic light-emitting diodes;[2] thus, they have attracted much interest. So far, dibenzo[*g*,*p*]chrysenes have mainly been synthesized via the following processes: (i) the intramolecular oxidative carbon–carbon bond formation of 9,10-diarylphenanthrenes,[3] 1,2-bis(biaryl-2-yl)ethynes,[4] or 9-(biaryl-2-yl)phenanthrenes,[5] (ii) the intramolecular Pd-catalyzed dehydrohalogenation of 9-(biaryl-2-yl)-10-iodophenanthrenes[6] or (*E*)-1,2-diaryl-1,2-bis(2-bromoaryl)ethenes,[7] and (iii) the intermolecular metal-catalyzed cross coupling between 9,10-diborylphenanthrenes and 2,2'-dibromobiaryls[8] or between phenanthrenes and dibenzosiloles.[9] Most of these methods were limited in substrate scope; for example phenanthrene frameworks were required (Scheme 1).



Scheme 1. Conventional method for the synthesis of dibenzo[*g*,*p*]chrysene

On the other hand, facile methods for PAH synthesis via Friedel–Crafts-type cyclizations of fluorinated cationic species were reported by Ichikawa's group.[10] In the reports, 1,1-difluoroethenes, bearing two 2-arylethyl groups afforded tetracyclic compounds in high yields on treatment with magic acid ($FSO_3H{\cdot}SbF_5$) in 1,1,1,3,3,3-hexafluoropropan-2-ol (HFIP) through the cleavage of two vinylic C–F bonds (Scheme 2a).[10a,c] The cyclized products successfully underwent subsequent oxidation by trityl tetrafluoroborate or palladium on carbon to yield helicenes. These facts promoted me to investigate the application of the concept of C–C bond formation to dibenzo[*g*,*p*]chrysene synthesis. Herein, I demonstrate the magic acid- or titanium(IV) fluoride-mediated synthesis of dibenzo[*g*,*p*]chrysenes **10** via the domino Friedel–Crafts-type cyclization of 1,1-difluoroethenes bearing two biaryl groups **7**, which were prepared in Chapter 2 (Scheme 2b). In this approach, the activation of both vinylic and aromatic C–F bonds was examined to achieve direct construction of two aromatic rings without any oxidation processes.[11]

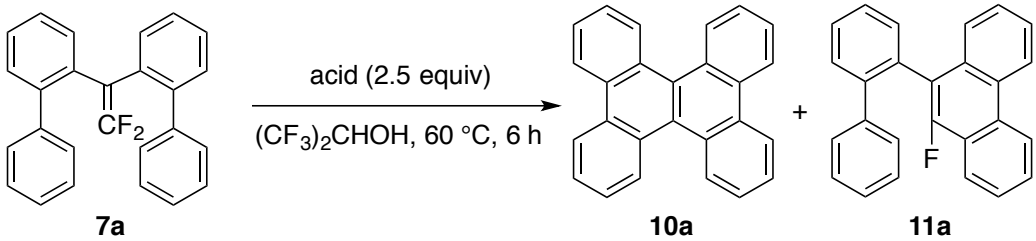


Scheme 2. Domino Friedel−Crafts-type cyclization of 1,1-difluoro-1-ethenes

3-2. Cyclization of 1,1-Bis(biaryl-2-yl)-2,2-difluoroethenes

Using 1,1-bis(biphenyl-2-yl)-2,2-difluoroethene (**7a**) as a model compound, I sought suitable conditions for the domino Friedel–Crafts-type cyclization with a series of Brønsted and Lewis acids (Table 1). The reactions of **7a** with acids were performed in 1,1,1,3,3,3-hexafluoropropan-2-ol (HFIP), which possesses a substantial cation stabilization effect.[10,15,16] When *p*-toluenesulfonic acid (TsOH) was employed, no cyclization products were observed (entry 1). However, on treatment with 2.5 equiv of trifluoromethanesulfonic acid (TfOH), the desired domino-cyclization product, dibenzo[*g*,*p*]chrysene (**10a**), was obtained in 59% yield (entry 2). The use of magic acid ($FSO_3H{\cdot}SbF_5$) improved the yield of **10a** to 95% (entry 3). In contrast, among the Lewis acids examined ($BF_3{\cdot}OEt_2$, Me_3SiOTf, ZrF_4, $TiCl_4$, TiF_4; entries 4–8), TiF_4 in HFIP specifically promoted the cyclization of **7a** to afford **10a** in 93% yield (entry 8), while reaction in CH_2Cl_2 instead of HFIP selectively gave the monocyclization product, fluorophenanthrene **11a**, in 85% yield (entry 9). These results indicated that the stabilizing effect of HFIP on carbocations might be highly important for the second cyclization.[10,15,16]

Table 1. Screening of Acids for the Domino Friedel–Crafts-type Cyclization of Difluoroethene **7a**

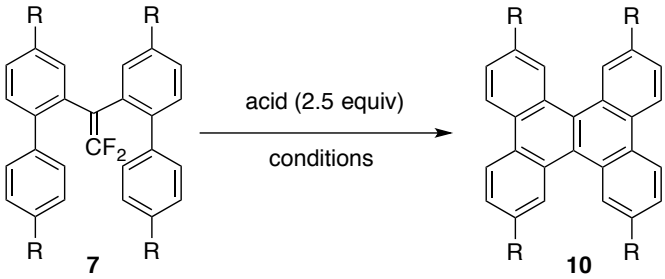


entry	acid	**10a** / %[a]	**11a** / %[a]
1	TsOH	N.D.[b]	N.D.[b]
2	TfOH	59	N.D.[b]
3[c]	$FSO_3H{\bullet}SbF_5$	95	N.D.[b]
4	$BF_3{\bullet}OEt_2$	trace	N.D.[b]
5	Me_3SiOTf	trace	N.D.[b]
6	ZrF_4	N.D.[b]	N.D.[b]
7	$TiCl_4$	N.D.[b]	N.D.[b]
8	TiF_4	93	N.D.[b]
9[d]	TiF_4	N.D.[b]	85

[a] ^{1}H NMR yield using CH_2Br_2 as an internal standard. [b] N.D. = Not detected.
[c] $(CF_3)_2CHOH–CH_2Cl_2$ (10:1), 0 °C, 10 min. [d] CH_2Cl_2, 40 °C, 6 h.

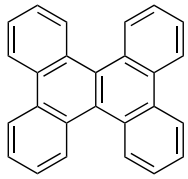
Cyclization of other difluoroethenes **7** with magic acid or TiF_4 (methods A or B) was examined for the synthesis of substituted dibenzo[*g*,*p*]chrysenes **10** (Table 2). Both symmetrically-substituted difluoroethenes **7b**–**7d** and unsymmetrically-substituted ones **7e**–**7m** successfully underwent a domino Friedel–Crafts-type cyclization with the appropriate choice of acid promotors. Use of TiF_4 (method B) was preferable for cyclization of alkyl- and aryl-substituted (more reactive) substrates **7b**, **7c**, **7e**, **7f**, **7i**, **7j**, and **7k**, which led to the effective formation of the corresponding dibenzo[*g*,*p*]chrysenes **10b**, **10c**, **10e**, **10f**, **10i**, **10j**, and **10k**. Rapid completion of the reactions with magic acid (method A) was observed for cyclization of the halogen-substituted (less reactive) precursors **7d**, **7g**, **7h**, **7l**, and **7m**, affording the halogen-substituted dibenzo[*g*,*p*]chrysenes **10d**, **10g**, **10h**, **10l**, and **10m**, in good yields.

Table 2. Synthesis of Substituted Dibenzo[*g*,*p*]chrysenes **10**[a]

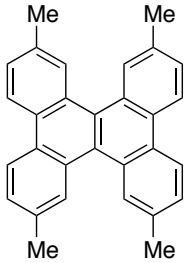


Method A:
$FSO_3H{\bullet}SbF_5$
/$(CF_3)_2CHOH–CH_2Cl_2$ (10:1), 0 °C, 10 min

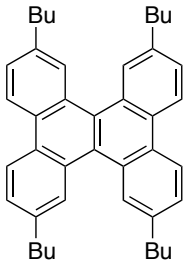
Method B:
TiF_4
/$(CF_3)_2CHOH$, 60 °C, 6 h



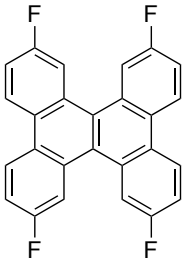
10a
Method A: 95%
Method B: 93%



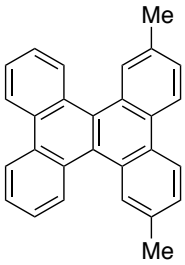
10b
Method B: 93%



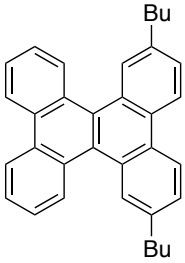
10c
Method B: 99%



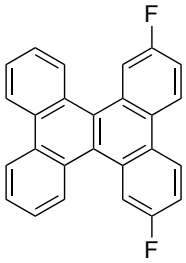
10d
Method A: 80%



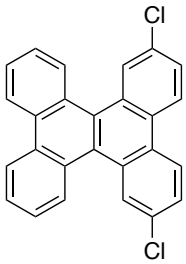
10e
Method B: 90%



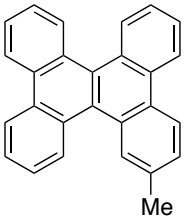
10f
Method B: 94%



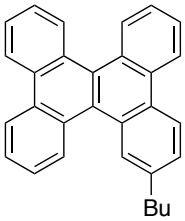
10g
Method A: 81%



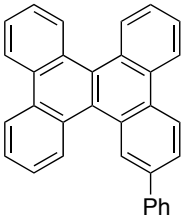
10h
Method B: 49%



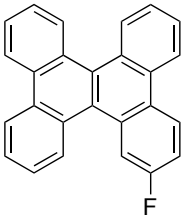
10i
Method B: 82%



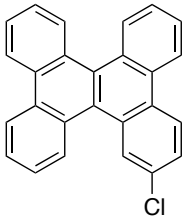
10j
Method B: 98%



10k
Method B: 72%



10l
Method A: 80%

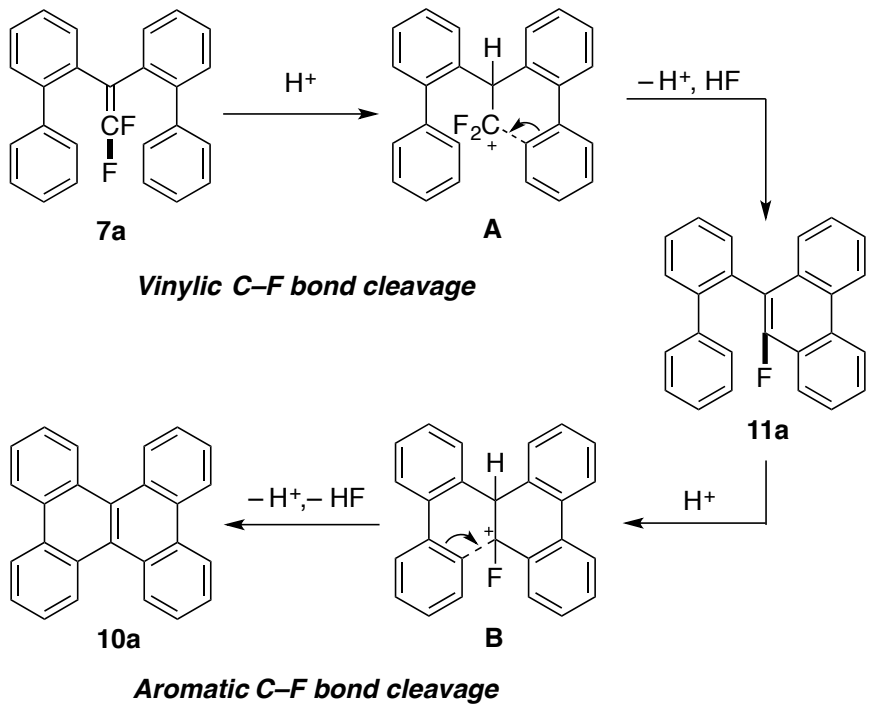


10m
Method A: 54%

[a] Isolated yield.

3-3. Mechanistic Study

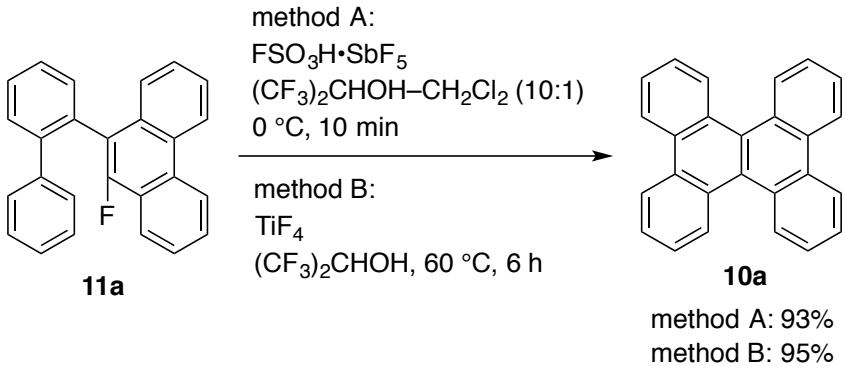
A plausible reaction mechanism for this cyclization is shown in Scheme 3. First, protonation of the difluoroethene moiety in **7a** regioselectively generates the cationic intermediate **A**, in which the carbocation is stabilized by the α-fluorine substituents. A Friedel–Crafts-type cyclization followed by the elimination of HF allows C–C bond formation and vinylic C–F bond cleavage to afford 9-(biphenyl-2-yl)-10-fluorophenanthrene **11a**. The second cyclization is induced by the protonation of the phenanthryl moiety in **11a**. Thus, a further Friedel–Crafts-type cyclization proceeds through the fluorine-stabilized arenium ion **B**,[10] resulting in aromatic C–F bond cleavage via HF elimination.[17]



Scheme 3. Proposed Reaction Mechanism

To gain some experimental evidence to support the proposed reaction mechanism, we attempted the acid-mediated cyclization of fluorophenanthrene **11a**, which was prepared via cyclization of **7a** with TiF_4 in CH_2Cl_2 as mentioned above (Table 1, entry 9). Treatment of **11a** with magic acid or

TiF_4 in HFIP–CH_2Cl_2 (10:1) or HFIP afforded dibenzo[*g*,*p*]chrysene (**10a**) in excellent yields, respectively (Scheme 4). These results suggested that **11a** was generated in situ as an intermediate by the first cyclization, and then underwent the second cyclization, where the aromatic C–F bond cleavage was accomplished. It was noted that cleavage of an aromatic C–F bond, which has been considered to be difficult to activate, was readily achieved under cationic conditions with the aid of a Brønsted or Lewis acid in HFIP.[17]



Scheme 4. Cyclization of Fluorophenanthrene **11a**

3-4. Summary

In conclusion, I have achieved a domino Friedel–Crafts-type cyclization of difluoroethenes, which provides easy access to dibenzo[*g*,*p*]chrysenes. A scalable synthesis of dibenzo[*g*,*p*]chrysenes is conducted by starting from accessible, storable 1,1,1-trifluoro-2-iodoethane or 1,1-difluoroethene. Dibenzo[*g*,*p*]chrysenes possess a double helical structure due to the presence of two inherent helicene moieties. Their application to new electronic materials will be stimulated by the approach presented in this study.

3-5. References and Notes

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3-6. Experimental Section

General statements

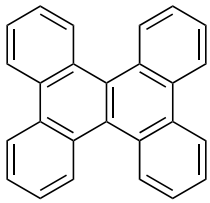
^{1}H NMR, ^{13}C NMR, and ^{19}F NMR spectra were recorded on a Bruker Avance 500 or a JEOL ECS-400 spectrometer. Chemical shift values are given in ppm relative to internal Me_4Si (for ^{1}H NMR: δ = 0.00 ppm), $CDCl_3$ (for ^{13}C NMR: δ = 77.0 ppm), and C_6F_6 (for ^{19}F NMR: δ = 0.00 ppm). IR spectra were recorded on a Horiba FT-300S spectrometer by the attenuated total reflectance (ATR) method. Mass spectra were measured on a JEOL JMS-T100GCV or a JMS-T100CS spectrometer. Elemental analyses were carried out at the Elemental Analysis Laboratory, Division of Chemistry, Faculty of Pure and Applied Sciences, University of Tsukuba.

Column chromatography and preparative thin-layer chromatography (PTLC) were conducted on silica gel (Silica Gel 60 N, Kanto Chemical Co., Inc. for column chromatography and Wakogel B-5F, Wako Pure Chemical Industries for PTLC, respectively). All the reactions were conducted under nitrogen.

1,1,1,3,3,3-Hexafluoropropan-2-ol (HFIP) was distilled from CaH_2 and stored over activated molecular sieves 4A. Fluorophenanthrene **10a**[1] were prepared according to the literature procedures. Unless otherwise noted, materials were obtained from commercial sources and used directly without further purifications.

Cyclization of Difluoroethenes Bearing Two Biaryl Groups

Dibenzo[*g*,*p*]chrysene (10a)



method A:

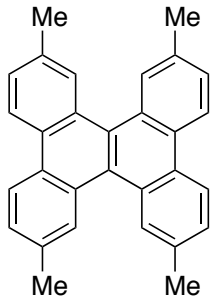
In a 5 mL flask was placed $FSO_3H \cdot SbF_5$ (79 mg, 0.25 mmol). After the flask was cooled to 0 °C, HFIP (1.0 mL) was added. After stirring at the same temperature for 5 min, a dichloromethane (0.10 mL) solution of 1,1-bis(biphenyl-2-yl)-2,2-difluoroethene (**7a**, 37 mg, 0.10 mmol) was added to the flask. After vigorous stirring at 0 °C for 10 min, the reaction was quenched with aqueous NaOH (1 M), and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20:1) to give **10a** (31 mg, 95%) as a pale yellow solid.

method B:

In a Schlenk tube were placed TiF_4 (31 mg, 0.25 mmol), 1,1-bis(biphenyl-2-yl)-2,2-difluoroethene (**7a**, 37 mg, 0.10 mmol), and HFIP (1.0 mL). After vigorous stirring at 60 °C for 6 h, the reaction was quenched with saturated aqueous $NaHCO_3$, and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20:1) to give **10a** (31 mg, 93%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.64 (ddd, *J* = 8.3, 7.2, 1.5 Hz, 4H), 7.69 (ddd, *J* = 8.3, 7.2, 1.5 Hz, 4H), 8.70 (dd, *J* = 7.2, 1.5 Hz, 4H), 8.72 (dd, *J* = 7.2, 1.5 Hz, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 123.6, 126.56, 126.56, 127.5, 128.9, 129.2, 130.9. IR (neat): ν 3072, 2927, 1452, 1427, 1232, 762, 727 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{26}H_{17}$ $[M+H]^+$: 329.1330; Found: 329.1340.

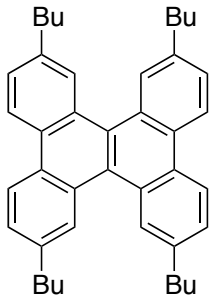
2,7,10,15-Tetramethyldibenzo[*g*,*p*]chrysene (10b)



Dibenzochrysene **10b** was synthesized by method B described for **10a** using 1,1-bis(4,4'-dimethylbiphenyl-2-yl)-2,2-difluoroethene (**7b**, 43 mg, 0.10 mmol) and TiF_4 (31 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10b** (36 mg, 93%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.49 (s, 12H), 7.40 (d, *J* = 8.3 Hz, 4H), 8.40 (s, 4H), 8.46 (d, *J* = 8.3 Hz, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.9, 123.2, 127.5, 127.8, 128.58, 128.62, 129.1, 135.6. IR (neat): ν 2918, 2854, 1612, 1483, 802, 669 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{30}H_{25}$ $[M+H]^+$: 385.1956; Found: 385.1955.

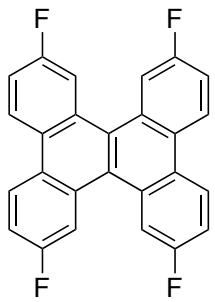
2,7,10,15-Tetrabutyldibenzo[*g*,*p*]chrysene (10c)



Dibenzochrysene **10c** was synthesized by method B described for **10a** using 1,1-bis(4,4'-dibutylbiphenyl-2-yl)-2,2-difluoroethene (**7c**, 60 mg, 0.10 mmol) and TiF_4 (31 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10c** (55 mg, 99%) as an orange solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.95 (t, *J* = 7.4 Hz, 12H), 1.40–1.47 (m, 8H), 1.71–1.77 (m, 8H), 2.81 (t, *J* = 7.6 Hz, 8H), 7.48 (d, *J* = 8.3 Hz, 4H), 8.50 (s, 4H), 8.56 (d, *J* = 8.3 Hz, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 14.0, 22.4, 33.8, 36.0, 123.2, 127.3, 127.7, 128.2, 128.8, 129.1, 140.5. IR (neat): ν 2956, 2926, 2856, 1684, 1614, 1466, 808, 739 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{42}H_{49}$ $[M+H]^+$: 553.3834; Found: 553.3817.

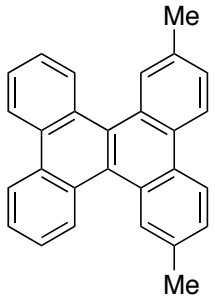
2,7,10,15-Tetrafluorodibenzo[*g*,*p*]chrysene (10d)



Dibenzochrysene **10d** was synthesized by method A described for **10a** using 1,1-bis(4,4'-difluorobiphenyl-2-yl)-2,2-difluoroethene (**7d**, 44 mg, 0.10 mmol) and $FSO_3H \cdot SbF_5$ (79 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10d** (32 mg, 80%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.46 (ddd, J_{HF} = 10.2 Hz, J = 9.1, 2.6 Hz, 4H), 8.31 (dd, J_{HF} = 11.2 Hz, J = 2.6 Hz, 4H), 8.61 (d, J = 9.1 Hz, J_{HF} = 5.6 Hz, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 113.5 (d, J_{CF} = 23 Hz), 115.9 (d, J_{CF} = 23 Hz), 125.9 (d, J_{CF} = 9 Hz), 127.2, 128.2, 129.9 (d, J_{CF} = 9 Hz), 161.4 (J_{CF} = 123 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 47.0–47.3 (m, 4F). IR (neat): ν 2954, 2854, 1483, 1475, 1232, 1163, 798 cm^{-1}. HRMS (APCI+): *m/z* Calcd. for $C_{26}H_{12}F_4$ $[M]^+$: 400.0875; Found: 400.0869.

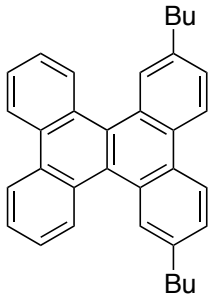
2,7-Dimethyldibenzo[*g,p*]chrysene (10e)



Dibenzochrysene **10e** was synthesized by method B described for **10a** using 1-(biphenyl-2-yl)-1-(4,4'-dimethylbiphenyl-2-yl)-2,2-difluoroethene (**7e**, 40 mg, 0.10 mmol) and TiF_4 (31 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10e** (32 mg, 90%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.57 (s, 6H), 7.49 (d, J = 8.5 Hz, 2H), 7.64 (dd, J = 7.8, 7.8 Hz, 2H), 7.68 (dd, J = 7.8, 7.8 Hz, 2H), 8.47 (s, 2H), 8.56 (d, J = 8.5 Hz, 2H), 8.70 (d, J = 7.8 Hz, 2H), 8.71 (d, J = 7.8 Hz, 2H) ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.8, 123.3, 123.5, 126.3, 126.4, 127.5, 128.0, 128.6, 128.7, 128.8, 129.0, 129.4, 130.8, 135.7. IR (neat): ν 3068, 2922, 2846, 1261, 1051, 804, 760, 731 cm^{-1}. HRMS (APCI+): *m/z* Calcd. for $C_{28}H_{21}$ $[M+H]^+$: 357.1643; Found: 357.1634.

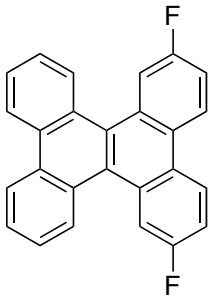
2,7-Dibutyldibenzo[*g*,*p*]chrysene (10f)



Dibenzochrysene **10f** was synthesized by method B described for **10a** using 1-(biphenyl-2-yl)-1-(4,4'-dibutylbiphenyl-2-yl)-2,2-difluoroethene (**7f**, 48 mg, 0.10 mmol) and TiF_4 (31 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10f** (41 mg, 94%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.96 (t, *J* = 7.4 Hz, 6H), 1.39–1.47 (m, 4H), 1.69–1.75 (m, 4H), 2.84 (t, *J* = 7.7 Hz, 4H), 7.50 (d, *J* = 8.1 Hz, 2H), 7.64 (dd, *J* = 7.5, 7.5 Hz, 2H), 7.69 (dd, *J* = 7.5, 7.5 Hz, 2H), 8.48 (s, 2H), 8.58 (d, *J* = 8.1 Hz, 2H), 8.715 (d, *J* = 8.1 Hz, 2H), 8.718 (d, *J* = 8.1 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 14.0, 22.3, 33.7, 35.9, 123.3, 123.6, 126.3, 126.4, 127.4, 127.6, 128.1, 128.8, 128.9, 129.4, 130.7, 140.7. IR (neat): ν 3726, 2954, 2926, 1616, 1481, 758, 731 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{34}H_{33}$ $[M+H]^+$: 441.2582; Found: 441.2574.

2,7-Difluorodibenzo[*g*,*p*]chrysene (10g)

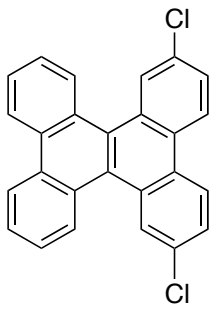


Dibenzochrysene **10g** was synthesized by method A described for **10a** using 1-(biphenyl-2-yl)-1-(4,4'-difluorobiphenyl-2-yl)-2,2-difluoroethene (**7g**, 40 mg, 0.10 mmol) and $FSO_3H \cdot SbF_5$ (79 mg, 0.25 mmol). Purification by silica gel column chromatography

(hexane/EtOAc = 20:1) gave dibenzochrysene **10g** (30 mg, 81%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.42 (ddd, J_{HF} = 9.0, J = 9.0, 2.7 Hz, 2H), 7.67 (ddd, J = 8.2, 8.2, 1.4 Hz, 2H), 7.72 (ddd, J = 8.2, 8.2, 1.4 Hz, 2H), 8.35 (dd, J_{HF} = 11.4, J = 2.7 Hz, 2H), 8.59 (dd, J = 9.0, J_{HF} = 5.6 Hz, 2H), 8.65 (dd, J = 8.2, 1.4 Hz, 2H), 8.71 (dd, J = 8.2, 1.4 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 114.0 (d, J_{CF} = 23 Hz), 115.3 (d, J_{CF} = 23 Hz), 123.8, 125.6 (d, J_{CF} = 9 Hz), 126.97, 127.03, 127.2, 127.8, 128.2, 128.8, 130.3 (d, J_{CF} = 9 Hz), 131.0, 161.3 (d, J_{CF} = 245 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): 47.16–47.21 (m, 2F). IR (neat): ν 3072, 2924, 1616, 1581, 1483, 1452, 1255, 1219, 1173, 745 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{26}H_{14}F_2$ $[M]^+$: 364.1064; Found: 306.1051.

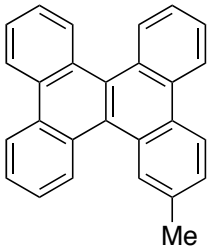
2,7-Dichlorodibenzo[*g*,*p*]chrysene (10h)



Dibenzochrysene **10h** was synthesized by method A described for **10a** using 1-(biphenyl-2-yl)-1-(4,4'-dichlorobiphenyl-2-yl)-2,2-difluoroethene (**7h**, 44 mg, 0.10 mmol) and $FSO_3H \cdot SbF_5$ (79 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10h** (20 mg, 49%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.64 (dd, J = 8.8, 2.1 Hz, 2H), 7.69 (dd, J = 7.9, 7.9 Hz, 2H), 7.73 (dd, J = 7.9, 7.9 Hz, 2H), 8.56 (d, J = 8.8 Hz, 2H), 8.62 (d, J = 7.9 Hz, 2H), 8.66 (d, J = 2.1 Hz, 2H), 8.72 (d, J = 7.9 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 123.7, 125.0, 126.99, 127.03, 127.1, 127.3, 128.0, 128.3, 128.48, 128.53, 130.2, 131.0, 132.7. IR (neat): ν 2926, 1101, 974, 874, 804, 756 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{26}H_{14}Cl_2$ $[M]^+$: 396.0473; Found: 396.0467.

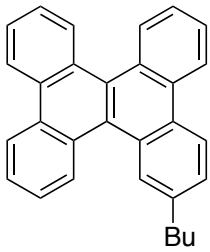
2-Methyldibenzo[*g*,*p*]chrysene (10i)



Dibenzochrysene **10i** was synthesized by method B described for **10a** using 1-(biphenyl-2-yl)-2,2-difluoro-1-(4'-methylbiphenyl-2-yl)ethene (**7i**, 38 mg, 0.10 mmol) and TiF_4 (31 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10i** (28 mg, 82%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.58 (s, 3H), 7.51 (d, *J* = 8.5 Hz, 1H), 7.59–7.70 (m, 6H), 8.50 (s, 1H), 8.60 (d, *J* = 9.0 Hz, 1H), 8.67–8.73 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.9, 123.3, 123.5, 123.52, 123.54, 123.6, 126.1, 126.45, 126.45, 126.47, 126.50, 126.6, 127.2, 127.4, 127.6, 127.6, 128.1, 128.4, 128.5, 128.6, 128.8, 128.9, 129.3, 130.77, 130.81, 130.9, 136.2. IR (neat): ν 3072, 2914, 1616, 1450, 1429, 912, 797, 766, 746, 729 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{27}H_{19}$ $[M+H]^+$: 342.1409; Found: 342.1393.

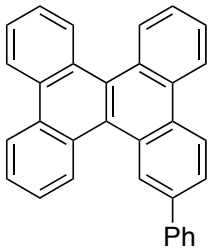
2-Butyldibenzo[*g*,*p*]chrysene (10j)



Dibenzochrysene **10j** was synthesized by method B described for **10a** using 1-(biphenyl-2-yl)-1-(4'-butylbiphenyl-2-yl)-2,2-difluoroethene (**7j**, 42 mg, 0.10 mmol) and TiF_4 (31 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10j** (38 mg, 98%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.95 (t, *J* = 7.4 Hz, 3H), 1.38–1.46 (m, 2H), 1.69–1.75 (m, 2H), 2.84 (t, *J* = 7.5 Hz, 2H), 7.52 (dd, *J* = 8.2, 1.5 Hz, 1H), 7.60–7.71 (m, 6H), 8.49 (dd, *J* = 1.3 Hz, 1H), 8.62 (d, *J* = 8.4 Hz, 1H), 8.67–8.72 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 14.0, 22.3, 33.7, 35.9, 123.4, 123.5, 123.55, 123.60, 126.1, 126.44, 126.44, 126.44, 126.49, 126.49, 127.4, 127.5, 127.6, 128.2, 128.79, 128.83, 128.86, 128.87, 128.91, 129.2, 129.29, 129.34, 130.77, 130.82, 130.9, 141.2. IR (neat): ν 3072, 3055, 2954, 2927, 2875, 2856, 1452, 760, 729 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{30}H_{24}$ $[M]^+$: 384.1878; Found: 384.1870.

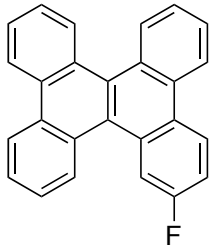
2-Phenyldibenzo[*g*,*p*]chrysene (10k)



Dibenzochrysene **10k** was synthesized by method B described for **10a** using 1-(biphenyl-2-yl)-2,2-difluoro-1-(1,1':4',1''-terphenyl-2-yl)ethene (**7k**, 44 mg, 0.10 mmol) and TiF_4 (31 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 15:1) gave dibenzochrysene **10k** (29 mg, 72%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.39 (ddd, *J* = 7.3, 7.3, 1.7 Hz, 1H), 7.49 (dd, *J* = 7.3, 7.3 Hz, 2H), 7.62–7.71 (m, 6H), 7.74 (dd, *J* = 7.3, 1.4 Hz, 2H), 7.93 (dd, *J* = 8.5, 1.9 Hz, 1H), 8.70–8.77 (m, 7H), 8.92 (d, *J* = 1.8 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 123.57, 123.61, 123.7, 124.2, 125.7, 126.59, 126.59, 126.59, 126.64, 126.66, 126.72, 127.2, 127.3, 127.4, 127.6, 127.9, 128.8, 128.89, 128.93, 129.0, 129.2, 129.27, 129.27, 129.5, 129.9, 130.6, 130.90, 130.90, 139.2, 141.1. IR (neat): ν 3061, 3028, 2926, 1599, 1479, 1452, 1427, 906, 758, 729 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{32}H_{21}$ $[M+H]^+$: 405.1643; Found: 405.1651.

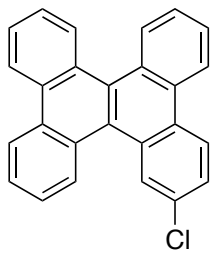
2-Fluorodibenzo[*g,p*]chrysene (10l)



Dibenzochrysene **10l** was synthesized by method A described for **10a** using 1-(biphenyl-2-yl)-2,2-difluoro-1-(4'-fluorobiphenyl-2-yl)ethene (**7l**, 39 mg, 0.10 mmol) and $FSO_3H \cdot SbF_5$ (79 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave dibenzochrysene **10l** (28 mg, 80%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.42 (ddd, J_{HF} = 8.9, J = 7.9, 2.4 Hz, 1H), 7.61–7.72 (m, 6H), 8.38 (dd, J_{HF} = 11.5, J = 2.4 Hz, 1H), 8.63 (d, J = 8.0 Hz, 1H), 8.66–8.72 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 113.8 (d, J_{CF} = 24 Hz), 114.9 (d, J_{CF} = 24 Hz), 123.4, 123.6, 123.7, 125.8 (d, J_{CF} = 9 Hz), 126.3, 126.6, 126.75, 126.83, 126.83, 126.9, 127.4, 128.11, 128.11, 128.6, 128.9, 128.98, 128.98, 129.03, 129.1, 130.5, 130.7 (d, J_{CF} = 9 Hz), 130.8, 131.0, 161.5 (d, J_{CF} = 246 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): 47.3–47.4 (m). IR (neat): ν 3068, 2922, 2854, 1616, 1481, 1452, 1186, 764, 725 cm^{-1}. HRMS (APCI+): *m/z* Calcd. for $C_{26}H_{16}F$ $[M+H]^+$: 346.1158; Found: 346.1153.

2-Chlorodibenzo[*g,p*]chrysene (10m)

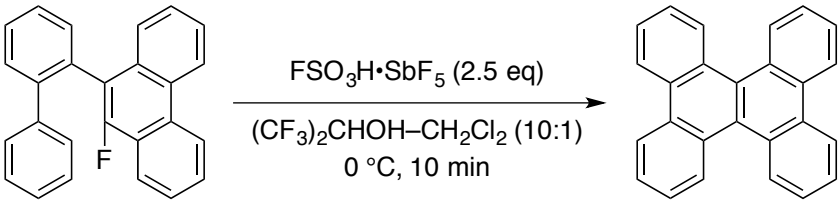


Dibenzochrysene **10m** was synthesized by method A described for **10a** using 1-(biphenyl-2-yl)-1-(4'-chlorobiphenyl-2-yl)-2,2-difluoroethene (**7m**, 40 mg, 0.10 mmol) and

$FSO_3H \cdot SbF_5$ (79 mg, 0.25 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 30:1) gave dibenzochrysene **10m** (20 mg, 54%) as a white solid.

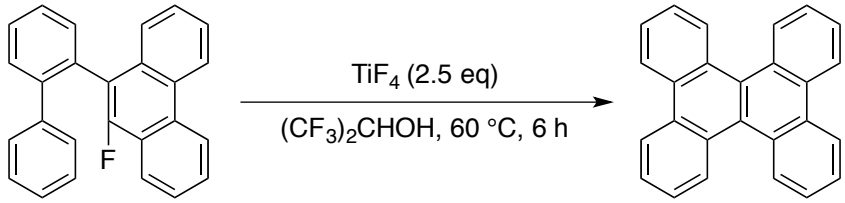
^{1}H NMR (500 MHz, $CDCl_3$): δ 7.62–7.72 (m, 7H), 8.62–8.65 (m, 3H), 8.68–8.72 (m, 5H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 123.5, 123.6, 123.7, 125.2, 126.4, 126.7, 126.80, 126.80, 126.80, 126.84, 126.95, 126.95, 128.0, 128.36, 128.40, 128.8, 128.9, 128.99, 129.01, 129.1, 129.2, 130.3, 130.4, 130.9, 131.0, 132.5. IR (neat): ν 3064, 2924, 1597, 1477, 1450, 1232, 1198, 1101, 912, 764, 725 cm^{-1}. HRMS (APCI+): *m/z* Calcd. for $C_{26}H_{15}Cl$ $[M]^+$: 362.0862; Found: 362.0848.

Mechanistic Study: Cyclization of Fluorophenanthrene 11a



method A:

In a 5 mL flask was placed $FSO_3H \cdot SbF_5$ (79 mg, 0.25 mmol). After the flask was cooled to 0 °C, HFIP (1.0 mL) was added. After stirring at the same temperature for 5 min, a dichloromethane (0.10 mL) solution of 9-(biphenyl-2-yl)-10-fluorophenanthrene (**11a**, 35 mg, 0.10 mmol) was added to the flask. After vigorous stirring at 0 °C for 10 min, the reaction was quenched with aqueous NaOH (1 M), and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20:1) to give **10a** (31 mg, 93%) as a pale yellow solid.



method B:

In a Schlenk tube were placed TiF_4 (31 mg, 0.25 mmol), 9-(biphenyl-2-yl)-10-fluorophenanthrene (**11a**, 35 mg, 0.10 mmol), and HFIP (1.0 mL). After vigorous stirring at 60 °C for 6 h, the reaction was quenched with saturated aqueous $NaHCO_3$, and organic materials were extracted with dichloromethane three times. The combined extracts were washed with brine and dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20:1) to give **10a** (31 mg, 95%) as a pale yellow solid.

References for experimental section

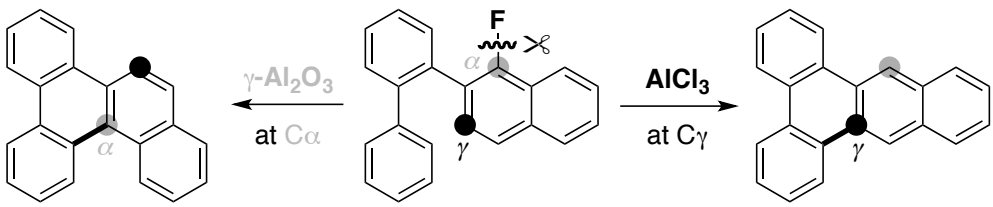
(3) Fuchibe, K.; Mayumi, Y.; Zhao, N.; Watanabe, S.; Yokota, M.; Ichikawa, J. *Angew. Chem., Int. Ed.* 2013, *52*, 7825–7828.

CHAPTER 4

Acid-Promoted Regioswitchable Aromatic C–F Bond Activation: Synthesis of Benzene-Fused Triphenylenes

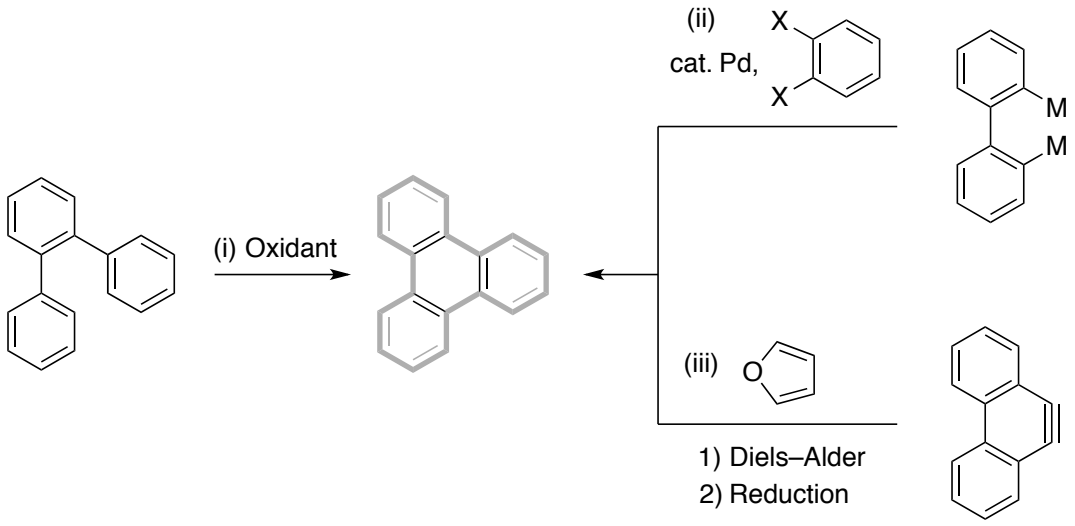
Abstract

The selective synthesis of benzo[*f*]tetraphenes or benzo[*g*]chrysenes was achieved via aromatic C–F bond cleavage and regioselective C–C bond formation depending upon the choice of aluminium reagents. On treatment with $AlCl_3$, 2-(biphenyl-2-yl)-1-fluoronaphthalenes afforded benzo[*f*]tetraphenes via regioselective C–C bond formation on the carbon atoms γ to the original position of the fluorine substituent. In contrast, α-selective C–C bond formation was promoted by treatment with γ-Al_2O_3 to give benzo[*g*]chrysenes.



4-1. Introduction

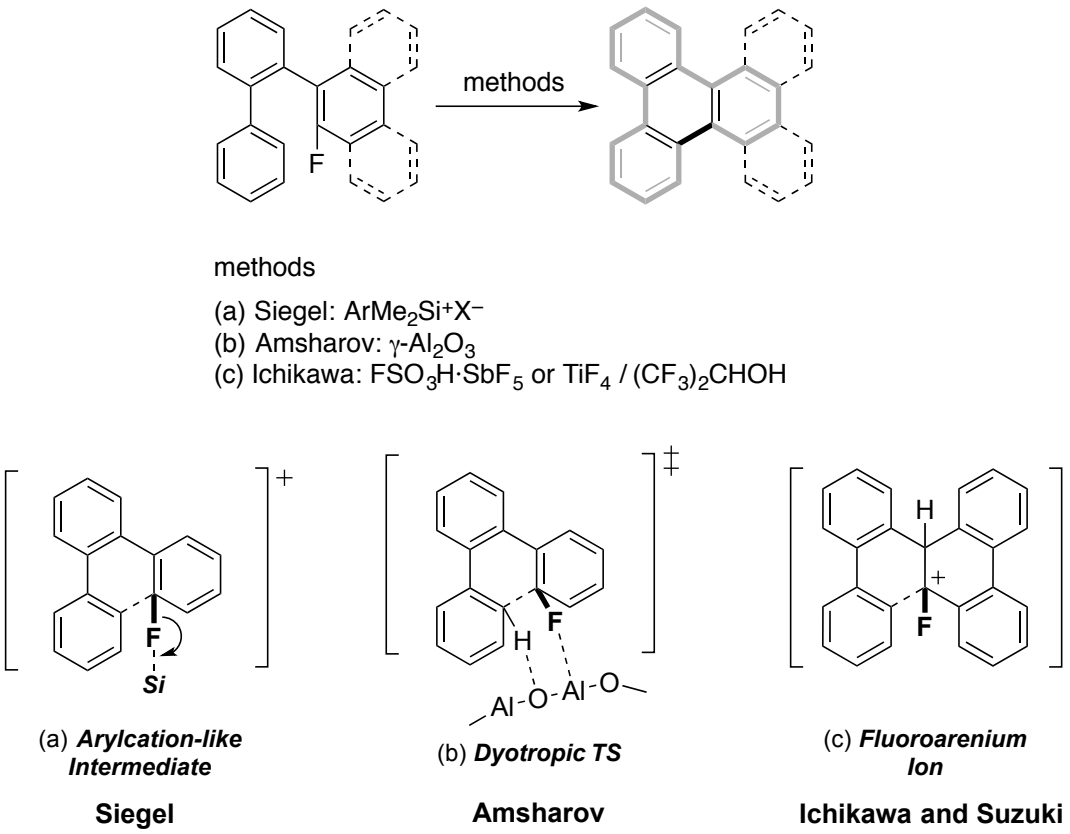
Triphenylenes are important class of polycyclic aromatic hydrocarbons (PAHs). Their rigid, planar structures are susceptible to π–π interaction leading to formation of columnar alignments. Thus, triphenylene derivatives have attracted much attention in materials science as liquid crystals and organic semiconductors.[1,2] Triphenylenes have typically been synthesized via the following processes: (i) the oxidative carbon–carbon bond formation of *o*-terphenyls, (ii) the Pd-catalyzed cross coupling of dimetallobiphenyls, and (iii) the Diels–Alder reaction of phenanthrynes (Scheme 1).[3]



Scheme 1. Conventional methods for the synthesis of triphenylenes

As new approaches to triphenylene derivatives, I focused on aromatic C–F bond activation using acid. Siegel and Amsharov independently reported the synthesis of polycyclic aromatic hydrocarbons (PAHs) including triphenylenes by cationic cyclizations, which proceeded through aromatic C–F bond activation using silylium equivalents (Scheme 2a)[4] and γ-Al_2O_3 (Scheme 2b),[5] respectively.[6] In contrast, I accomplished dibenzo[*g*,*p*]chrysene synthesis via the $FSO_3H{\cdot}SbF_5$- or TiF_4-promoted double C–F bond activation of 1,1-difluro-1-alkenes bearing two biaryl groups,

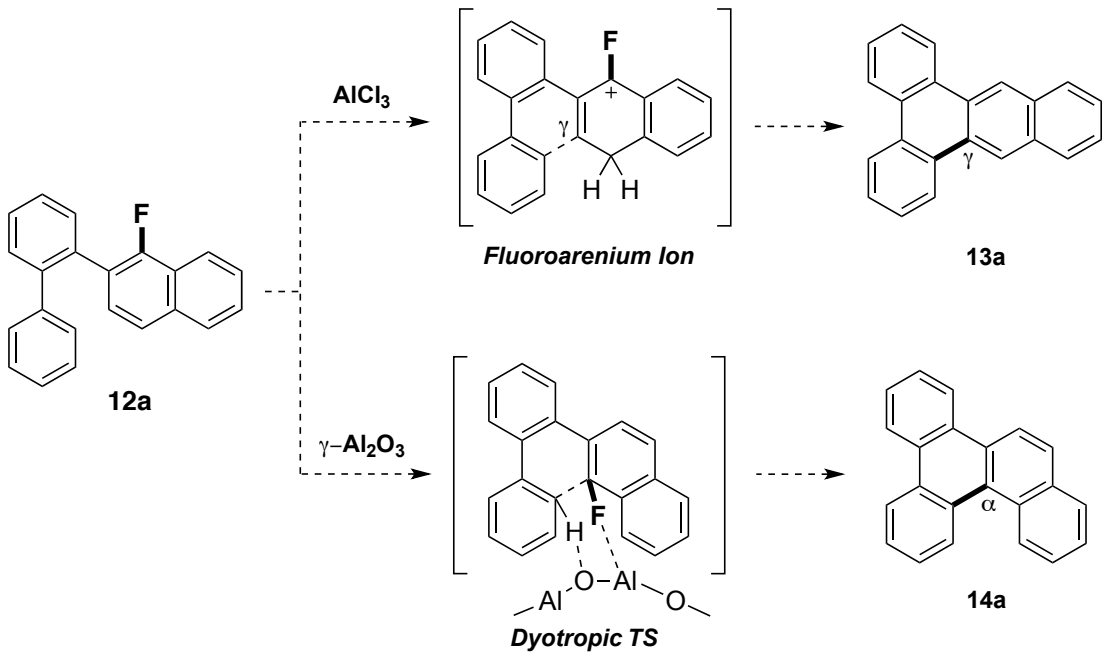
where aromatic C–F bond activation was involved in the second cyclization of intermediary 9-(biaryl-2-yl)-10-fluorophenanthrenes via fluoroarenium intermediates (Scheme 2c).[7]



Scheme 2. Triphenylene synthesis by cationic cyclization via aromatic C–F bond activation

In the course of my studies on acid-promoted aromatic C–F bond activation,[7,8] I found that treating 2-(biphenyl-2-yl)-1-fluoronaphthalene (**12a**) with $FSO_3H{\cdot}SbF_5$ or TiF_4 selectively afforded benzo[*f*]tetraphene (**13a**). In this reaction, by utilizing fluoroarenium ions mentioned in Chapter 1, fluoronaphthalene **12a** underwent intramolecular cyclization via C–F bond cleavage and selective C–C bond formation at the carbon atom γ to the original position of the fluorine substituent.[9] As a result of acid screening, $AlCl_3$ was found to be the best acid for this reaction. Conversely, when **12a** was treated with γ-Al_2O_3, benzo[*g*]chrysene (**14a**) was selectively obtained via C–F bond cleavage and C–C bond formation at the α-carbon atom. Thus, I achieved the complete switching of the

regioselectivity in defluorinative intramolecular cyclization of the single substrate **12a** using different aluminium reagents, which led to the synthesis of differently benzene-fused triphenylene compounds (Scheme 3).[10,11]

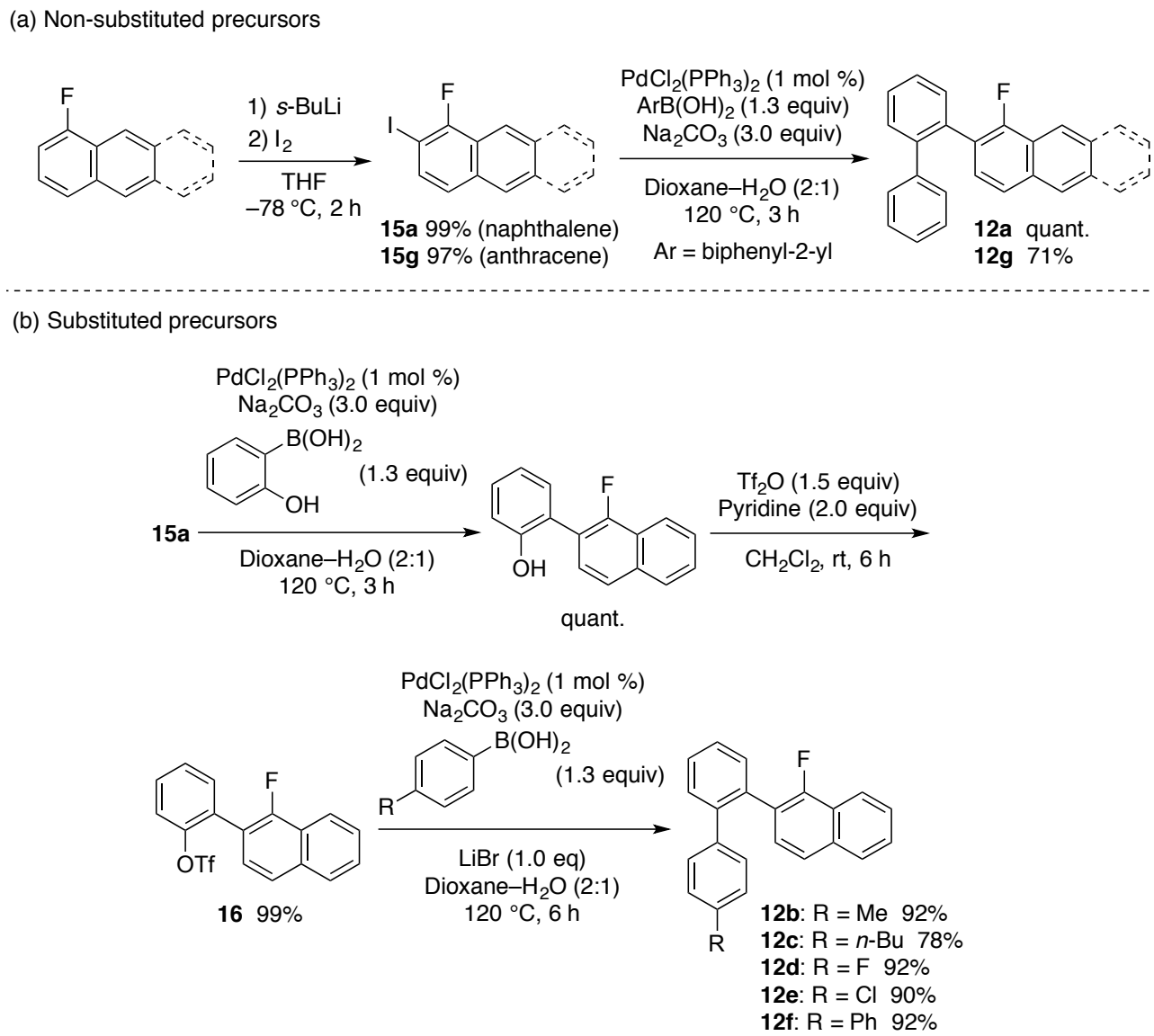


Scheme 3. Regioswichable synthesis of benzene-fused triphenylenes depending on aluminium reagents

4-2. Preparation of Cyclization Precursors

The cyclization precursors, 2-(biaryl-2-yl)-1-fluoronaphthalenes **12** were prepared from 1-fluoronaphthalene (Scheme 3). 2-(Biphenyl-2-yl)-1-fluoronaphthalene (**12a**) was prepared directly from 1-fluoro-2-iodonaphthalene (**15a**) via the Suzuki–Miyaura coupling with (biphenyl-2-yl)boronic acid in a quantitative yield (Scheme 4a). The preparation of ring-substituted precursors involved double Suzuki–Miyaura coupling reactions of **15a** with (2-hydroxyphenyl)boronic acid and of the resulting 2-(1-fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (**16**) with 4-substituted phenylboronic acids (Scheme 4b). Thus, methyl-,

butyl-, fluoro-, chloro-, and phenyl-bearing 2-(biaryl-2-yl)-1-fluoronaphthalenes **12b–1f** were obtained in high yields. Furthermore, 2-(biphenyl-2-yl)-1-fluoroanthracene (**12g**) was prepared via the Suzuki–Miyaura coupling of 1-fluoro-2-iodoanthracene (**15g**) with (biphenyl-2-yl)boronic acid according to the procedure for the preparation of **12a** from **15a** (Scheme 4a).

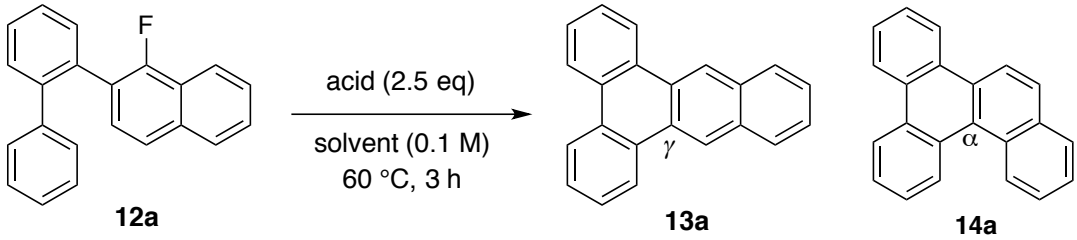


Scheme 4. Preparation of cyclization precursors **12**.

4-3. Cyclization of 2-(Biaryl-2-yl)-1-fluoronaphthalenes

Upon treatment with $FSO_3H{\cdot}SbF_5$ or TiF_4, which were suitable acids for the synthesis of dibenzo[*g*,*p*]chrysenes from the 1,1-difluoro-1-alkenes in 1,1,1,3,3,3-hexafluoropropan-2-ol (HFIP),[7,8] 2-(biphenyl-2-yl)-1-fluoronaphthalene (**12a**) selectively afforded benzo[*f*]tetraphene (**13a**) in 12% or 47% yield (Table 1, entries 3 and 4). In these cases, C–C bond formation at the carbon γ to the fluorine substituent proceeded instead of C–C bond formation at the α carbon, probably avoiding steric hindrance. I thus sought suitable conditions for the synthesis of **13a** via defluorinative cyclization of **12a** with a series of Brønsted and Lewis acids (Table 1). While *p*-toluenesulfonic acid (TsOH) gave no cyclized products (entry 1), treating **12a** with 2.5 equiv of trifluoromethanesulfonic acid (TfOH) selectively afforded **13a** in 97% yield (entry 2). Among the Lewis acids examined (entries 4–10), $AlCl_3$ and $ZrCl_4$ effectively promoted the cyclization of **12a** in HFIP to give **13a** in almost quantitative yields (entries 7 and 10). Screening of solvents used with $AlCl_3$ revealed that chlorobenzene also exhibited a high efficiency comparable to that of HFIP (entry 11). I thus decided to use $AlCl_3$ as the reagent and chlorobenzene as the solvent for cyclization of **12a** owing to their low cost. Finally, the reaction still proceeded with quantitative yield when the amount of $AlCl_3$ was decreased from 2.5 equiv to 1.5 equiv (entry 12).

Table 1. Screening of Conditions for Selective Synthesis of Benzo[*f*]tetraphene (**12a**)



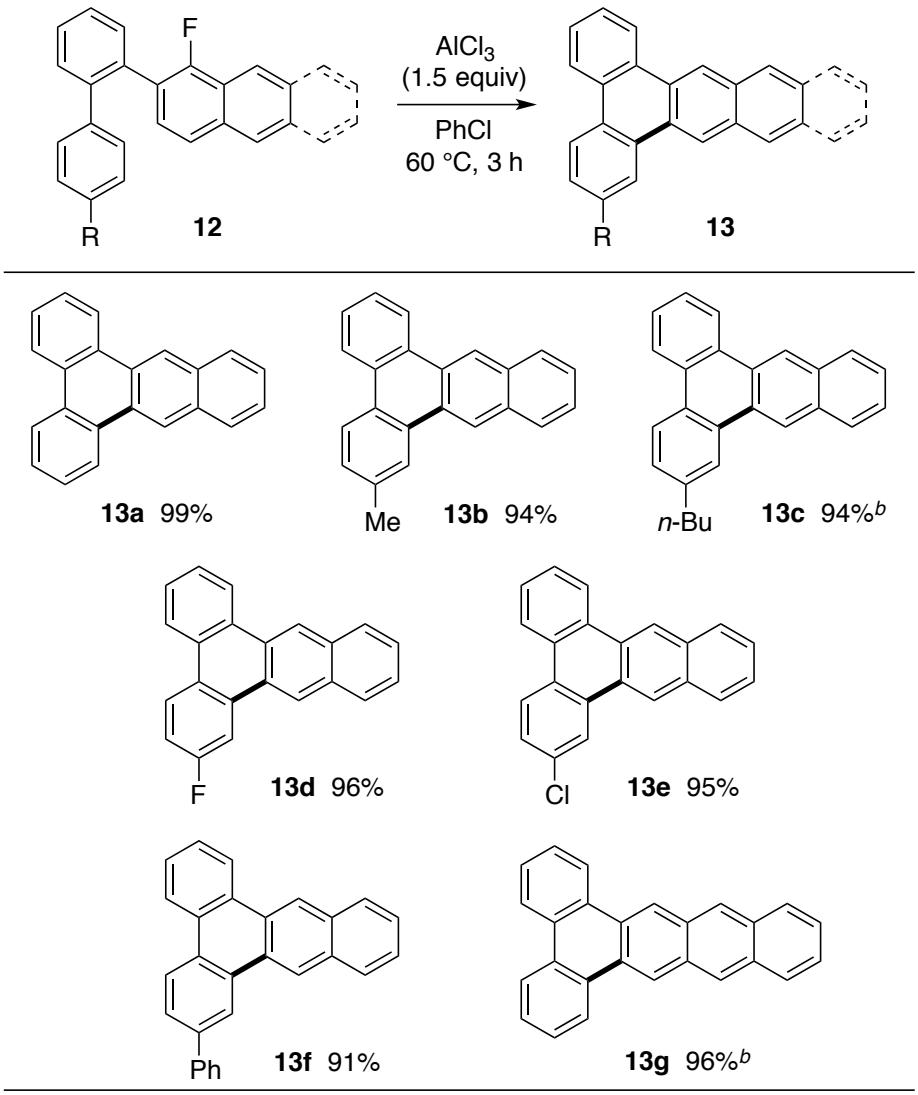
entry	acid	solvent	**13a** / %[a]	**14a** / %[a]
1	TsOH	$(CF_3)_2CHOH$	N.D.[b]	N.D.[b]
2	TfOH	$(CF_3)_2CHOH$	97	<1
3	$FSO_3H{\cdot}SbF_5$	$(CF_3)_2CHOH$	12	N.D.[b]
4	TiF_4	$(CF_3)_2CHOH$	47	N.D.[b]
5	$TiCl_4$	$(CF_3)_2CHOH$	-	N.D.[b]
6	ZrF_4	$(CF_3)_2CHOH$	-	N.D.[b]
7	$ZrCl_4$	$(CF_3)_2CHOH$	99	<1
8	Me_3SiOTf	$(CF_3)_2CHOH$	52	N.D.[b]
9	$BF_3{\cdot}OEt_2$	$(CF_3)_2CHOH$	-	N.D.[b]
10	$AlCl_3$	$(CF_3)_2CHOH$	99 (98)	<1
11	$AlCl_3$	PhCl	99	<1
12	$AlCl_3$	PhCl	99 (99)	<1

[a]Yield was determined by ^{1}H NMR measurement using CH_2Br_2 as an internal standard. [b]N.D. = Not detected. [c]0 °C, 1 h. [d]$AlCl_3$ (1.5 equiv).

The defluorinative cyclization of 2-(biaryl-2-yl)-1-fluoronaphthalenes **12** with different substituents was examined using the optimized conditions obtained above for the synthesis of **13a** from **12a** (Table 2). Alkyl-substituted 2-(biphenyl-2-yl)-1-fluoronaphthalenes **12b** and **12c** successfully underwent defluorinative cyclization to afford the corresponding benzo[*f*]tetraphenes **13b** and **13c** in high yields; however, the effective cyclization of butyl-bearing substrate required HFIP as the solvent instead of chlorobenzene. The cyclization of the fluorinated and chlorinated 2-(biphenyl-2-yl)-1-fluoronaphthalenes **12d** and **12e** proceeded without the loss of the halogen

atoms at the 4'-positions. Phenyl-substituted benzo[*f*]tetraphene **13f** was also obtained in 88% yield from 1-fluoronaphthalene **12f** bearing a *p*-terphenyl moiety. The reaction of fluoroanthracene derivative **12g** proceeded in HFIP to afford dibenzo[*a*,*c*]tetracene (**13g**) in 96% yield.

Table 2. Selective Synthesis of Benzo[*f*]tetraphenes **13**[a]

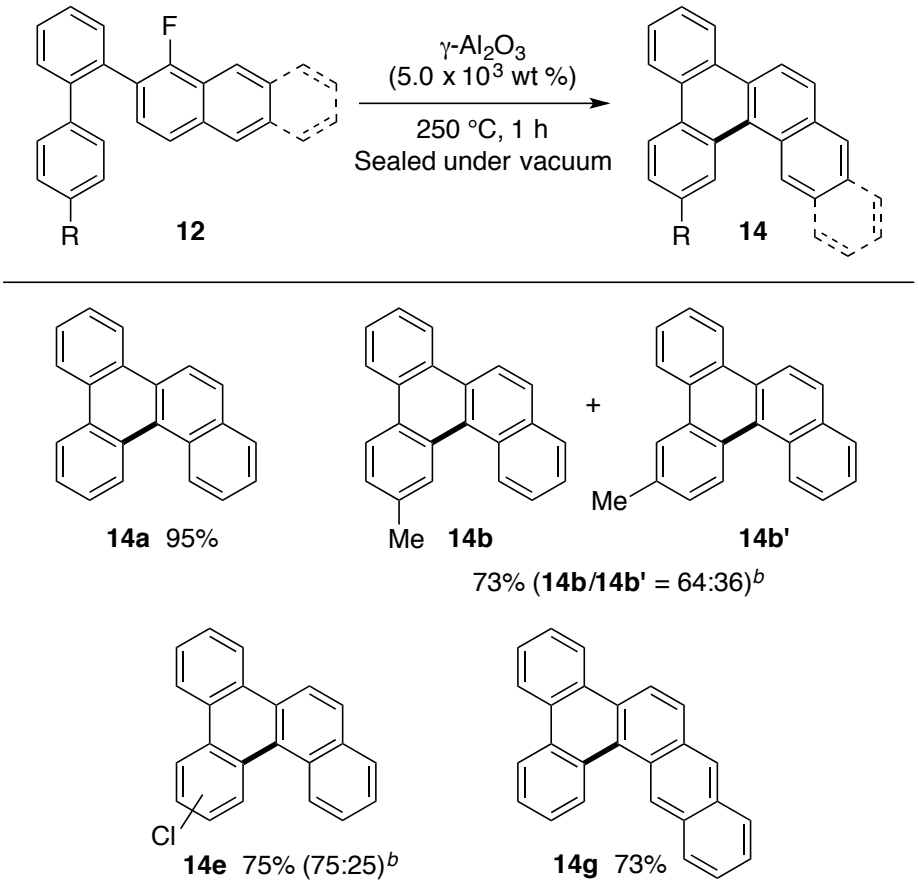


[a] Isolated yield. [b]HFIP was used as the solvent instead of PhCl.

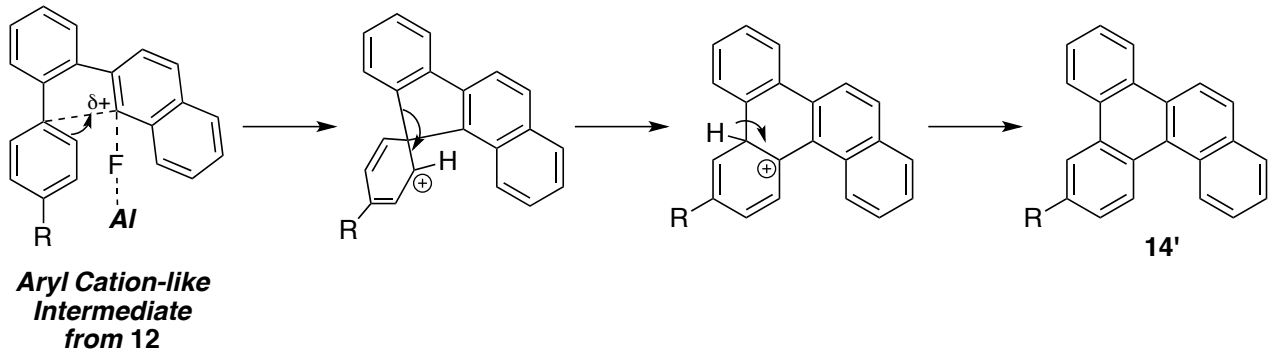
In contrast to the reactions with $AlCl_3$, γ-Al_2O_3 promoted defluorinative cyclization of fluoronaphthalenes **12** at the carbon α to the fluorine substituent (Table 3). Treatment of **12a** with 5.0 x 10^3 wt% of γ-Al_2O_3 at 250 °C in a pre-evacuated sealed tube afforded benzo[*g*]chrysene (**14a**)

in 95% yield as the sole product. α-Selective cylization of methyl- and chlorine-substituted fluoronaphthalenes **12b** and **12e** also proceeded successfully to afford the corresponding benzo[*g*]chrysenes in 73% and 75% yields, respectively. In these reactions, partial migration of the substituents occurred during cyclizations probably by *ipso* attack to the biaryl moiety, indicating that the reaction would proceed via C–F bond polarization leading to an aryl cation-like intermediate (Scheme 5).[12] Because of the high tolerance of C–F bond activation conditions to aryl C–Cl bonds as shown in Tables 2 and 3, both approaches open a facile way to various chlorinated PAHs, which are less accessible by other methods. Furthermore, dibenzo[*a*,*c*]tetraphene (**14g**) was produced by the reaction of 2-(biphenyl-2-yl)-1-fluoroanthracene (**12g**) in 73% yield under the same conditions.

Table 3. Selective Synthesis of Benzo[*g*]chrysenes **14**[a]



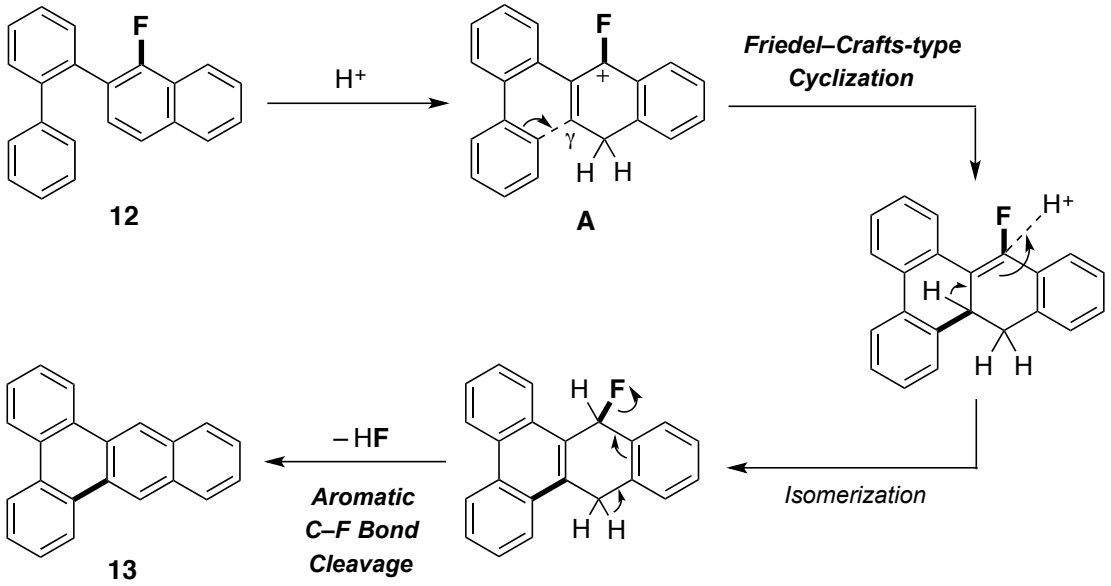
[a] Isolated yield. [b] Regioisomer ratio was determined by ^{1}H NMR measurement.



Scheme 5. Plausible migration mechanism via ipso-attack of an aryl cation-like intermediate to the biaryl moiety

4-4. Mechanistic Study

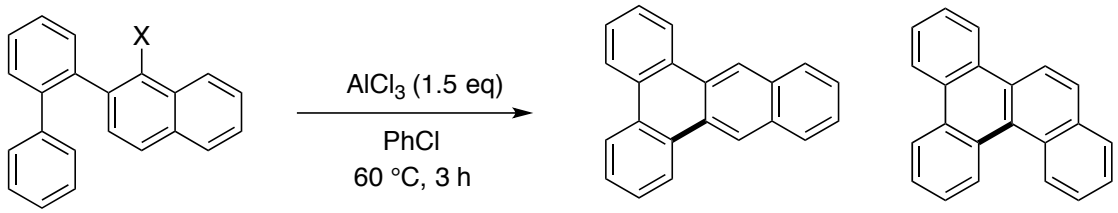
A plausible mechanism of cyclization using $AlCl_3$ is shown in Scheme 6. First, the protonation of naphthalene skeleton of **12** afforded an arenium intermediate **A**, in whitch the carbocation is stabilized by α-fluorine substituent. Then, a Friedel–Crafts-type cyclization proceeded, at the position γ to the fluorine because of steric hindrance. Second, isomerization occurred driven by forming a phenanthrene skeleton followed by the elimination of HF afforded the desired product, benzo[*f*]tetraphene (**13**).



Scheme 6. Plausible reaction mechanism of cyclization via fluoroarenium intermediate

In order to gain mechanistic insight into the γ-selective cyclization of 2-(biaryl-2-yl)-1-fluoronaphthalenes **12**, the effect of the fluorine substituent was investigated by comparing the efficiency of the cyclization with the corresponding halonaphthalenes (Table 4). When 1-chlorinated, -brominated, and -iodinated 2-(biphenyl-2-yl)naphthalenes **17a–c** were subjected to the optimal conditions used for γ-selective cyclization of fluoro substrate **12a**, all the halides exhibited diminished yields of cyclized product **13a** compared to that of **12a** (entries 2–4 vs. entry 1). These results indicate that the high efficiency in γ-selective cyclization of **12a** can be attributed to the relatively ready generation of the fluorine-stabilized intermediary arenium ions **A** (Scheme 6).[7, 11]

Table 4. Effect of Leaving Groups

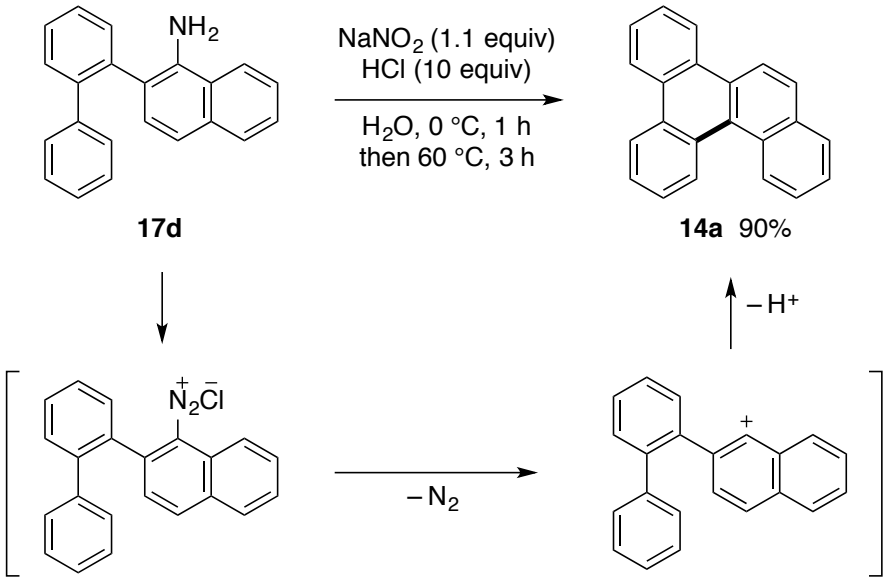


12a, 17a–c **13a** **14a**

entry	X	**13a** / %[a]	**14a** / %[a]
1	F (**12a**)	quant	< 1
2	Cl (**17a**)	73	2
3	Br (**17b**)	39	4
4	I (**17c**)	22	3

[a]Yield was determined by ^{1}H NMR measurement using CH_2Br_2 as an internal standard.

On the other hand, cyclization via an aryl cation intermediate generated from a fluorine-free precursor exhibited opposite regioselectivity (Scheme 7). When 2-(biphenyl-2-yl)naphthalene-1-diazonium chloride, prepared from 2-(biphenyl-2-yl)naphthalen-1-amine (**17d**), was heated at 60 °C, benzo[*g*]chrysene (**14a**) was obtained in 90% yield as the sole product.[14] This result suggested that the reaction of 2-(biphenyl-2-yl)-1-fluoronaphthalene (**12a**) with γ-Al_2O_3 might proceed via an aryl cation-like intermediate.



Scheme 7. Cyclization of an aryl cation intermediate

4-5. Summary

In summary, I have achieved highly effective cyclizations of 1-fluoronaphthalenes bearing biaryl groups via aromatic C–F bond activation mediated by aluminium reagents. It is noteworthy that the choice of aluminium reagents altered the regioselectivities in the cyclization of common 2-(biaryl-2-yl)-1-fluoronaphthalene precursors, enabling the selective synthesis of two different benzotriphenylenes, i.e., benzo[*f*]tetraphenes and benzo[*g*]chrysenes. Since higher order PAHs are particularly promising constituents in organic electronic devices,[15] the formation of extended π-systems by the current methodology appears to be a powerful route to functional materials.

4-6. References and Notes

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4-7. Experimental Section

General statements

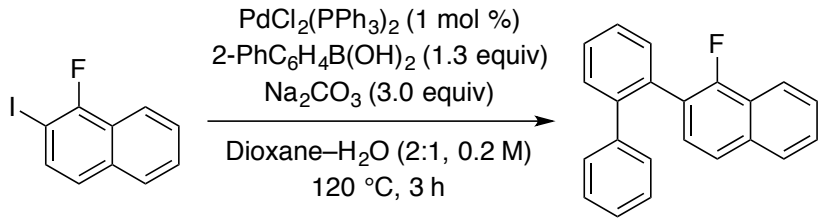
^{1}H NMR, ^{13}C NMR, and ^{19}F NMR spectra were recorded on a Bruker Avance 500 or a JEOL ECS-400 spectrometer. Chemical shift values are given in ppm relative to internal Me_4Si (for ^{1}H NMR: δ = 0.00 ppm), $CDCl_3$ (for ^{13}C NMR: δ = 77.0 ppm), and C_6F_6 (for ^{19}F NMR: δ = 0.00 ppm). IR spectra were recorded on a Horiba FT-300S spectrometer by the attenuated total reflectance (ATR) method. Mass spectra were measured on a JEOL JMS-T100GCV or a JMS-T100CS spectrometer. Elemental analyses were carried out at the Elemental Analysis Laboratory, Division of Chemistry, Faculty of Pure and Applied Sciences, University of Tsukuba.

Column chromatography and preparative thin-layer chromatography (PTLC) were conducted on silica gel (Silica Gel 60 N, Kanto Chemical Co., Inc. for column chromatography and Wakogel B-5F, Wako Pure Chemical Industries for PTLC). All the reactions were conducted under nitrogen. Diethyl ether, tetrahydrofuran (THF), and dichloromethane were purified by a solvent-purification system (GlassContour) equipped with columns of activated alumina and supported-copper catalyst (Q-5) before use. 1,1,1,3,3,3-Hexafluoropropan-2-ol (HFIP) and chlorobenzene were distilled from CaH_2 and stored over activated molecular sieves 4A. 1-Fluoro-2-iodonaphthalene (**15a**)[1], 1-chloronaphthalen-2-yl trifluoromethanesulfonate,[2] and 1-(trimethylsilyl)naphthalen-2-yl trifluoromethanesulfonate[3] were prepared according to the literature procedures. Unless otherwise noted, materials were obtained from commercial sources and used directly without further purifications.

Preparation of Cyclization Precursors 12

Preparation of 1-Fluoronaphthalenes 12a–1f

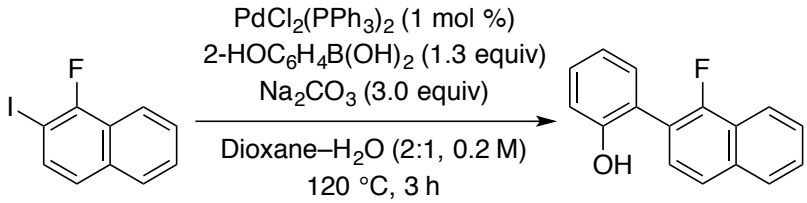
2-(Biphenyl-2-yl)-1-fluoronaphthalene (12a)



In a flask were placed 1-fluoro-2-iodonaphthalene (**15a**, 2.72 g, 10.0 mmol), (biphenyl-2-yl)boronic acid (2.57 g, 13.0 mmol), Na_2CO_3 (3.18 g, 30.0 mmol), and $PdCl_2(PPh_3)_2$ (70 mg, 0.10 mmol). After the flask was purged with nitrogen, a degassed mixture of 1,4-dioxane (33.3 mL) and water (16.7 mL) was added. The mixture was heated at 120 °C for 3 h, and then cooled to room temperature. After aqueous HCl (2 M, 30 mL) was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 50:1) to give **12a** (2.97 g, quant.) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.11 (dd, J = 8.4, 7.3 Hz, 1H), 7.14–7.16 (m, 3H), 7.17–7.19 (m, 2H), 7.44–7.53 (m, 7H), 7.77–7.79 (m, 1H), 8.02–8.03 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 120.8 (d, J = 6 Hz), 122.8 (d, J = 3 Hz), 123.3 (d, J = 15 Hz), 123.7 (d, J = 17 Hz), 126.2, 126.60, 126.60, 127.2, 127.4, 127.9, 128.2, 129.0 (d, J = 3 Hz), 129.3, 130.4, 131.4, 133.9 (d, J = 3 Hz), 134.4, 141.2, 141.7, 154.9 (d, J = 253 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 35.6 (d, J_{FH} = 7 Hz, 1F). IR (neat): ν 3059, 3020, 1483, 1464, 1377, 814, 760, 741, 700 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{22}H_{15}F$ $[M]^+$: 298.1158; Found: 298.1165.

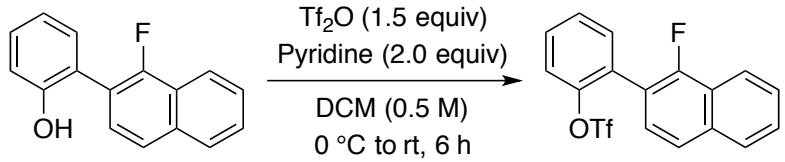
2-(1-Fluoronaphthalen-2-yl)phenol



In a flask were placed 1-fluoro-2-iodonaphthalene (**15a**, 5.44 g, 20.0 mmol), (2-hydroxyphenyl)boronic acid (3.59 g, 26.0 mmol), Na_2CO_3 (6.36 g, 60.0 mmol), and $PdCl_2(PPh_3)_2$ (140 mg, 0.20 mmol). After the flask was purged with nitrogen, a degassed mixture of 1,4-dioxane (66.7 mL) and water (33.3 mL) was added. The mixture was heated at 120 °C for 3 h, and then cooled to room tempurture. After aqueous HCl (2 M, 30 mL) was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 15:1) to give 2-(1-fluoronaphthalen-2-yl)phenol (4.76 g, quant.) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 4.99 (brs, 1H), 7.04–7.08 (m, 2H), 7.33–7.36 (m, 2H), 7.46 (dd, J = 8.4 Hz, J_{HF} = 7.2 Hz, 1H), 7.57–7.63 (m, 2H), 7.75 (d, J = 8.5 Hz, 1H), 7.90–7.92 (m, 1H), 8.17–8.19 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 116.1, 118.3 (d, J_{CF} = 15 Hz), 120.79, 120.84, 122.4, 123.8 (d, J_{CF} = 17 Hz), 124.2, 126.7, 127.2, 127.4 (d, J_{CF} = 3 Hz), 128.1 (d, J_{CF} = 4 Hz), 129.7, 131.2, 134.5 (d, J_{CF} = 5 Hz), 152.9, 155.2 (d, J = 253 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 37.8 (d, J_{FH} = 7 Hz, 1F). IR (neat): ν 3537, 3423, 3059, 1448, 1379, 1282, 1176, 1049, 889, 808, 783, 748, 715, 667, 602, 565 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{16}H_{11}FO$ $[M]^+$: 238.0794; Found: 238.0802.

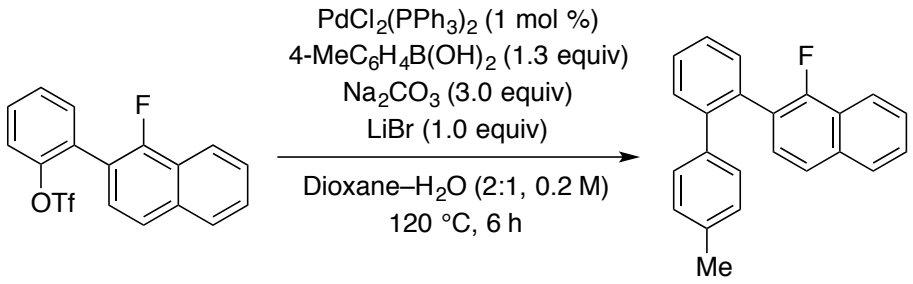
2-(1-Fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (16)



To a dichloromethane (40 mL) solution of 2-(1-fluoronaphthalen-2-yl)phenol (4.77 g, 20.0 mmol) and pyridine (3.22 mL, 39.8 mmol) was added Tf_2O (5.05 mL, 30.0 mmol) dropwise at 0 °C. After stirring at 0 °C for 5 min, the mixture was warmed to room temperature and stirred for another 6 h. After water (40 mL) was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 25:1) to give **16** (7.33 g, 99%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.42 (dd, J = 8.5 Hz, J_{HF} = 7.2 Hz, 1H), 7.45–7.48 (m, 1H), 7.49–7.54 (m, 2H), 7.56–7.58 (m, 1H), 7.59–7.61 (m, 2H), 7.73 (d, J = 8.5 Hz, 1H), 7.90–7.92 (m, 1H), 8.17–8.19 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 117.2 (d, J_{CF} = 14 Hz), 118.3 (q, J_{CF} = 322 Hz), 121.0 (d, J_{CF} = 6 Hz), 121.9, 123.5 (d, J_{CF} = 17 Hz), 123.7 (d, J_{CF} = 4 Hz), 126.8, 127.49, 127.51, 127.6 (d, J_{CF} = 2 Hz), 128.4, 129.76, 129.80 (d, J_{CF} = 12 Hz), 132.7, 134.8 (d, J_{CF} = 5 Hz), 147.3, 155.3 (d, J_{CF} = 256 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 37.8 (d, J_{FH} = 7 Hz, 1F), 87.6 (s, 3F). IR (neat): ν 3068, 1495, 1421, 1383, 1248, 1209, 1138, 1080, 1049, 903, 877, 852, 816, 768, 598 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{17}H_{10}F_4O_3S$ $[M]^+$: 370.0287; Found: 370.0282.

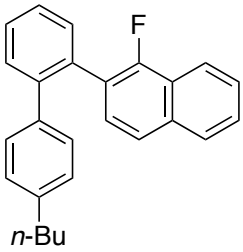
1-Fluoro-2-(4'-methylbiphenyl-2-yl)naphthalene (12b)



In a Schlenk tube were placed 2-(1-fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (**16**, 222 mg, 0.600 mmol), (4-methylphenyl)boronic acid (106 mg, 0.78 mmol), Na_2CO_3 (191 mg, 1.8 mmol), LiBr (52 mg, 0.60 mmol), and $PdCl_2(PPh_3)_2$ (4.2 mg, 6 μmol). After the tube was purged with nitrogen, a degassed mixture of 1,4-dioxane (2.0 mL) and water (1.0 mL) was added. The mixture was heated at 120 °C for 6 h, and then cooled to room tempurture. After aqueous HCl (2 M, 3 mL) was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 50:1) to give **12b** (173 mg, 92%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.24 (s, 3H), 6.96 (d, J = 8.0 Hz, 2H), 7.07 (d, J = 8.0 Hz, 2H), 7.11 (dd, J = 8.3 Hz, J_{HF} = 7.2 Hz, 1H), 7.42–7.53 (m, 7H), 7.78–7.80 (m, 1H), 8.03–8.05 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.0, 120.8 (d, J = 6 Hz), 122.8, 123.4 (d, J = 14 Hz), 123.7 (d, J = 17 Hz), 126.2, 126.5, 126.9, 127.3, 128.1, 128.6, 129.1, 130.4, 131.4, 133.87, 133.89, 134.3, 136.2, 138.3, 141.7, 154.9 (d, J = 252 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 35.5 (d, J_{FH} = 7 Hz, 1F). IR (neat): ν 3055, 3022, 2918, 1487, 1464, 1377, 814, 758, 729, 710 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{23}H_{17}F$ $[M]^+$: 312.1314; Found: 312.1320.

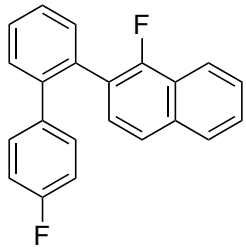
2-(4'-Butylbiphenyl-2-yl)-1-fluoronaphthalene (12c)



1-Fluoronaphthalene **12c** was prepared by the method described for **12b** using 2-(1-fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (**16**, 222 mg, 0.600 mmol), (4-butylphenyl)boronic acid (139 mg, 0.78 mmol), Na_2CO_3 (191 mg, 1.8 mmol), LiBr (52 mg, 0.60 mmol), and $PdCl_2(PPh_3)_2$ (4.2 mg, 6 μmol). Purification by silica gel column chromatography (hexane/EtOAc = 50:1) gave **12c** (167 mg, 78%) as a colorless oil.

^{1}H NMR (500 MHz, $CDCl_3$): δ 0.86 (t, J = 7.4 Hz, 3H), 1.23–1.30 (m, 2H), 1.48–1.54 (m, 2H), 2.50 (t, J = 7.7 Hz, 2H), 6.95 (d, J = 8.2 Hz, 2H), 7.07 (d, J = 8.2 Hz, 2H), 7.11 (dd, J = 8.3, J_{HF} = 7.4 Hz, 1H), 7.41–7.51 (m, 7H), 7.77–7.80 (m, 1H), 8.02–8.04 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 13.9, 22.3, 33.3, 35.2, 120.8 (d, J_{CF} = 6 Hz), 122.7 (d, J_{CF} = 5 Hz), 123.4 (d, J_{CF} = 15 Hz), 123.7 (d, J_{CF} = 17 Hz), 126.1 (d, J_{CF} = 2 Hz), 126.5, 126.9, 127.3 (d, J_{CF} = 3 Hz), 127.9, 128.1, 129.1, 129.2 (d, J_{CF} = 4 Hz), 130.4, 131.4, 133.9 (d, J_{CF} = 5 Hz), 134.4, 138.4, 141.2, 141.8, 154.9 (d, J_{CF} = 253 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 35.6 (d, J_{FH} = 7 Hz, 1F). IR (neat): ν 3055, 2954, 2927, 2856, 1604, 1487, 1464, 1377, 1259, 1192, 1059, 814, 760, 744, 602, 565 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{26}H_{23}F$ $[M]^+$: 354.1784; Found: 354.1768.

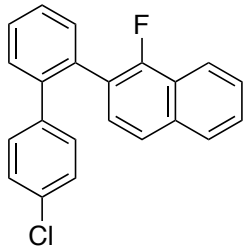
1-Fluoro-2-(4'-fluorobiphenyl-2-yl)naphthalene (12d)



1-Fluoronaphthalene **12d** was prepared by the method described for **12b** using 2-(1-fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (**16**, 222 mg, 0.600 mmol), (4-fluorophenyl)boronic acid (109 mg, 0.78 mmol), Na_2CO_3 (191 mg, 1.8 mmol), LiBr (52 mg, 0.60 mmol), and $PdCl_2(PPh_3)_2$ (4.2 mg, 6 μmol). Purification by silica gel column chromatography (hexane/EtOAc = 50:1) gave **12d** (174 mg, 92%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 6.84 (dd, J = 8.7 Hz, J_{HF} = 7.9 Hz, 2H), 7.10–7.15 (m, 3H), 7.44–7.53 (m, 7H), 7.79–7.81 (m, 1H), 8.01–8.03 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 114.8 (d, J_{CF} = 21 Hz), 120.8 (d, J_{CF} = 6 Hz), 122.99 (d, J_{CF} = 14 Hz), 123.01 (d, J_{CF} = 4 Hz), 123.6 (d, J_{CF} = 17 Hz), 126.3 (d, J_{CF} = 1 Hz), 126.7, 127.3, 127.4 (d, J_{CF} = 3 Hz), 128.2, 128.8 (d, J_{CF} = 4 Hz), 130.2, 130.8 (d, J_{CF} = 8 Hz), 131.4, 134.0 (d, J_{CF} = 5 Hz), 134.5, 137.2 (d, J_{CF} = 3 Hz), 140.7, 154.8 (d, J_{CF} = 252 Hz), 161.7 (d, J_{CF} = 247 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 35.9 (d, J_{FH} = 8 Hz, 1F), 45.58–45.64 (m, 1F). IR (neat): ν 3060, 3020, 1604, 1514, 1487, 1466, 1377, 1223, 1159, 1057, 837, 814, 760, 744 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{22}H_{14}F_2$ $[M]^+$: 316.1064; Found: 316.1068.

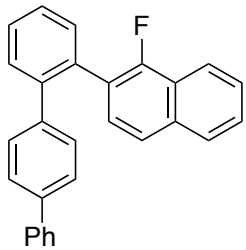
2-(4'-Chlorobiphenyl-2-yl)-1-fluoronaphthalene (12e)



1-Fluoronaphthalene **12e** was prepared by the method described for **12b** using 2-(1-fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (**16**, 222 mg, 0.600 mmol), (4-chlorophenyl)boronic acid (122 mg, 0.78 mmol), Na_2CO_3 (191 mg, 1.8 mmol), LiBr (52 mg, 0.60 mmol), and $PdCl_2(PPh_3)_2$ (4.2 mg, 6 μmol). Purification by silica gel column chromatography (hexane/EtOAc = 50:1) gave **12e** (180 mg, 90%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.09–7.13 (m, 5H), 7.45–7.53 (m, 7H), 7.79–7.81 (m, 1H), 8.01–8.03 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 120.8 (d, J_{CF} = 6 Hz), 122.8 (d, J_{CF} = 15 Hz), 123.1 (d, J_{CF} = 4 Hz), 123.6 (d, J_{CF} = 17 Hz), 126.4, 126.8, 127.4 (d, J_{CF} = 3 Hz), 127.5, 128.1, 128.3, 128.8 (d, J_{CF} = 4 Hz), 130.2, 130.5, 131.5, 132.7, 134.0 (d, J_{CF} = 5 Hz), 134.4, 139.7, 140.5, 154.8 (d, J_{CF} = 252 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 35.9 (d, J_{FH} = 7 Hz, 1F). IR (neat): ν 3060, 3020, 1604, 1514, 1487, 1466, 1377, 1223, 1159, 1157, 837, 814, 760, 744 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{22}H_{14}ClF$ $[M]^+$: 332.0768; Found: 332.0770.

1-Fluoro-2-(1,1':4',1''-terphenyl-2-yl)naphthalene (12f)



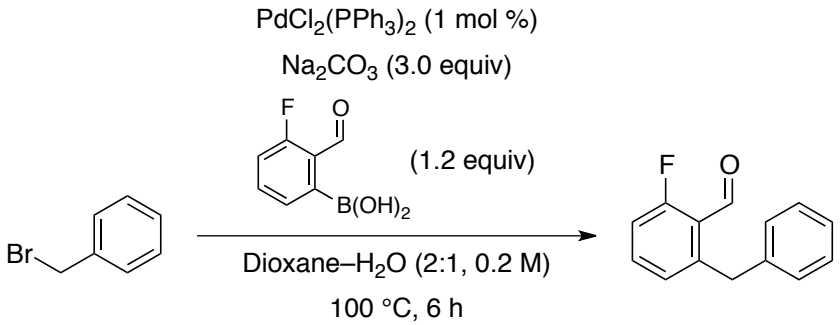
1-Fluoronaphthalene **12f** was prepared by the method described for **12b** using 2-(1-fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (**16**, 222 mg, 0.600 mmol),

(biphenyl-4-yl)boronic acid (155 mg, 0.78 mmol), Na_2CO_3 (191 mg, 1.8 mmol), LiBr (52 mg, 0.60 mmol), and $PdCl_2(PPh_3)_2$ (4.2 mg, 6 μmol). Purification by silica gel column chromatography (hexane/EtOAc = 50:1) gave **12f** (207 mg, 92%) as a yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.15 (dd, J = 8.4 Hz, J_{HF} = 7.3 Hz, 1H), 7.24–7.30 (m, 2H), 7.36–7.41 (m, 4H), 7.45–7.57 (m, 10H), 7.78–7.80 (m, 1H), 8.03–8.05 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 120.8 (d, J_{CF} = 6 Hz), 123.0 (d, J_{CF} = 4 Hz), 123.2 (d, J_{CF} = 15 Hz), 123.7 (d, J_{CF} = 17 Hz), 126.3, 126.55, 126.64, 126.9, 127.17, 127.23, 127.4 (d, J_{CF} = 3 Hz), 128.2, 128.7, 129.1 (d, J_{CF} = 4 Hz), 129.7, 130.4, 131.5, 134.0 (d, J_{CF} = 5 Hz), 134.4, 139.2, 140.2, 140.6, 141.3, 154.9 (d, J_{CF} = 252 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 35.6 (d, J_{FH} = 7 Hz, 1F). IR (neat): ν 3057, 3028, 1603, 1483, 1464, 1377, 1257, 1061, 1007, 908, 841, 816, 752, 729, 698, 565 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{28}H_{19}F$ $[M]^+$: 374.1471; Found: 374.1478.

Preparation of 1-Fluoroanthracene 12g

2-Benzyl-6-fluorobenzaldehyde

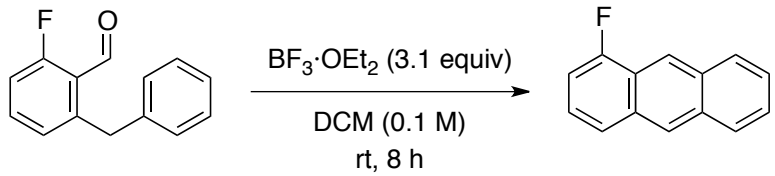


In a flask were placed benzyl bromide (0.299 mL, 2.51 mmol), (3-fluoro-2-formylphenyl)boronic acid (504 mg, 3.00 mmol), Na_2CO_3 (795 mg, 7.50 mmol), and $PdCl_2(PPh_3)_2$ (18 mg, 25 μmol). After the flask was purged with nitrogen, a degassed mixture of 1,4-dioxane (8.3 mL) and water (4.2 mL) was added. The mixture was heated at 100 °C for 6 h, and then cooled to room tempurture. After saturated aqueous NH_4Cl (15 mL) was added to the reaction mixture, the organic materials

were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20:1) to give 2-benzyl-6-fluorobenzaldehyde (398 mg, 74%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 4.43 (s, 2H), 7.00 (d, J = 7.9 Hz, 1H), 7.06 (dd, J_{HF} = 10.7 Hz, J = 8.3 Hz, 1H), 7.16 (d, J = 8.1 Hz, 2H), 7.20 (t, J = 7.4 Hz, 1H), 7.28 (dd, J = 8.1, 7.4 Hz, 2H), 7.47 (ddd, J = 8.3, 7.9 Hz, J_{HF} = 5.9 Hz, 1H), 10.52 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 38.6, 114.4 (d, J_{CF} = 21 Hz), 126.3, 127.3 (d, J_{CF} = 4 Hz), 128.4, 128.6 (d, J_{CF} = 15 Hz), 129.0, 135.1 (d, J_{CF} = 12 Hz), 139.7, 144.8, 166.4 (d, J_{CF} = 248 Hz), 188.9 (d, J_{CF} = 11 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 41.0 (dd, J_{FH} = 11, 6 Hz, 1F). IR (neat): ν 3030, 2791, 1697, 1612, 1572, 1471, 1456, 1417, 1254, 1186, 822, 785, 725, 700 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{14}H_{11}FO$ $[M]^+$: 214.0794; Found: 214.0803.

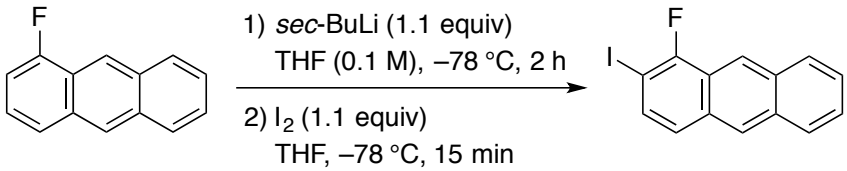
1-Fluoroanthracene[4]



To a dichloromethane (15.0 mL) solution of 2-benzyl-6-fluorobenzaldehyde (321 mg, 1.50 mmol) was added $BF_3{\cdot}OEt_2$ (0.565 mL, 4.58 mmol) at room temperature. After stirring at room temperature for 8 h, the reaction was quenched with saturated aqueous $NaHCO_3$. The organic materials were extracted with CH_2Cl_2 thrice, and the combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane) to give 1-fluoroanthracene (244 mg, 83%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.11 (dd, J_{HF} = 10.9 Hz, J = 7.4 Hz, 1H), 7.37 (ddd, J = 8.6, 7.4 Hz, J_{HF} = 5.3 Hz, 1H), 7.49–7.52 (m, 2H), 7.79 (d, J = 8.6 Hz, 1H), 7.99–8.02 (m, 1H), 8.04–8.07 (m, 1H), 8.45 (s, 1H), 8.68 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 107.6 (d, J_{CF} = 20 Hz), 119.6 (d, J_{CF} = 4 Hz), 122.9 (d, J_{CF} = 17 Hz), 124.0 (d, J_{CF} = 4 Hz), 124.6 (d, J_{CF} = 8 Hz), 125.9, 126.07, 126.10 (d, J_{CF} = 4 Hz), 128.1, 128.6, 131.6, 131.1, 132.7 (d, J_{CF} = 4 Hz), 158.9 (d, J_{CF} = 253 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 39.2 (dd, J_{FH} = 11, 5 Hz, 1F). IR (neat): ν 3060, 3043, 1639, 1556, 1537, 1460, 1313, 1250, 1200, 1134, 889, 789, 744, 729 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{14}H_9F$ $[M]^+$: 196.0688; Found: 196.0695.

1-Fluoro-2-iodonaphthalene (15g)

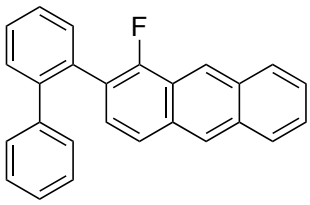


To a THF (12 mL) solution of 1-fluoroanthracene (236 mg, 1.20 mmol) was added *sec*-BuLi (1.03 M in hexane, 1.28 mL, 1.32 mmol) at –78 °C. After stirring at –78 °C for 2 h, a THF (1.3 mL) solution of I_2 (335 mg, 1.32 mmol) was added to the reaction mixture. The mixture was stirred at –78 °C for another 15 min, and then warmed to room temperature. The reaction was quenched with saturated aqueous $NaHCO_3$, and the organic materials were extracted with ether thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane) to give **15g** (377 mg, 97%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.51–7.56 (m, 3H), 7.62 (dd, J = 9.0, J_{HF} = 5.9 Hz, 1H), 7.98–8.00 (m, 1H), 8.04–8.06 (m, 1H), 8.41 (s, 1H), 8.62 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 74.1 (d, J_{CF} = 25 Hz), 119.3 (d, J_{CF} = 3 Hz), 122.6 (d, J_{CF} = 19 Hz), 125.3 (d, J_{CF} = 5 Hz), 126.35 (d, J_{CF} = 3

Hz), 126.42, 126.5, 128.1, 128.7, 131.8, 132.0 (d, J_{CF} = 4 Hz), 132.3, 133.1, 158.5 (d, J_{CF} = 252 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 61.0 (d, J_{FH} = 6 Hz, 1F). IR (neat): ν 3049, 1620, 1574, 1533, 1454, 1360, 1309, 1192, 1136, 881, 742, 731 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{14}H_8FI$ [M]$^+$: 321.9655; Found: 321.9660.

2-(Biphenyl-2-yl)-1-fluoroanthracene (12g)

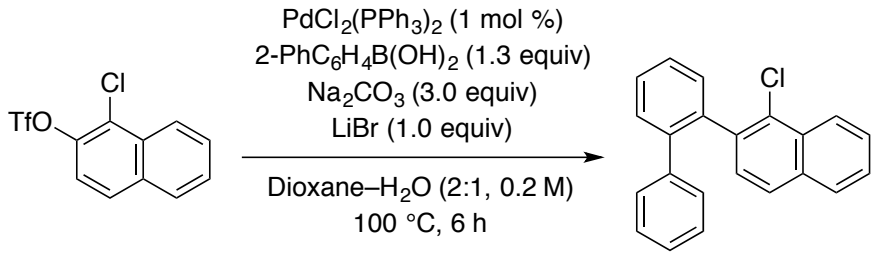


1-Fluoroanthracene **12g** was prepared by the method described for **12a** using 1-fluoro-2-iodonaphthalene (**15g**, 193 mg, 0.60 mmol), (biphenyl-2-yl)boronic acid (154 mg, 0.78 mmol), Na_2CO_3 (191 mg, 1.8 mmol), and $PdCl_2(PPh_3)_2$ (4.2 mg, 6 μmol). Purification by silica gel column chromatography (hexane/EtOAc = 40:1) gave **12g** (149 mg, 71%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.08 (dd, *J* = 8.8 Hz, J_{HF} = 7.3 Hz, 1H), 7.13–7.15 (m, 3H), 7.21–7.23 (m, 2H), 7.46–7.54 (m, 5H), 7.58–7.61 (m, 2H), 7.97–7.99 (m, 1H), 8.00–8.02 (m, 1H), 8.36 (s, 1H), 8.60 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 119.8 (d, J_{CF} = 5 Hz), 121.4 (d, J_{CF} = 15 Hz), 122.9 (d, J_{CF} = 18 Hz), 123.1 (d, J_{CF} = 5 Hz), 125.85, 125.89 (d, J_{CF} = 3 Hz), 126.0, 126.7, 127.2, 127.9, 128.1, 128.2, 128.49, 128.52, 129.3, 130.4, 131.4, 131.7, 131.9 (d, J_{CF} = 2 Hz), 131.1, 134.4, 141.2, 141.8, 154.7 (d, J_{CF} = 254 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 36.3 (d, J_{FH} = 7 Hz). IR (neat): ν 3053, 2924, 2852, 1460, 1430, 1362, 1323, 881, 742, 700 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{26}H_{17}F$ [M]$^+$: 348.1314; Found: 348.1331.

Preparation of 1-Halonaphthalenes 17a–17c

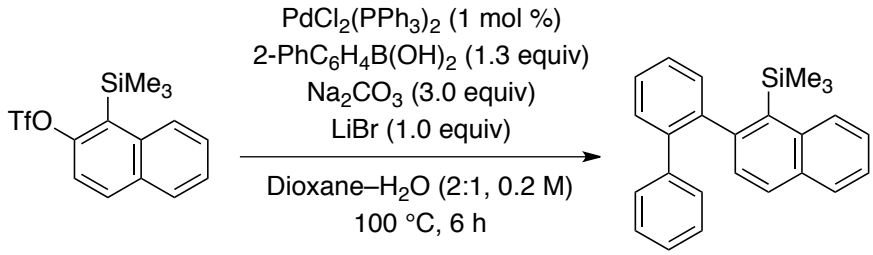
2-(Biphenyl-2-yl)-1-chloronaphthalene (17a)



In a flask were placed 1-chloronaphthalen-2-yl trifluoromethanesulfonate (311 mg, 1.00 mmol), (biphenyl-2-yl)boronic acid (257 mg, 1.30 mmol), Na_2CO_3 (318 mg, 3.00 mmol), LiBr (87 mg, 1.0 mmol), and $PdCl_2(PPh_3)_2$ (7.0 mg, 0.01 mmol). After the flask was purged with nitrogen, a degassed mixture of 1,4-dioxane (3.33 mL) and water (1.67 mL) was added to the flask. The mixture was heated at 100 °C for 6 h, and then cooled to room tempurture. After saturated aqueous NH_4Cl (10 mL) was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 50:1) to give **17a** (274 mg, 87%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.10–7.18 (m, 6H), 7.42–7.47 (m, 2H), 7.49–7.53 (m, 3H), 7.57–7.60 (m, 2H), 7.79 (d, J = 8.1 Hz, 1H), 8.30 (d, J = 8.5 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 124.8, 126.1, 126.4, 126.6, 126.9, 127.1, 127.8, 128.0, 128.1, 129.1, 129.2, 130.1, 130.4, 131.0, 131.1, 133.4, 137.9, 138.6, 141.0, 141.3. IR (neat): ν 3055, 3022, 1481, 1458, 1331, 1252, 974, 818, 741, 700, 538 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{22}H_{15}Cl$ $[M]^+$: 314.0862; Found: 314.0863.

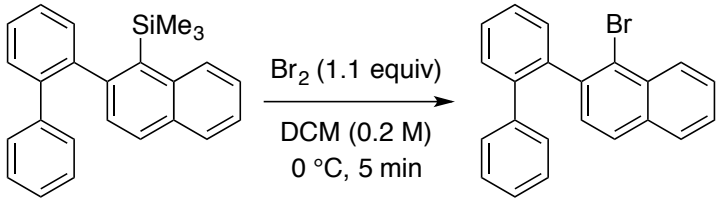
[2-(Biphenyl-2-yl)naphthalen-1-yl]trimethylsilane



In a flask were placed 1-(trimethylsilyl)naphthalen-2-yl trifluoromethanesulfonate (2.44 g, 7.00 mmol), 2-biphenylboronic acid (1.80 g, 9.09 mmol), Na_2CO_3 (2.23 g, 21.0 mmol), LiBr (608 mg, 7.00 mol), and $PdCl_2(PPh_3)_2$ (49 mg, 0.070 mmol). After the flask was purged with nitrogen, a degassed mixture of 1,4-dioxane (23.3 mL) and water (11.7 mL) was added. The mixture was heated at 100 °C for 6 h, and then cooled to room tempurture. After saturated aqueous NH_4Cl (40 mL) was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 50:1) to give [2-(biphenyl-2-yl)naphthalen-1-yl]trimethylsilane (2.30 g, 93%) as a white solid.

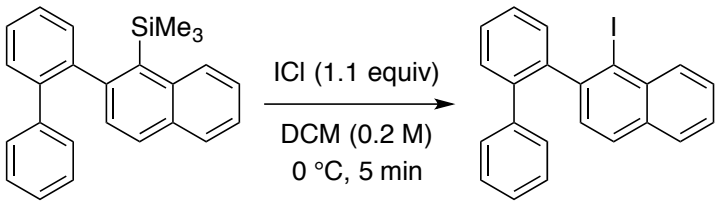
^{1}H NMR (500 MHz, $CDCl_3$): δ 0.12 (s, 9H), 7.01 (dd, *J* = 8.4, 2.2 Hz, 1H), 7.12–7.13 (m, 2H), 7.18–7.20 (m, 2H), 7.27 (d, *J* = 7.6 Hz, 1H), 7.36 (d, *J* = 6.6 Hz, 1H), 7.42–7.50 (m, 4H), 7.60 (d, *J* = 8.4 Hz, 2H), 7.78 (d, *J* = 8.0 Hz, 1H), 8.20 (d, *J* = 8.3 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 2.3, 124.9, 125.1, 126.5, 126.6, 127.8, 127.9, 128.5, 128.6, 128.9, 129.7, 129.8, 130.1, 132.1, 132.2, 135.6, 137.5, 140.0, 140.9, 143.5, 147.7. IR (neat): ν 3055, 2954, 2895, 1481, 1252, 854, 837, 766, 741, 700 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{25}H_{24}Si$ $[M]^+$: 352.1647; Found: 352.1646.

2-(Biphenyl-2-yl)-1-bromonaphthalene (17b)



To a dichloromethane (10 mL) solution of [2-(biphenyl-2-yl)naphthalen-1-yl]trimethylsilane (705 mg, 2.00 mmol) was added bromine (113 μL, 2.2 mmol) at 0 °C. After stirring at 0 °C for 5 min, the reaction was quenched with saturated aqueous $Na_2S_2O_3$, and the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 50:1) to give **17b** (635 mg, 88%) as a white solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.09–7.13 (m, 4H), 7.17–7.20 (m, 2H), 7.39–7.50 (m, 5H), 7.56–7.60 (m, 2H), 7.76 (d, *J* = 8.1 Hz, 1H), 8.32 (d, *J* = 8.6 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 123.7, 126.4, 126.6, 126.8, 126.9, 127.4, 127.7, 127.8, 128.07, 128.11, 129.2, 129.3, 130.1, 131.1, 132.3, 133.3, 140.60, 140.64, 140.9, 141.0. IR (neat): ν 3055, 3020, 1481, 1323, 957, 818, 760, 741, 700 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{22}H_{15}{}^{79}Br$ $[M]^+$: 358.0357; Found: 358.0341.

2-(Biphenyl-2-yl)-1-iodonaphthalene (17c)



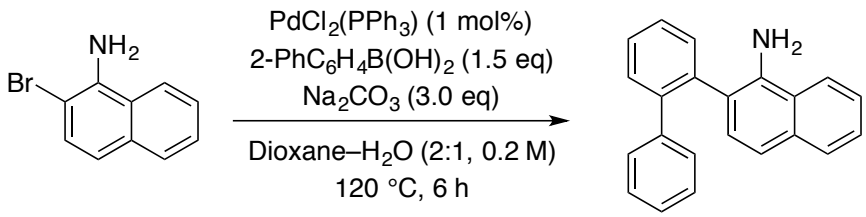
To a dichloromethane (5.0 mL) solution of [2-(biphenyl-2-yl)naphthalen-1-yl]trimethylsilane (705 mg, 2.00 mmol) was added a dichloromethane (5.0 mL) solution of ICl (357 mg, 2.20 mmol) at 0 °C. After stirring at 0 °C for 5 min, the reaction was quenched with saturated aqueous $Na_2S_2O_3$, and the organic materials were extracted with dichloromethane thrice. The combined extracts were

washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 50:1) to give **17c** (699 mg, 86%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.09–7.17 (m, 4H), 7.20–7.22 (m, 2H), 7.35 (dd, *J* = 7.7, 0.9 Hz, 1H), 7.43–7.58 (m, 5H), 7.62 (d, *J* = 8.3 Hz, 1H), 7.72 (d, *J* = 8.0 Hz, 1H), 8.24 (d, *J* = 8.4 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 105.6, 126.4, 126.6, 126.9, 127.7, 127.8, 127.9, 128.18, 128.21, 128.5, 129.5, 130.2, 131.3, 132.6, 133.1, 134.9, 140.6, 140.8, 144.2, 145.9. IR (neat): ν 3055, 3016, 1481, 1448, 1313, 947, 818, 762, 742, 700 cm^{-1}. HRMS (EI+): *m/z* Calcd. for $C_{22}H_{15}I$ $[M]^+$: 406.0218; Found: 406.0221.

Preparation of 1-Aminonaphthalene 17d

2-(Biphenyl-2-yl)naphthalen-1-amine (17d)



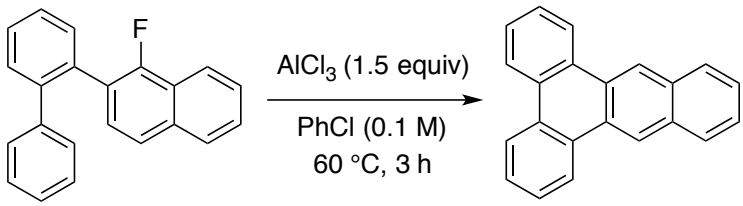
In a flask were placed 2-bromonaphthalen-1-amine (1.11 g, 5.00 mmol), biphenyl-2-ylboronic acid (1.48 g, 7.50 mmol), Na_2CO_3 (1.59 g, 15.0 mmol), and $PdCl_2(PPh_3)_2$ (35 mg, 0.050 mmol). After the flask was purged with nitrogen, a degassed mixture of 1,4-dioxane (16.7 mL) and water (8.3 mL) was added to the flask. The mixture was heated at 120 °C for 6 h and then cooled to room temperature. After saturated aqueous NH_4Cl was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 7:1) to give **17d** (1.34 g, 91%) as a

pale purple solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.05 (d, J = 8.3 Hz, 1H), 7.12–7.14 (m, 3H), 7.19–7.22 (m, 3H), 7.42–7.44 (m, 2H), 7.46–7.50 (m, 3H), 7.54 (d, J = 6.9 Hz, 1H), 7.74–7.76 (m, 1H), 7.79–7.80 (m, 1H). ^{13}C NMR (126 MHz, CDCl3): δ 118.2, 121.0, 121.8, 123.5, 124.9, 125.5, 126.7, 127.8, 127.9, 128.0, 128.4, 129.0, 129.2, 130.7, 131.5, 133.5, 137.9, 138.5, 141.0, 141.8. IR (neat): ν 3473, 3384, 3055, 3020, 1614, 1398, 804, 764, 740, 700 cm^{-1}. HRMS (EI+): m/z Calcd. for $C_{22}H_{17}N$ [M]+: 295.1361; Found: 295.1373.

$AlCl_3$-Mediated Cyclization of 1-Fluoronaphthalenes 12

Benzo[*f*]tetraphene (13a)

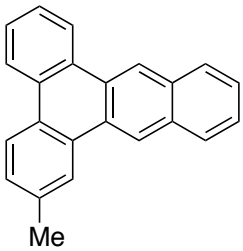


In a Schlenk tube were placed 2-(biphenyl-2-yl)-1-fluoronaphthalene (**12a**, 30 mg, 0.10 mmol) and $AlCl_3$ (20 mg, 0.15 mmol). After the tube was purged with nitrogen, chlorobenzene (1.0 mL) was added. The mixture was heated at 60 °C for 3 h, and then cooled to room temperature. After aqueous NaOH (1 M, 5 mL) was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20:1) to give **13a** (28 mg, 99%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.54 (dd, *J* = 6.4, 3.3 Hz, 2H), 7.60–7.65 (m, 4H), 8.05 (dd, *J* = 6.4, 3.3 Hz, 2H), 8.55 (d, *J* = 7.9 Hz, 2H), 8.74 (d, *J* = 7.9 Hz, 2H), 9.03 (s, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 122.0, 123.4, 123.6, 126.1, 127.4, 127.6, 128.1, 128.4, 130.0, 130.1, 132.2. IR (neat): ν 3735, 2927, 1684, 1506, 773, 669 cm^{-1}. HRMS (APCI+): *m/z* Calcd. for $C_{22}H_{14}$ $[M]^+$: 278.1096;

Found: 293.1090.

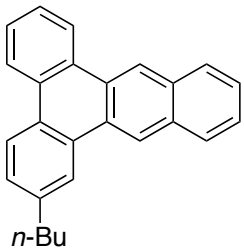
2-Methylbenzo[*f*]tetraphene (13b)



Benzo[*f*]tetraphene **13b** was synthesized by the method described for **13a** using 1-fluoronaphthalene **12b** (63 mg, 0.20 mmol) and $AlCl_3$ (40 mg, 0.30 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave **13b** (55 mg, 94%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 2.63 (s, 3H), 7.46 (dd, *J* = 8.3, 1.0 Hz, 1H), 7.54–7.58 (m, 2H), 7.61–7.65 (m, 2H), 8.07–8.10 (m, 2H), 8.46 (d, *J* = 8.3 Hz, 1H), 8.53–8.55 (m, 1H), 8.56 (brs, 1H), 8.74–8.78 (m, 1H), 9.07 (s, 1H), 9.07 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.8, 121.9, 122.0, 123.2, 123.4, 123.6, 123.8, 126.00, 126.01, 127.0, 127.6, 127.7, 128.07, 128.08, 128.4, 128.6, 129.0, 129.8, 130.1, 130.2, 132.17, 132.20, 137.2. IR (neat): ν 3053, 2914, 2854, 1616, 1516, 1491, 1439, 1346, 1242, 879, 814, 762, 717, 692 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{23}H_{17}$ $[M+H]^+$: 293.1330; Found: 293.1322.

2-Butylbenzo[*f*]tetraphene (13c)

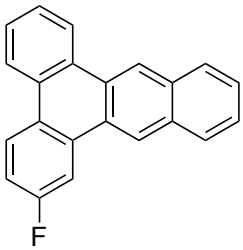


Benzo[*f*]tetraphene **13c** was synthesized by the method described for **13a** using 1-fluoronaphthalene **12c** (71 mg, 0.20 mmol), $AlCl_3$ (40 mg, 0.30 mmol), and HFIP (2.0 mL).

Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave **13c** (63 mg, 94%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 1.01 (t, J = 7.5 Hz, 3H), 1.48 (tq, J = 7.8, 7.5 Hz, 2H), 1.79 (tt, J = 7.8, 7.8 Hz, 2H), 2.89 (t, J = 7.8 Hz, 2H), 7.48 (dd, J = 8.3, 1.7 Hz, 1H), 7.54–7.57 (m, 2H), 7.61–7.64 (m, 2H), 8.07–8.11 (m, 2H), 8.48 (d, J = 8.4 Hz, 1H), 8.53–8.55 (m, 2H), 8.74–8.76 (m, 1H), 9.07 (s, 1H), 9.08 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 14.0, 22.5, 33.8, 36.0, 121.9, 122.0, 123.21, 123.21, 123.4, 123.6, 125.97, 125.99, 127.0, 127.6, 127.9, 128.05, 128.09, 128.3, 128.5, 128.6, 129.8, 130.0, 130.2, 132.15, 132.19, 142.2. IR (neat): ν 3053, 2954, 2927, 2856, 1614, 1491, 1454, 1412, 876, 764, 719 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{26}H_{23}$ $[M+H]^+$: 335.1800; Found: 335.1806.

2-Fluorobenzo[*f*]tetraphene (13d)

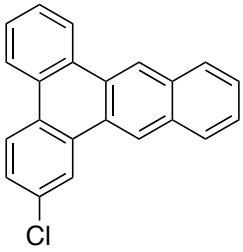


Benzo[*f*]tetraphene **13d** was synthesized by the method described for **13a** using 1-fluoronaphthalene **12d** (63 mg, 0.20 mmol) and $AlCl_3$ (40 mg, 0.30 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave **13d** (57 mg, 96%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.33 (ddd, J_{HF} = 10.6 Hz, J = 8.5, 2.5 Hz, 1H), 7.55–7.59 (m, 2H), 7.60–7.65 (m, 2H), 8.05–8.07 (m, 2H), 8.33 (dd, J = 11.0 Hz, J_{HF} = 2.5 Hz, 1H), 8.44–8.46 (m, 1H), 8.50 (dd, J = 8.5 Hz, J_{HF} = 5.9 Hz, 1H), 8.71–8.72 (m, 1H), 8.89 (s, 1H), 9.02 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 109.3 (d, J_{CF} = 23 Hz), 115.5 (d, J_{CF} = 23 Hz), 122.2, 122.4, 123.2, 123.7, 125.6 (d, J_{CF} = 9 Hz), 126.3, 126.4, 126.5 (d, J_{CF} = 3 Hz), 127.3, 127.6 (d, J = 3 Hz), 127.7, 128.07,

128.11, 128.5, 129.5, 129.6, 132.1, 132.2 (d, J_{CF} = 7 Hz), 132.5, 162.4 (d, J_{CF} = 246 Hz). ^{19}F NMR (470 MHz, $CDCl_3$): δ 47.56–47.61 (m, 1F). IR (neat): ν 3051, 1616, 1516, 1493, 1462, 1279, 1213, 1188, 876, 856, 764 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{22}H_{13}F$ $[M]^+$: 296.1001; Found: 296.0999.

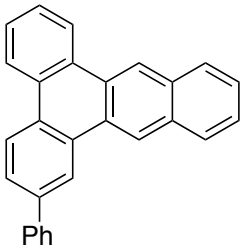
2-Chlorobenzo[*f*]tetraphene (13e)



Benzo[*f*]tetraphene **13e** was synthesized by the method described for **13a** using 1-fluoronaphthalene **12e** (67 mg, 0.20 mmol) and $AlCl_3$ (40 mg, 0.30 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave **13e** (60 mg, 95%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.53–7.60 (m, 3H), 7.61–7.66 (m, 2H), 8.02–8.08 (m, 2H), 8.42 (d, *J* = 8.8 Hz, 1H), 8,45 (d, *J* = 7.7 Hz, 1H), 8.62 (d, *J* = 1.7 Hz, 1H), 8.69 (d, *J* = 7.7 Hz, 1H), 8.89 (s, 1H), 8.98 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 122.1, 122.3, 123.3, 123.4, 123.7, 124.9, 126.3, 126.4, 127.2, 127.66, 127.70, 127.71, 128.06, 128.13, 128.38, 128.45, 129.2, 130.0, 131.6, 132.1, 132.5, 133.5. IR (neat): ν 3053, 2924, 1730, 1599, 1506, 1487, 1431, 1103, 876, 762, 715, 690 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{22}H_{14}Cl$ $[M+H]^+$: 313.0784; Found: 313.0792.

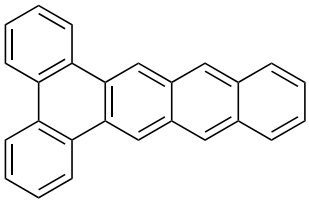
2-Phenylbenzo[*f*]tetraphene (13f)



Benzo[*f*]tetraphene **13f** was synthesized by the method described for **13a** using 1-fluoronaphthalene **12f** (75 mg, 0.20 mmol) and $AlCl_3$ (40 mg, 0.30 mmol). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave **13d** (65 mg, 91%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.45 (t, *J* = 7.6 Hz, 1H), 7.55–7.58 (m, 3H), 7.66–7.74 (m, 3H), 7.85 (d, *J* = 7.4 Hz, 2H), 7.88 (d, *J* = 8.6 Hz, 1H), 8.07–8.13 (m, 2H), 8.59–8.61 (m, 1H), 8.64 (d, *J* = 8.6 Hz, 1H), 8.78–8.79 (m, 1H), 8.95 (brs, 1H), 9.10 (s, 1H), 9.15 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 122.1, 122.17, 122.23, 123.5, 123.7, 124.0, 126.16, 126.17, 126.7, 127.4, 127.5, 127.6, 127.7, 128.10, 128.11, 128.5, 128.6, 129.0, 129.2, 129.9, 130.1, 130.4, 132.2, 132.3, 140.2, 141.2. IR (neat): ν 3051, 3030, 1485, 872, 756, 715, 692 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{28}H_{19}$ $[M+H]^+$: 355.1487; Found: 355.1482.

Dibenzo[*a*,*c*]tetracene (13g)



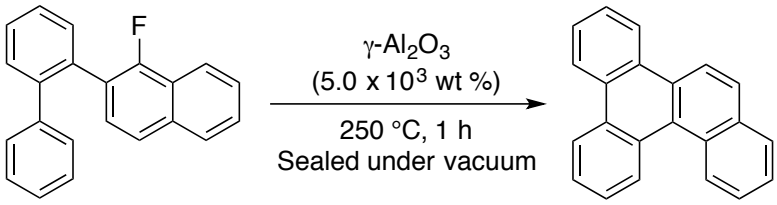
Dibenzo[*a*,*c*]tetraphene (**13g**) was synthesized by the method described for **13a** using 1-fluoronaphthalene **12c** (70 mg, 0.20 mmol), $AlCl_3$ (40 mg, 0.30 mmol), and HFIP (2.0 mL). Purification by silica gel column chromatography (hexane/EtOAc = 20:1) gave **13g** (63 mg, 96%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.48 (dd, *J* = 6.5, 3.1 Hz, 2H), 7.62–7.67 (m, 4H), 8.07 (dd, *J* = 6.3,

2.8 Hz, 2H), 8.53 (d, J = 7.6 Hz, 2H), 8.69 (s, 2H), 8.78 (d, J = 8.5 Hz, 2H), 9.24 (s, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 122.0, 123.4, 123.7, 125.3, 126.3, 127.6, 127.8, 128.2, 128.4, 130.2, 130.3, 130.5, 131.9. IR (neat): ν 2918, 2854, 1722, 1431, 1279, 891, 746, 729 cm^{-1}. HRMS (EI+): *m*/*z* Calcd. for $C_{26}H_{16}$ [M]$^+$: 328.1252; Found: 328.1244.

γ-Al_2O_3-Cyclization of 1-Fluoronaphthalenes 12

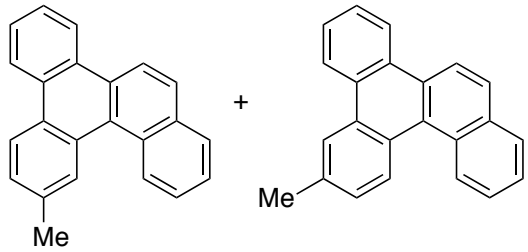
Benzo[*g*]chrysene (14a)



γ-Al_2O_3 (1.00 g) was activated by annealing at 500 °C for 30 min under vacuum (~10^{-2} mbar) in a glass ampule. To the ampule was added **12a** (20 mg, 0.067 mmol) under argon atmosphere, and the mixture was shaken for 2–3 min. The ampule was then evacuated (~10^{-2} mbar) and sealed. The mixture was heated at 250 °C for 1 h, and then cooled to room temperature. The reaction mixture was filtered through a glass filter (dichloromethane), and the filtrate was concentrated under reduced pressure to give **14a** (18 mg, 95%) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.58–7.72 (m, 6H), 7.99–8.02 (m, 2H), 8.61 (d, J = 8.9 Hz, 1H), 8.65–8.67 (m, 1H), 8.70–8.72 (m, 1H), 8.74 (d, J = 8.1 Hz, 1H), 8.91 (d, J = 8.2 Hz, 1H), 8.95 (d, J = 8.3 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 120.7, 123.0, 123.4, 123.7, 125.8, 125.9, 126.0, 126.6, 127.0, 127.21, 127.24, 127.6, 128.0, 128.1, 128.4, 129.3, 129.4, 129.7, 129.9, 130.1, 130.8, 133.5. IR (neat): ν 3055, 1493, 1479, 1450, 818, 758, 723 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{22}H_{14}$ [M]$^+$: 278.1096; Found: 278.1083.

12-Methylbenzo[*g*]chrysene (14b) and 13-Methylbenzo[*g*]chrysene (14b')



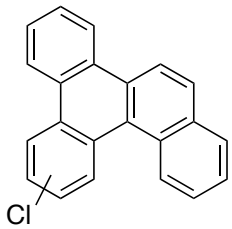
A mixture of benzo[*g*]chrysenes **14b** and **14b'** was synthesized by the method described for **14a** using 1-fluoronaphthalene **12b** (20 mg, 0.064 mmol) and γ-Al_2O_3 (1.00 g). The reaction mixture was filtered through a glass filter (dichloromethane), and the filtrate was concentrated under reduced pressure to give a mixture of **14b** and **14b'** (14 mg, 73%, 64:36) as a white solid.

14b + 14b': IR (neat): ν 3053, 2916, 2854, 1610, 1498, 1473, 1444, 1379, 1244, 906, 812, 789, 758, 725 cm^{-1}. HRMS (APCI+): *m/z* Calcd. for $C_{23}H_{17}$ $[M+H]^+$: 293.1330; Found: 293.1318.

14b: ^{1}H NMR (500 MHz, $CDCl_3$): δ 2.61 (s, 3H), 7.51 (d, *J* = 8.3 Hz, 1H), 7.57–7.70 (m, 4H), 7.96–8.02 (m, 2H), 8.60 (d, *J* = 8.9 Hz, 1H), 8.61–8.71 (m, 4H), 8.96 (d, *J* = 8.4 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.8, 120.8, 122.9, 123.4, 123.7, 125.7, 125.9, 126.9, 127.1, 127.2, 127.5, 128.10, 128.10, 128.12, 128.4, 128.6, 129.2, 129.4, 129.5, 130.0, 130.3, 133.5, 135.8.

14b': ^{1}H NMR (500 MHz, $CDCl_3$): δ 2.65 (s, 3H), 7.47 (d, *J* = 8.4 Hz, 1H), 7.57–7.70 (m, 4H), 7.96–8.02 (m, 2H), 8.53 (s, 1H), 8.59–8.71 (m, 3H), 8.79 (d, *J* = 8.4 Hz, 1H), 8.93 (d, *J* = 8.7 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 21.8, 120.8, 123.1, 123.4, 123.7, 125.77, 125.83, 127.0, 127.18, 127.20, 127.3, 127.4, 127.5, 127.6, 128.1, 128.4, 129.3, 129.8, 129.9, 130.2, 130.9, 133.5, 136.4.

Chlorobenzo[*g*]chrysenes 14e and 14e'



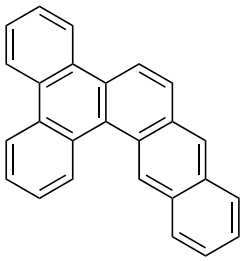
A mixture of benzo[*g*]chrysenes **14e** and **14e'** was synthesized by the method described for **14a** using 1-fluoronaphthalene **12e** (20 mg, 0.060 mmol) and γ-Al_2O_3 (1.00 g). The reaction mixture was filtered through a glass filter (dichloromethane), and the filtrate was concentrated under reduced pressure to give a mixture of **14e** and **14e'** (14 mg, 75%, 75:25) as a white solid.

14e + 14e': IR (neat): ν 3059, 2922, 2850, 1714, 1595, 1489, 1473, 1439, 1265, 1095, 810, 762, 719 cm^{-1}. HRMS (APCI+): *m/z* Calcd. for $C_{22}H_{14}Cl$ $[M+H]^+$: 313.0784; Found: 313.0773.

14e: ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.56–7.74 (m, 5H), 7.99–8.02 (m, 2H), 8.56–8.66 (m, 4H), 8.86 (d, *J* = 5.3 Hz, 1H), 8.87 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 120.6, 123.0, 123.8, 125.1, 126.08, 126.12, 126.5, 126.8, 127.4, 127.6, 127.8, 128.27, 128.34, 128.5, 128.6, 129.2, 129.4, 129.7, 130.0, 130.7, 132.2, 133.5.

14e': ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.56–7.74 (m, 5H), 7.99–8.02 (m, 2H), 8.56–8.66 (m, 4H), 8.80 (d, *J* = 8.9 Hz, 1H), 8.82 (d, *J* = 8.8 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 120.7, 123.16, 123.17, 123.8, 126.0, 126.2, 126.3, 126.7, 127.3, 127.8, 127.9, 127.96, 128.04, 128.1, 128.2, 128.9, 130.0, 130.1, 130.8, 132.2, 132.6, 133.6.

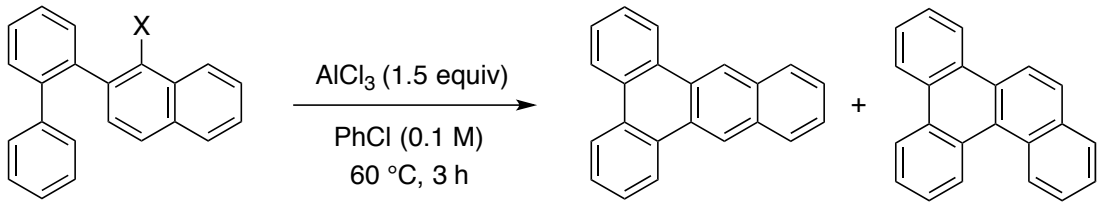
Dibenzo[*a*,*c*]tetraphene (14g)



Dibenzo[*a*,*c*]tetraphene (**14g**) was synthesized by the method described for **14a** using 1-fluoroanthracene **12g** (20 mg, 0.057 mmol) and γ-Al_2O_3 (1.00 g). The reaction mixture was filtered through a glass filter (dichloromethane), and the filtrate was concentrated under reduced pressure to give **14g** (13.8 mg, 73%) as a pale yellow solid.

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.53–7.58 (m, 2H), 7.69–7.75 (m, 4H), 8.08–8.11 (m, 3H), 8.52 (s, 1H), 8.54 (d, J = 9.2 Hz, 1H), 8.64–8.67 (m, 1H), 8.74–8.77 (m, 1H), 8.79 (dd, J = 7.8, 1.7 Hz, 1H), 9.08 (dd, J = 7.7, 1.5 Hz, 1H), 9.48 (s, 1H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 120.9, 123.1, 123.5, 123.8, 125.6, 125.9, 126.0, 126.3, 126.5, 127.0, 127.1, 127.3, 127.5, 127.8, 127.9, 128.1, 128.5, 128.7, 129.0, 129.6, 129.7, 130.1, 130.9, 131.4, 131.7, 131.8. IR (neat): ν 3053, 2927, 2850, 1496, 1433, 906, 885, 754, 739 cm^{-1}. HRMS (APCI+): *m*/*z* Calcd. for $C_{26}H_{16}$ $[M]^+$: 328.1252; Found: 328.1243.

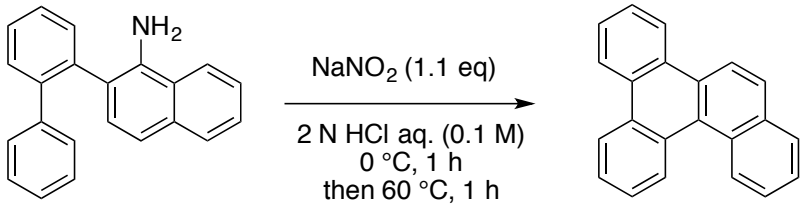
Mechanistic Study: $AlCl_3$-Mediated Cyclization of Halonaphthalenes 17a–c



In a Schlenk tube were placed 2-(biphenyl-2-yl)-1-halonaphthalene **17a**, **17b**, or **17c** (0.10 mmol) and $AlCl_3$ (20 mg, 0.15 mmol). After the tube was purged with nitrogen, chlorobenzene (1.0 mL) was added. The mixture was heated at 60 °C for 3 h, and then cooled to room temperature. After aqueous NaOH (1 M, 5 mL) was added to the reaction mixture, the organic materials were extracted

with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the yields of **13a** and **14a** were determined by ^{1}H NMR measurement using CH_2Br_2 as an internal standard.

Mechanistic Study 2: Cyclization of Diazonium Salt



In a two-necked flask were placed 2-(biphenyl-2-yl)naphthalen-1-amine (**17d**, 295 mg, 1.00 mmol) and aqueous HCl (2 M, 5.0 mL, 10 mmol) at 0 °C. After stirring at 0 °C for 15 min, $NaNO_2$ (76 mg, 1.1 mmol) was added. After stirring for another 1 h, the mixture was heated at 60 °C for 3 h, and then cooled to room temperature. After saturated aqueous $NaHCO_3$ was added to the reaction mixture, the organic materials were extracted with dichloromethane thrice. The combined extracts were washed with brine and dried over Na_2SO_4. After removing the solvent under reduced pressure, the residue was purified by silica gel column chromatography (hexane/EtOAc = 25:1) to give **3a** (250 mg, 90%) as a white solid.

References for experimental section

(1) Rausis, T.; Schlosser, M. *Eur. J. Org. Chem.* **2002**, 3351–3358.

(2) Barluenga, J.; Jiménez-Aquino, A.; Aznar, F.; Valdés, C. *J. Am. Chem. Soc.* **2009**, *131*, 4031–4041.

(3) Peña, D.; Cobas, A.; Pérez, D.; Guitián, E. *Synthesis* **2002**, 1454–1458.

(4) Rafiq, S. M.; Sivasakthikumaran, R.; Karunakaran, J.; Mohanakrishnan, A. K. *Eur. J. Org. Chem.* **2015**, 5099–5114.

CHAPTER 5

Conclusions

I developed new and facile synthetic methods for sp^2 C–F bond activation directed toward polycyclic aromatic hydrocarbons (PAHs), which are expected to be used as advanced materials such as liquid crystals and/or organic semiconductors.

In Chapter 2, unsymmetrically and symmetrically disubstituted 1,1-diaryl-2,2-difluoroethenes was synthesized via stepwise coupling reactions, starting from easily available and/or preparable 1,1-difluoroethene derivatives. The key to success was using the appropriate ligand in each coupling step. These products serve not only as promising medicine and material candidates, but also as precursors of PAHs as illustrated in the next chapter.

In Chapter 3, a domino Friedel–Crafts-type cyclization of difluoroethenes which enables easy access to dibenzo[*g*,*p*]chrysenes was demonstrated. The activation of both vinylic and aromatic C–F bonds was effected to form new C–C bonds by using suitable acids such as $FSO_3H{\cdot}SbF_5$ and TiF_4.

In Chapter 4, the selective synthesis of benzene-fused triphenylene frameworks was achieved via aromatic C–F bond cleavage and regioselective C–C bond formation depending upon the choice of aluminium reagents. On treatment with $AlCl_3$, 2-(biphenyl-2-yl)-1-fluoronaphthalenes afforded benzo[*f*]tetraphenes via regioselective C–C bond formation on the carbon atoms γ to the original position of the fluorine substituent. In contrast, α-selective C–C bond formation was promoted by treatment with γ-Al_2O_3 to give benzo[*g*]chrysenes.

Throughout these studies, I disclosed unprecedented methods for vinylic and aromatic C–F bond activation by utilizing carbocation intermediates which are stabilized with fluorine atoms. These protocols consist of efficient C–C bond formation by Friedel–Crafts-type cyclizations and C–F bond cleavage by elimination of HF.

LIST OF PUBLICATIONS

1) Takeshi Fujita, Naoto Suzuki, Tomohiro Ichitsuka, Junji Ichikawa

Facile synthesis of unsymmetrical 1,1-diaryl-2,2-difluoroethenes via stepwise coupling of 1,1-Difluoro-2,2-dibromoethenes

J. Fluorine Chem. **2013**, *155*, 97–101.

2) Naoto Suzuki, Takeshi Fujita, Junji Ichikawa

Method for the Synthesis of Dibenzo[*g*,*p*]Chrysenes: Domino Friedel–Crafts-type Cyclization of Difluoroethenes Bearing Two Biaryl Groups

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3) Naoto Suzuki, Takeshi Fujita, Konstantin Yu. Amsharov, Junji Ichikawa

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