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Copper-Catalyzed Decarboxylative Difluoroalkylation and Perfluoroalkylation of α,β-Unsaturated Carboxylic Acids

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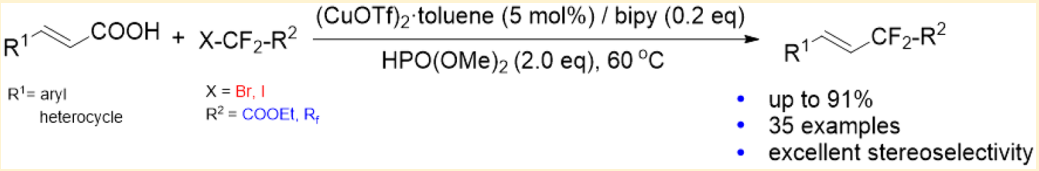
Supporting Information



ABSTRACT: Copper-catalyzed decarboxylative difluoroalkylation and perfluoroalkylation of α,β-unsaturated carboxylic acids is described. Promoted by dialkyl phosphite, this novel reaction affords fluoroalkylated motifs with excellent stereoselectivity and broad substrate scope under mild reaction conditions from readily available fluoroalkyl iodides and bromides. Preliminary mechanism study suggests that radical pathway was involved in the catalytic cycle and dialkyl phosphite had played an indispensable role in this reaction.

INTRODUCTION

The incorporation of fluorine into organic molecules has long been an important strategy in medicinal chemistry.[1] Along with the intensive studies and advances reported on the fluoroalkylation of aromatic compounds,[2] the construction of $C_{vinyl}-C_{Rf}$ bonds has also been achieved in recent decades.[3] Decarboxylative coupling reactions catalyzed by transition metals have attracted significant attention in synthetic organic chemistry and have emerged as valuable tools for the construction of carbon−carbon bonds.[4] It is envisioned that decarboxylative coupling reactions of vinyl carboxylic acids may ensure high efficient and stereoselective synthesis of alkenes bearing fluoroalkylated groups, and methods for decarboxylative fluoroalkylation of vinyl carboxylic acids have gained considerable attention recently.[5−8] By using Togni-type electrophilic fluoroalkylating agent[5a,e] or Langlois reagent,[5b−d] approaches to the synthesis of $C_{vinyl}-C_{Rf}$ bonds through decarboxylative cross-coupling reactions have been developed by several groups (Scheme 1a). Recently, Wang's group developed an elegant nickel-catalyzed decarboxylative difluoromethylation of vinyl carboxylic acids using ethyl iododifluoroacetate in the presence of a base (Scheme 1b).[6] More recently, Wang and co-workers reported a method for decarboxylative difluoroacetamidation of vinyl carboxylic acids with stoichiometric amounts of $CuSO_4$ as metal mediator at the high temperatures (Scheme 1c).[7] During the preparation of this article, a photocatalyzed decarboxylative difluoroalkylation of α,β-unsaturated carboxylic acids was reported by Liu's group (Scheme 1d).[8] Although these works represent very promising advances, general method with full scope for the difluorinated and perfluoroalkylated alkenes through decarboxylative cross coupling using relatively low-cost and commonly available fluoroalkylating reagents, in particular fluoroalkyl bromides, are still highly desired. As one part of our continuous efforts to develop copper catalyzed fluoroalkylations,[9] we report here copper−catalyzed decarboxylative difluoroalkylation and perfluoroalkylation of α,β-unsaturated carboxylic acids with fluoroalkyl iodides and bromides in good to excellent yields with a wide substrate scope, excellent functional-group tolerance and excellent *E* selectivity under mild reaction condition (Scheme 1e).

RESULTS AND DISCUSSION

To start the investigation, we chose (*E*)-cinnamic acid **1a** (0.4 mmol) as the substrate and ethyl iododifluoroacetate **2a** (0.2 mmol) as the fluoroalkyl coupling partner. By using Cu_2O (5 mol%) as a catalyst and 2,2′- bipyridine (20 mol%) as the ligand the desired difluoromethylated product **3a** was obtained in a yield of 83% in the presence of $HPO(OMe)_2$ (0.4 mmol) in DMF for 48 h (Table 1, entry 1). Surprisingly, no (*E*)-dimethyl styrylphosphonate was detected. Encouraged by this result, a number of other copper catalysts were investigated (Table 1, entries 2−6). The results demonstrated that copper(I) was more efficient than copper(II) as a catalyst (Table 1, entry 4 vs 6), and $(CuOTf)_2$·toluene gave the best yield and excellent *E* selectivity (*E*/*Z* > 99:1) for this reaction (Table 1, entry 4). Next, a series of other reductive additives,[10] namely $HPO(OEt)_2$, $HPO(O^tBu)_2$, Et_3SiH, B_2pin_2, and $Na_2S_2O_4$ were screened (Table 1, entries 7−11). $HPO(OMe)_2$ was found to be the most efficient additive in this system. Meanwhile, ligands were screened and it was found that 2,2′-bipyridine was the optimal choice (Table 1, entries 4, 12−14). Solvents were also investigated, and DMF was found to be the

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Scheme 1. Synthesis of Fluoroalkylated Alkenes from Vinyl Carboxylic Acids

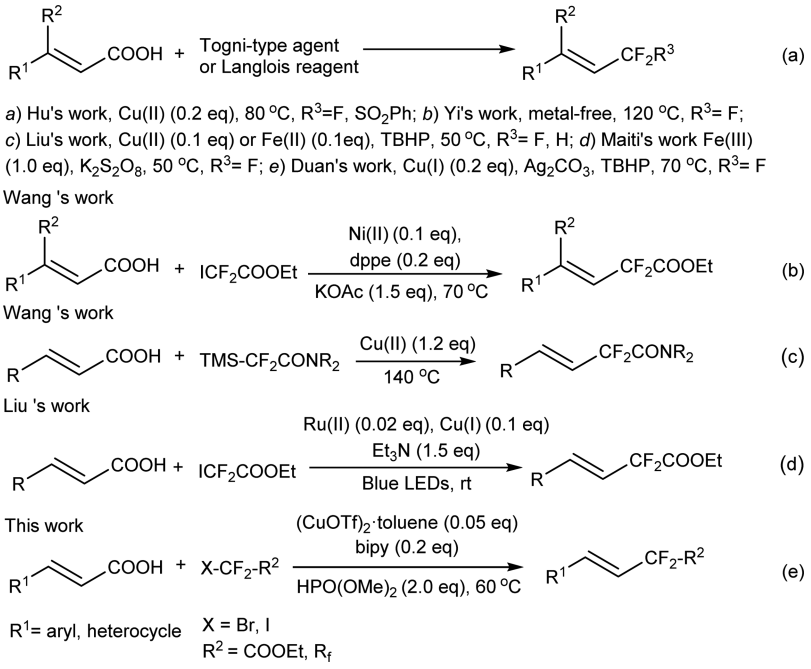
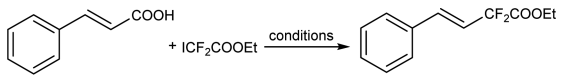


Table 1. Optimization of Reaction Conditions[a]



entry	catalyst	ligand	additive	solvent	yield[b] (%), (*E*/*Z*)
1	Cu_2O	bipy	$HPO(OMe)_2$	DMF	83, (=98:2)
2[c]	CuI	bipy	$HPO(OMe)_2$	DMF	81, (>99:1)
3[d]	CuSCN	bipy	$HPO(OMe)_2$	DMF	85, (=95:5)
4	$(CuOTf)_2$·toluene	bipy	$HPO(OMe)_2$	DMF	92, (>99:1)
5[e]	$[Cu(MeCN)_4]PF_6$	bipy	$HPO(OMe)_2$	DMF	66, (>99:1)
6	$Cu(OTf)_2$	bipy	$HPO(OMe)_2$	DMF	73, (=98:2)
7	$(CuOTf)_2$·toluene	bipy	$HPO(OEt)_2$	DMF	84, (>99:1)
8	$(CuOTf)_2$·toluene	bipy	$HPO(O^tBu)_2$	DMF	55, (>99:1)
9	$(CuOTf)_2$·toluene	bipy	Et_3SiH	DMF	25, (=94:6)
10	$(CuOTf)_2$·toluene	bipy	B_2pin_2	DMF	30, (=96:4)
11	$(CuOTf)_2$·toluene	bipy	$Na_2S_2O_4$	DMF	15, (=91:9)
12	$(CuOTf)_2$·toluene	mebipy	$HPO(OMe)_2$	DMF	82, (>99:1)
13	$(CuOTf)_2$·toluene	dtbbipy	$HPO(OMe)_2$	DMF	63, (>99:1)
14	$(CuOTf)_2$·toluene	1,10-phen	$HPO(OMe)_2$	DMF	78, (>99:1)
15	$(CuOTf)_2$·toluene	bipy	$HPO(OMe)_2$	CH_3CN	82, (>99:1)
16	$(CuOTf)_2$·toluene	bipy	$HPO(OMe)_2$	DMSO	45, (>99:1)
17	$(CuOTf)_2$·toluene	bipy	$HPO(OMe)_2$	dioxane	74, (>99:1)
18[f]	$(CuOTf)_2$·toluene	bipy	$HPO(OMe)_2$	DMF	61, (>97:3)

[a]Reaction conditions: **1a** (0.4 mmol), **2a** (0.2 mmol), Cu catalyst (5 mol%), ligand (20 mol%), additive (0.4 mmol), solvent (0.6 mL), 60 °C, 48 h, under N_2. [b]The yield of the product was determined by ^1H NMR spectroscopy, *E*/*Z* ratios were calculated on the basis of ^{19}F NMR spectroscopy. [c]CuI (10 mol%). [d]CuSCN (10 mol%). [e]$[Cu(MeCN)_4]PF_6$ (10 mol%). [f]Under air. bipy = 2,2′-bipyridyl; mebipy = 4,4′-dimethyl-2,2′-dipyridyl; dtbbipy = 4,4′-di*tert*-butyl-2,2′-dipyridyl; 1,10-phen = 1,10-phenanthroline.

most suitable solvent for this reaction (Table 1, entries 4, 15–17). For the results of changing the substrates ratio, see SI Table S3. The reaction also proceeded under air to afford the product in a 61% yield (Table 1, entry 18).

With the optimized reaction conditions in hand (Table 1, entry 4), a series of *α*,*β*-unsaturated carboxylic acids were further evaluated. As presented in Table 2, the reaction proceeded smoothly with various cinnamic acids to afford good to excellent yields of the corresponding difluoroalkylated products (**3a**–**u**). Noteworthily, *para*-, *meta*-, or *ortho*-substituted cinnamic acids, bearing either an electron-donating group (Me and OMe, **3b**–**c**, **3k**–**l**, and **3o**–**p**) or an electron-withdrawing (Cl and Br, **3d**–**e**) group on the aryl ring, gave high yields of the desired products. For the strong electron-withdrawing groups (NO_2, CF_3, COOH, CHO, and OAc, **3f**–**j**, **3m**–**n**, and **3q**), good yields were also obtained in the presence of CF_3COOH.[17] Moreover, cinnamic acid with a naphthyl group (**3r**) also participated in this reaction with high reactivity

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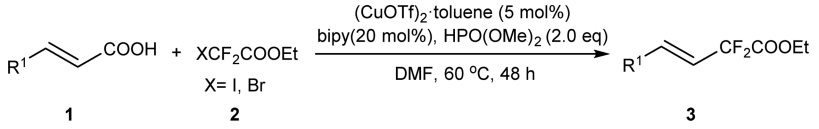
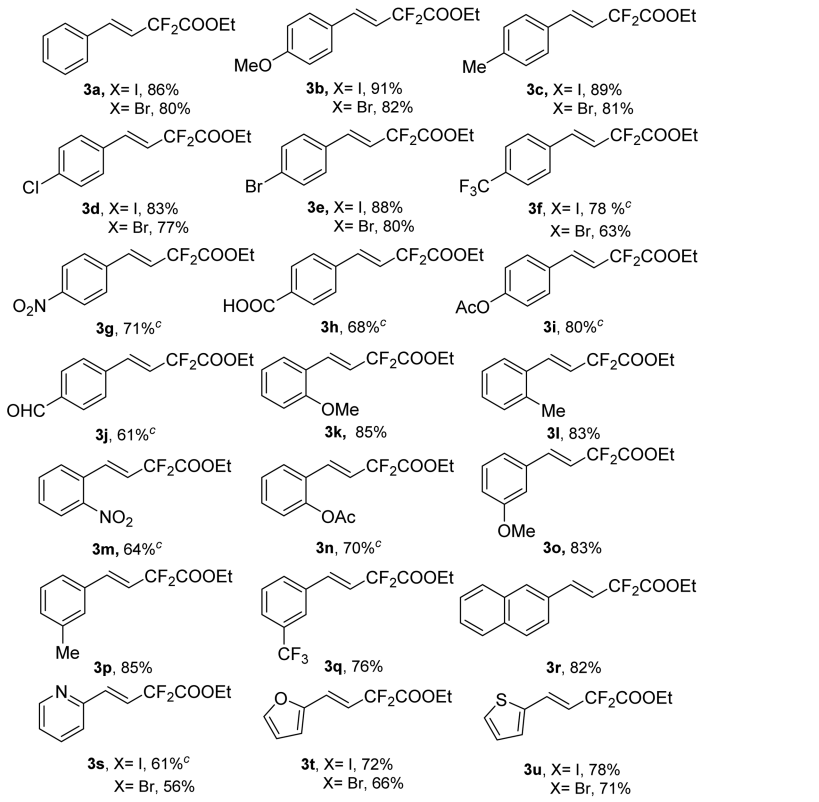
Table 2. Copper-Catalyzed Decarboxylative Difluoroalkylation of α,β-Unsaturated Carboxylic Acids[a,b]





[a]Reaction conditions: **1** (0.4 mmol), **2** (0.2 mmol), $(CuOTf)_2$·toluene (5 mol%), bipy (20 mol%), $HPO(OMe)_2$ (0.4 mmol), DMF (0.6 mL), 60 °C, 48 h, under N_2. [b]Yield; the *E*/*Z* ratios were determined by ^{19}F NMR spectroscopy of the crude product mixture. [c]Mebipy was used as ligand, CF_3COOH (0.1 mmol) was added. dtbbipy = 4,4′-dimethyl-2,2′-dipyridyl.

to afford the desired product in 82% of yield. Heteroarene-based acrylic acids were also good substrates for this process and afforded the desired products in moderate to good yields (**3s**–**u**). Intriguingly, excellent *E* selectivity (*E*/*Z* > 99:1) were observed in all cases. When bromodifluoroacetate ($BrCF_2COOEt$), a much cheaper fluoroalkyl coupling partner, was employed, the reactions could also proceed smoothly to afford the corresponding fluoroalkylated products in moderate to good yields (**3a**–**f** and **3s**–**u**).

To further examine the scope of this reaction, perfluoroalkyl halides were also used to react with various cinnamic acids. Gratefully, the reaction proceeded smoothly with high yield by changing the substrates ratio, solvent, and the phosphite loading (see Supporting Information Table S4). As shown in Table 3, a series of electron-rich and electron-deficient cinnamic acids were good reaction partners with perfluoroalkyl iodide, and the corresponding products (**5a**–**n**) were obtained in moderate to good yields. Similarly, perfluoroalkyl bromides also underwent this transformation to produce good yields (**5a**–**f**, **i**, and **l**–**n**). Moreover, excellent *E* selectivity (*E*/*Z* > 99:1) was observed in all cases.

In addition, a satisfactory result (76% yield) was obtained when the reaction was performed on a gram-scale. Intriguingly, when bromodifluoroacetate was employed, the reaction also proceeded smoothly to afford the corresponding fluoroalkylated product in a 70% yield (Scheme 2).

In order to gain some insights into the reaction mechanism, a series of control experiments were examined. When radical scavenger TEMPO (3.0 equiv) was added under the standard conditions, the reaction was completely quenched and TEMPO–CF_2COOEt **7** was obtained in 76% of yield (Scheme 3, eq 1). It implied that this reaction might have proceeded through a radical pathway which involved ·CF_2COEt. To further verify this transformation, a radical clock, ethene-1,1-diyldibenzene, was used to trap the difluoromethyl radical. As we expected, ·CF_2COEt was successfully captured and the desired product **10** was obtained in 81% (Scheme 3, eq 3).

To determine the key intermediates of the reaction, the standard reaction in the absence of iododifluoroacetate **2a** was carried out and most of the **1a** was recovered with trace of (*E*)-methyl cinnamic acetate **13** detected (Scheme 4, eq 4). No trace of (*E*)-dimethyl styrylphosphonate **11** was observed. Then compound **11** was prepared according to the literature and was subjected to the standard reaction, no desired product **3a** was obtained (Scheme 4, eq 5). These results suggested that (*E*)-dimethyl styrylphosphonate **11** was not the intermediate although it has been reported that it was accessible in the presence of Cu catalyst and $HPO(OMe)_2$.[11] Next, styrene **12**

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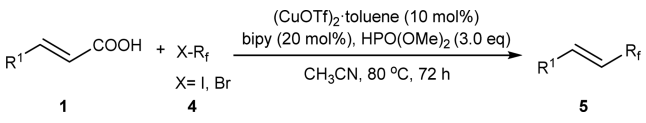
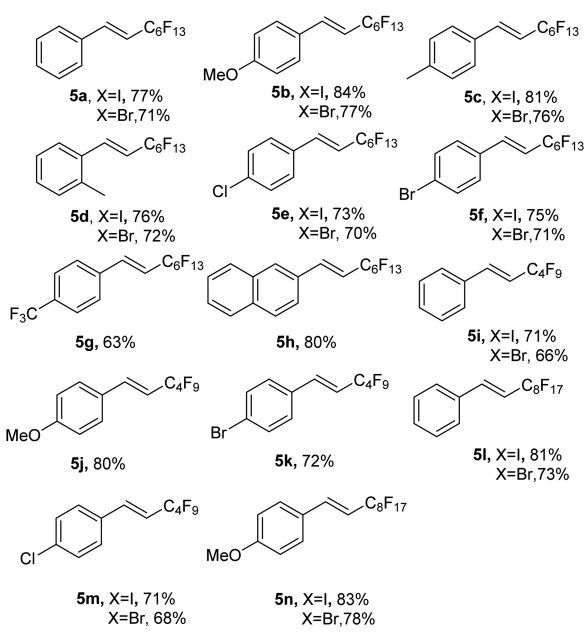
Table 3. Copper-Catalyzed Decarboxylative Perfluoroalkylation of α,β-Unsaturated Carboxylic Acids[a,b]





[a]Reaction conditions: **1** (0.2 mmol), **4** (0.45 mmol), $(CuOTf)_2$·toluene (10 mol%), bipy (20 mol%), $HPO(OMe)_2$ (0.6 mmol), CH_3CN (0.6 mL), 80 °C, 72 h, under N_2. [b]Yield; the *E*/*Z* ratios were determined by ^{19}F NMR spectroscopy of the crude product mixture.

and (*E*)-methyl cinnamic acetate **13** were also examined (Scheme 4, eq 6 and 7) and it was demonstrated that styrene or (*E*)-methyl cinnamic acetate **13** could not be an intermediate for this reaction, either.

Next, the effect of copper and dialkyl phosphite was studied. Under the standard conditions, only 26% of product **3a** was obtained in the absence of $HPO(OMe)_2$ (Table 4, entry 1). And when the above reaction was repeated in the presence of TEMPO, compound **7** was generated in 14% of yield only (Scheme 3, eq 2).The results of eq 1 and eq 2 showed that $HPO(OMe)_2$ had promoted the process of the production of the $\cdot CF_2COEt$. However, when the amount of $(CuOTf)_2$·toluene increased to 0.5 equiv, 72% of product was collected (Table 4, entry 2). When the above reaction was repeated with $Cu(OTf)_2$ (1.0 equiv) or Cu powder (1.0 equiv) instead of $(CuOTf)_2$·toluene (0.5 equiv), only trace or 10% of **3a** was afforded (Table 4, entries 3–4). But when 2.0 equiv of $HPO(OMe)_2$ was added into the reaction with $Cu(OTf)_2$ (1.0 equiv), 74% of **3a** was obtained (Table 4, entry 5). No product was observed in the absence of copper even if 2.0 equiv of $HPO(OMe)_2$ was added (Table 4, entry 6). Hence, our results showed that in our reaction system, partial of Cu(II) had been reduced to Cu(I) which had ensured the completion of the catalytic cycle.[12,13] It is noteworthy that other reductive reagents did not work as well as $HPO(OMe)_2$ on this catalytic cycle (Table 1, entries 9–11 and ref 10).

On the basis of the above results and salient literature,[4,5b,c,e,7,8,12−14] a possible reaction pathway was proposed as presented in Scheme 5. Copper(I) species was oxidized by fluoroalkylated reagent **2** through a single-electron transfer to afford the fluoroalkyl radical **2′** and copper(II) species.[15] Subsequently, complex **I** reacted with the fluoroalkyl radical **2′** to furnish the radical species **II**. Finally, the radical species **II** underwent a decarboxylation to provide the desired fluoroalkyl product **3**. Here we proposed that partial of the Cu(II) in the reaction system might have been reduced constantly by $HPO(OMe)_2$ to Cu(I), which is very important for the generation of fluoroalkyl radical.

CONCLUSIONS

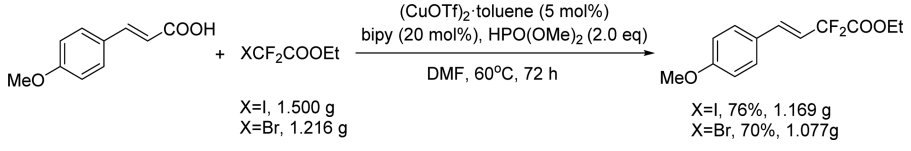
In conclusion, copper-catalyzed decarboxylative difluoroalkylation and perfluoroalkylation of α,β-unsaturated carboxylic acids has been developed. The method offers a reliable tool to produce fluoroalkylated motifs in good to excellent yields from commonly available fluoroalkyl iodides and bromides. With a wide substrate scope and excellent functional-group tolerance, the reaction proceeds in excellent *E* selectivity under mild reaction conditions. Preliminary mechanism study suggests that radical pathway was involved in the catalytic cycle and dialkyl phosphite had played an indispensable role in this reaction. Further studies to uncover the reaction mechanism and possible synthetic applications are underway in our laboratory.

EXPERIMENTAL SECTION

General Information. Solvents and reagents were commercially available and used as received without further treatment. Reactions were monitored by thin-layer chromatography (TLC). ^1H NMR, ^{13}C NMR, and ^{19}F NMR spectra were recorded at 400, 100, and 375 MHz, respectively. Chemical shifts of ^1H NMR and ^{13}C NMR spectra were reported as in units of parts per million (ppm) downfield from $SiMe_4$ (δ 0.0 ppm) and relative to the signal of chloroform-*d* (δ 7.26 ppm for ^1H NMR and δ 77.0 ppm for ^{13}C NMR).^{19}F NMR chemical shifts were determined relative to $CFCl_3$ at δ 0.0. Multiplicities were given as s (singlet); br s (broad singlet); d (doublet); t (triplet); q (quartet); m (multiplets), etc. The number of protons (*n*) for a given resonance was indicated by nH. (*E*)-Dimethyl styrylphosphonate was prepared according to the previously reported procedures.[16] Cinnamic acids and other reagents were commercially available.

General Procedure for Copper-Catalyzed Decarboxylative Difluoromethylation of α,β-Unsaturated Carboxylic Acids with Ethyl Iododifluoroacetate or Ethyl Bromodifluoroacetate. To a 25 mL of Schlenk tube were added α,β-unsaturated carboxylic acids **1** (2.0 equiv, 0.4 mmol), $(CuOTf)_2$·toluene (5 mol%, 0.01 mmol), and bipy (20 mol%, 0.04 mmol) under air. The mixture was evacuated and backfilled with N_2 (3 times). DMF (0.6 mL), ethyl iododifluoroacetate or ethyl bromodifluoroacetate **2** (1.0 equiv, 0.2 mmol), and $HPO(OMe)_2$ (2.0 equiv, 0.4 mmol) were added subsequently. The

Scheme 2. Gram-Scale Experiment



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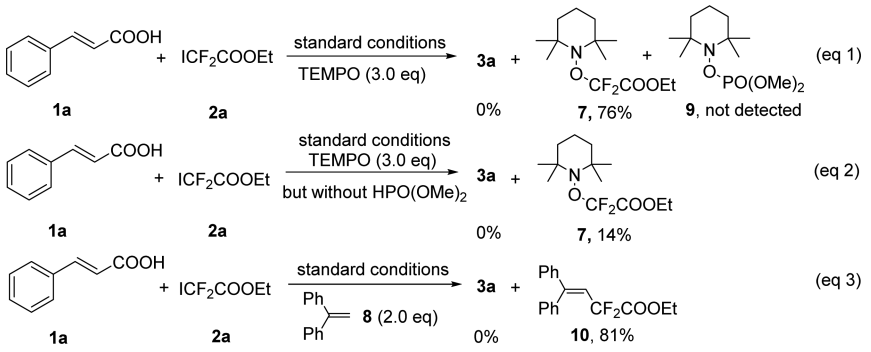
Scheme 3. Studies on a Radical Pathway



Scheme 4. Studies on Proposed Intermediates

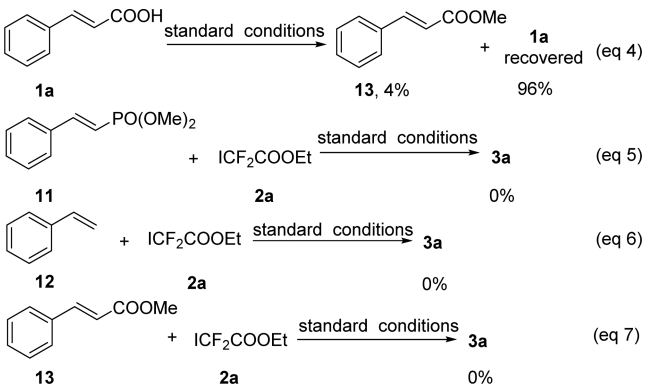
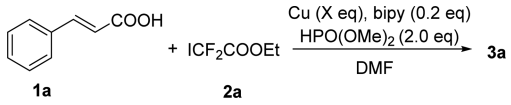


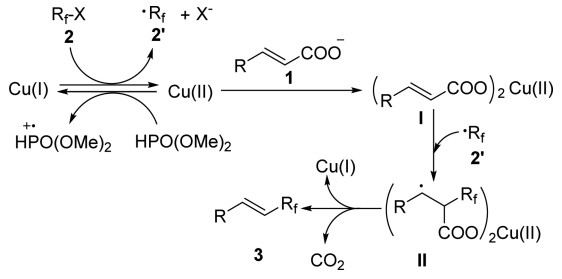
Table 4. Studies on the Effect of Copper and Dialkyl Phosphite[a]



entry	catalyst (equiv)	$HPO(OMe)_2$	yield[b] (%)
1	$(CuOTf)_2$·toluene (0.05)	–	26
2	$(CuOTf)_2$·toluene (0.5)	–	72
3	$Cu(OTf)_2$ (1.0)	–	trace
4	Cu (1.0)	–	10
5	$Cu(OTf)_2$ (1.0)	+	74
6	–	+	0

[a]Reaction conditions: **1a** (0.4 mmol), **2** (0.2 mmol), Cu (X equiv), bipy (20 mol%), $HPO(OMe)_2$ (2.0 equiv), DMF (0.6 mL), 60 °C, 48 h, under N_2. [b]The yield of the product was determined by ^1H NMR spectroscopy.

Scheme 5. Possible Mechanism



Schlenk tube was then sealed with a Teflon lined cap and put into a preheated oil bath (60 °C). After stirring for 48 h, the reaction mixture was cooled to room temperature. The reaction mixture was diluted with EtOAc and filtered through a pad of Celite. The filtrate was concentrated under vacuum and purified by flash column chromatography on silica gel to give product **3**.

General Procedure for Copper-Catalyzed Decarboxylative Perfluoroalkylation of α,β-Unsaturated Carboxylic Acids with Perfluoroalkyl Iodides or Perfluoroalkyl Bromides. To a 25 mL of Schlenk tube were added α,β-unsaturated carboxylic acids **1** (1.0 equiv, 0.2 mmol), $(CuOTf)_2$·toluene (10 mol %, 0.02 mmol), and bipy (20 mol%, 0.04 mmol) under air. The mixture was evacuated and backfilled with N_2 (3 times). CH_3CN (0.6 mL), perfluoroalkyl iodides or perfluoroalkyl bromides **4** (2.25 equiv, 0.45 mmol), and $HPO(OMe)_2$ (3.0 equiv, 0.6 mmol) were added subsequently. The Schlenk tube was then sealed with a Teflon lined cap and put into a preheated oil bath (80 °C). After stirring for 72 h, the reaction mixture was cooled to room temperature. The reaction mixture was diluted with EtOAc or diethyl ether and filtered through a pad of Celite. The filtrate was concentrated under vacuum and purified by flash column chromatography on silica gel to give product **5**.

(E)-Ethyl-2,2-difluoro-4-phenyl-3-butenoate ***3a.*** The product **3a** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (38.9 mg, 86% yield, *E*/*Z* > 99:1). Analytical data for **3a** was consistent with that previously reported.[6] ^1H NMR (400 MHz, $CDCl_3$): δ 7.45 (dd, J_1 = 4.0 Hz, J_2 = 8.0 Hz, 2H), 7.40−7.35 (m, 3H), 7.11−7.35 (m, 1H), 6.36−6.26 (m, 1H), 4.36 (q, *J* = 8.0 Hz, 2H), 1.37 (t, *J* = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.9 (t, J_{C-F} = 30.0 Hz), 136.9 (t, J_{C-F} = 10.0 Hz), 134.1, 129.6, 128.9, 127.5, 118.9 (t, J_{C-F} = 30.0 Hz), 112.7 (t, J_{C-F} = 250.0 Hz), 63.1, 14.0. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.22 (s, 2F). (*Z*)-isomer: δ −93.98 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(4-methoxyphenyl)-3-butenoate ***3b.*** The product **3b** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (46.7 mg, 91% yield, *E*/*Z* > 99:1). Analytical data for **3b** was consistent with that previously reported.[6] ^1H NMR (400 MHz, $CDCl_3$): δ 7.39 (d, *J* = 8.0 Hz, 2H), 7.04−6.99 (m, 1H), 6.89 (d, *J* = 8.0 Hz, 2H), 6.21−6.12 (m, 1H), 4.35 (q, *J* = 8.0 Hz, 2H), 3.82 (s, 3H), 1.36 (t, *J* = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ164.1 (t, J_{C-F} = 30.0 Hz), 160.8, 136.3 (t, J_{C-F} = 10.0 Hz), 128.9, 126.8, 116.4 (t, J_{C-F} = 20.0 Hz), 114.3, 113.0 (t, J_{C-F} = 250.0 Hz), 63.1, 55.3, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −102.57 (s, 2F). (*Z*)-isomer: δ −94.11 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(p-tolyl)-3-butenoate ***3c.*** The product **3c** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (43.0 mg, 89% yield, *E*/*Z* > 99:1). Analytical data for **3c** was consistent with that previously reported.[6] ^1H NMR (400 MHz, $CDCl_3$): δ.7.35 (d, *J* = 8.0 Hz, 2H), 7.18 (d, *J* = 8.0 Hz, 2H), 7.08−7.02 (m, 1H), 6.30−6.21 (m, 1H), 4.35 (q, *J* = 8.0 Hz, 2H), 2.37 (s, 3H), 1.37 (t, *J* = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 164.0 (t, J_{C-F} = 40.0 Hz), 139.9, 136.8 (t, J_{C-F} = 10.0 Hz), 131.4, 129.6, 127.4, 117.8 (t, J_{C-F} = 20.0 Hz), 112.9 (t, J_{C-F} = 250.0 Hz), 63.1, 21.3, 14.0. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −102.95 (s, 2F). (*Z*)-isomer: δ −94.04 (s, 2F).

(E)-Ethyl-4-(4-chlorophenyl)-2,2-difluoro-3-butenoate ***3d.*** The product **3d** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (43.2 mg, 83% yield, *E*/*Z* > 99:1). Analytical

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data for **3d** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39−7.32 (m, 4H), 7.06−7.00 (m, 1H), 6.33−6.23 (m, 1H), 4.35 (q, J = 8.0 Hz, 2H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.72 (t, J_{C-F} = 35.0 Hz), 135.52 (t, J_{C-F} = 10.0 Hz), 135.48, 132.58, 129.04, 128.62, 119.45 (t, J_{C-F} = 25.0 Hz), 112.50 (t, J_{C-F} = 248.0 Hz), 63.15, 13.89. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.27 (s, 2F). (*Z*)-isomer: δ −95.06 (s, 2F).

(E)-Ethyl-4-(4-bromophenyl)-2,2-difluoro-3-butenoate ***3e***. The product **3e** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (53.6 mg, 88% yield, *E*/*Z* > 99:1). Analytical data for **3e** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.50 (d, J = 8.0 Hz, 2H), 7.31 (d, J = 8.0 Hz, 2H), 7.04−7.00 (m, 1H), 6.34−6.25 (m, 1H), 4.35 (q, J = 8.0 Hz, 2H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.7 (t, J_{C-F} = 30.0 Hz), 135.6 (t, J_{C-F} = 10.0 Hz), 133.0, 132.0, 128.9, 123.8, 119.6 (t, J_{C-F} = 20.0 Hz), 112.5 (t, J_{C-F} = 250.0 Hz), 63.2, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.37 (s, 2F). (*Z*)-isomer: δ −95.10 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(4-(trifluoromethyl)phenyl)-3-butenoate ***3f***. The product **3f** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (45.9 mg, 78% yield, *E*/*Z* > 99:1). Analytical data for **3f** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.63 (d, J = 8.0 Hz, 2H), 7.55 (d, J = 8.0 Hz, 2H), 7.14−7.10 (m, 1H), 6.44−6.35 (m, 1H), 4.36 (q, J = 8.0 Hz, 2H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.6 (t, J_{C-F} = 40.0 Hz), 137.5, 135.4 (t, J_{C-F} = 10.0 Hz), 131.2 (t, J_{C-F} = 30.0 Hz), 127.7, 125.8 (q, J_{C-F} = 10.0 Hz), 125.2 (m), 121.5 (t, J_{C-F} = 30.0 Hz), 112.3 (t, J_{C-F} = 250.0 Hz), 63.3, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: −62.85 (s, 3F), −103.70 (s, 2F). (*Z*)-isomer: δ −62.85 (s, 3F), −95.56 (s, 2F)

(E)-Ethyl-2,2-difluoro-4-(4-nitrophenyl)-3-butenoate ***3g***. The product **3g** was purified with silica gel chromatography (PE/EA = 10:1) a yellow solid (38.5 mg, 71% yield, *E*/*Z* > 99:1). Analytical data for **3g** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.26−8.22 (m, 2H), 7.62−7.59 (m, 2H), 7.18−7.12 (m, 1H), 6.51−6.42 (m, 1H), 4.37 (q, J = 8.0 Hz, 2H), 1.38 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.37 (t, J_{C-F} = 30.0 Hz), 148.26, 140.23, 134.54 (t, J_{C-F} = 10.0 Hz), 128.19, 124.14, 123.28 (t, J_{C-F} = 86.0 Hz), 112.08 (t, J_{C-F} = 248.0 Hz), 63.44, 13.93. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.90 (s, 2F). (*Z*)-isomer: δ −96.61 (s, 2F).

(E)-4-(4-Ethoxy-3,3-difluoro-4-oxo-1-buten-1-yl)benzoic Acid ***3h***. The product **3h** was purified with silica gel chromatography (PE/EA = 10:1) as a colorless oil (36.7 mg, 68% yield, *E*/*Z* > 99:1). Analytical data for **3h** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.11 (d, J = 8.0 Hz, 2H), 7.55 (d, J = 8.0 Hz, 2H), 7.16−7.12 (m, 1H), 6.48−6.38 (m, 1H), 4.37 (q, J = 8.0 Hz, 2H), 1.38 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 171.0, 163.6 (t, J_{C-F} = 40.0 Hz), 139.2, 135.7 (t, J_{C-F} = 10.0 Hz), 130.7, 130.1, 127.5, 121.8 (t, J_{C-F} = 20.0 Hz), 112.3 (t, J_{C-F} = 250.0 Hz), 63.3, 14.0. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.63 (s, 2F). (*Z*)-isomer: δ −95.42 (s, 2F).

(E)-Ethyl-4-(4-acetoxyphenyl)-2,2-difluoro-3-butenoate ***3i***. The product **3i** was purified with silica gel chromatography (PE/EA = 10:1) as a yellow oil (45.5 mg, 80% yield, *E*/*Z* > 99:1). Analytical data for **3i** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46 (d, J = 8.0 Hz, 2H), 7.11 (d, J = 8.0 Hz, 2H), 7.08−7.04 (m, 1H), 6.30−6.21 (m, 1H), 4.35 (q, J = 8.0 Hz, 2H), 2.30(s, 3H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 169.2, 163.8 (t, J_{C-F} = 40.0 Hz), 151.6, 135.8 (t, J_{C-F} = 10.0 Hz), 131.9, 128.5, 122.1, 119.1 (t, J_{C-F} = 20.0 Hz), 112.6 (t, J_{C-F} = 250.0 Hz), 63.1, 21.1, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.28(s, 2F). (*Z*)-isomer: δ −94.42 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(4-formylphenyl)-3-butenoate ***3j***. The product **3j** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (31.0 mg, 61% yield, *E*/*Z* > 99:1). Analytical data for **3j** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.00 (s, 1H), 7.88 (d, J = 8.0 Hz, 2H), 7.59 (d, J = 8.0 Hz, 2H), 7.14−7.09 (m, 1H), 6.48−6.39 (m, 1H), 4.35 (q, J = 8.0 Hz, 2H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 191.4, 163.5 (t, J_{C-F} = 30.0 Hz), 139.8, 136.9, 135.5 (t, J_{C-F} = 10.0 Hz), 130.2, 128.0, 122.1 (t, J_{C-F} = 30.0 Hz), 112.3 (t, J_{C-F} = 250.0 Hz), 63.3, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.66 (s, 2F). (*Z*)-isomer: δ −95.64 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(2-methoxyphenyl)-3-butenoate ***3k***. The product **3k** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (43.5 mg, 85% yield, *E*/*Z* > 99:1). Analytical data for **3k** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ7.44−7.42 (m, 1H), 7.39−7.30 (m, 2H), 6.95 (t, J = 8.0 Hz, 1H), 6.92−6.90 (m, 1H), 6.45−6.36 (m, 1H), 4.35 (q, J = 8.0 Hz, 2H), 3.87(s, 3H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 164.2 (t, J_{C-F} = 30.0 Hz), 157.8, 132.3 (t, J_{C-F} = 10.0 Hz), 130.8, 128.4, 123.1, 120.7, 119.4 (t, J_{C-F} = 20.0 Hz), 113.1 (t, J_{C-F} = 240.0 Hz), 111.1, 63.0, 55.5, 14.0. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −102.82 (s, 2F). (*Z*)-isomer: δ −94.33 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(o-tolyl)-3-butenoate ***3l***. The product **3l** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (39.9 mg, 83% yield, *E*/*Z* > 99:1). Analytical data for **3l** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45 (d, J = 8.0 Hz, 1H), 7.33 (d, J = 16.0 Hz, 1H), 7.24−7.17 (m, 3H), 6.24−6.15 (m, 1H), 4.35 (q, J = 4.0 Hz, 2H), 2.37 (s, 3H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 164.0 (t, J_{C-F} = 30.0 Hz), 136.8, 134.7 (t, J_{C-F} = 10.0 Hz), 133.3, 130.7, 129.4, 126.3, 126.1, 120.1 (t, J_{C-F} = 30.0 Hz), 112.8 (t, J_{C-F} = 250.0 Hz), 63.1, 19.6, 14.0. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.02 (s, 2F). (*Z*)-isomer: δ −93.84 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(2-nitrophenyl)-3-butenoate ***3m***. The product **3m** was purified with silica gel chromatography (PE/EA = 30:1) as a light yellow solid (34.7 mg, 64% yield, *E*/*Z* > 99:1). Analytical data for **3m** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.06 (d, J = 8.0 Hz, 1H), 7.68−7.52 (m, 4H), 6.31−6.22 (m, 1H), 4.38 (q, J = 8.0 Hz, 2H), 1.39 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 133.6, 133.3 (t, J_{C-F} = 10.0 Hz), 130.4, 130.0, 129.2, 124.9, 124.0 (t, J_{C-F} = 20.0 Hz), 112.1 (t, J_{C-F} = 240.0 Hz), 63.4, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.27 (s, 2F). (*Z*)-isomer: δ −96.83 (s, 2F).

(E)-Ethyl-4-(2-acetoxyphenyl)-2,2-difluoro-3-butenoate ***3n***. The product **3n** was purified with silica gel chromatography (PE/EA = 20:1) as a colorless oil (39.8 mg, 70% yield, *E*/*Z* > 99:1). Analytical data for **3n** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.59−7.56 (m, 1H), 7.42−7.38 (m, 1H), 7.30−7.28 (m, 1H),7.18−7.13 (m, 2H), 6.40−6.30 (m, 1H), 4.37 (q, J = 8.0 Hz, 2H), 2.37(s, 3H), 1.39 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 169.0, 163.7 (t, J_{C-F} = 40.0 Hz), 148.8, 130.7, 130.5 (t, J_{C-F} = 10.0 Hz), 127.5, 126.9, 126.3, 123.1, 121.3 (t, J_{C-F} = 20.0 Hz), 112.4, 63.2, 20.9, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.67 (s, 2F). (*Z*)-isomer: δ −95.50 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(3-methoxyphenyl)-3-butenoate ***3o***. The product **3o** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (42.5 mg, 83% yield, *E*/*Z* > 99:1). Analytical data for **3o** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.20 (t, J = 8.0 Hz, 1H), 6.96 (t, J = 8.0 Hz, 2H), 6.88 (s, 1H), 6.83−6.81 (m, 1H), 6.26−6.16 (m, 1H), 4.37 (q, J = 8.0 Hz, 2H), 3.75 (s, 3H), 1.28 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.9 (t, J_{C-F} = 40.0 Hz), 159.9, 136.8 (t, J_{C-F} = 10.0 Hz), 135.5, 129.9, 120.1, 119.2 (t, J_{C-F} = 20.0 Hz), 115.3, 112.7 (t, J_{C-F} = 250.0 Hz), 112.6, 63.1, 55.3, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.20 (s, 2F). (*Z*)-isomer: δ −93.75 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(m-tolyl)-3-butenoate ***3p***. The product **3p** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (40.9 mg, 85% yield, *E*/*Z* > 99:1). Analytical data for **3p** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.20−7.17 (m, 3H), 7.09−7.07 (m, 1H), 6.99−6.95 (m, 1H), 6.25−6.16 (m, 1H), 4.27 (q, J = 8.0 Hz, 2H), 2.28 (s, 3H), 1.28 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 164.0 (t, J_{C-F} = 30.0 Hz), 138.5, 137.0 (t, J_{C-F} = 10.0 Hz), 134.1, 130.4, 128.7, 128.1, 124.6, 118.6 (t, J_{C-F} = 30.0 Hz), 112.8 (t, J_{C-F} = 250.0 Hz), 63.1, 21.3, 14.0. ^{19}F NMR (376 MHz, $CDCl_3$): (*E*)-isomer: δ −103.12 (s, 2F). (*Z*)-isomer: δ −93.65 (s, 2F).

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(E)-Ethyl-2,2-difluoro-4-(3-(trifluoromethyl)phenyl)-3-butenoate ***3q***. The product **3q** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (44.7 mg, 76% yield, E/Z > 99:1). Analytical data for **3q** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.67 (s, 1H), 7.62 (t, J = 8.0 Hz, 2H), 7.51 (t, J = 8.0 Hz, 1H), 7.14−7.09 (m, 1H), 6.43−6.34 (m, 1H), 4.37 (q, J = 8.0 Hz, 2H), 1.38 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.6 (t, J_{C-F} = 40.0 Hz), 135.4 (t, J_{C-F} = 10.0 Hz), 134.9, 131.3 (t, J_{C-F} = 30.0 Hz), 130.6, 129.4, 126.1 (q, J_{C-F} = 10.0 Hz), 125.2 (t, J_{C-F} = 250.0 Hz), 124.1 (q, J_{C-F} = 10.0 Hz), 120.9 (t, J_{C-F} = 30.0 Hz), 112.3 (t, J_{C-F} = 250.0 Hz), 63.3, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (E)-isomer: δ −62.93 (s, 3F), −103.59 (s, 2F). (Z)-isomer: δ −62.93 (s, 3F), −95.72 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(naphthalen-2-yl)-3-butenoate ***3r***. The product **3r** was purified with silica gel chromatography (PE/EA = 30:1) as a white solid (45.3 mg, 82% yield, E/Z > 99:1). Analytical data for **3r** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.74−7.72 (m, 4H), 7.52−7.49 (m, 1H),7.43−7.39 (m, 2H), 7.18−7.13 (m, 1H), 6.38−6.28 (m, 1H), 4.28 (q, J = 8.0 Hz, 2H), 1.29 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 164.0 (t, J_{C-F} = 30.0 Hz), 136.9 (t, J_{C-F} = 10.0 Hz), 133.9, 133.3, 131.6, 128.8. 128.7, 128.4, 127.8, 127.0, 126.7, 123.3, 119.1 (t, J_{C-F} = 30.0 Hz), 112.9 (t, J_{C-F} = 250.0 Hz), 63.2, 14.0. ^{19}F NMR (376 MHz, $CDCl_3$): (E)-isomer: δ −102.93 (s, 2F). (Z)-isomer: δ −93.60 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(pyridin-2-yl)-3-butenoate ***3s***. The product **3s** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (27.8 mg, 61% yield, E/Z > 99:1). Analytical data for **3s** was consistent with that previously reported.[3a] ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.54 (d, J = 4.0 Hz, 1H), 7.65−7.60 (m, 1H), 7.34(d, J = 8.0 Hz, 1H), 7.70−7.60(m, 1H), 7.08−7.02 (m, 1H), 6.86−6.77 (m, 1H), 4.27 (q, J = 8.0 Hz, 2H), 1.29 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.7 (t, J_{C-F} = 30.0 Hz), 152.5, 150.0, 136.8, 136.0 (t, J_{C-F} = 10.0 Hz), 123.9, 123.7, 123.2(t, J_{C-F} = 20.0 Hz), 112.7 (t, J_{C-F} = 240.0 Hz), 63.2, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (E)-isomer: δ −103.87(s, 2F). (Z)-isomer: δ −94.36 (s, 2F).

(E)-Ethyl-2,2-difluoro-4-(furan-2-yl)-3-butenoate ***3t***. The product **3t** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (31.2 mg, 72% yield, E/Z > 99:1). Analytical data for **3t** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (s, 1H), 6.86 (d, J = 16.0 Hz, 1H), 6.46 (d, J = 8.0 Hz, 2H), 6.27−6.17 (m, 1H), 4.34 (q, J = 8.0 Hz, 2H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 163.8 (t, J_{C-F} = 40.0 Hz), 150.2, 143.9, 124.2 (t, J_{C-F} = 10.0 Hz), 116.7 (t, J_{C-F} = 30.0 Hz), 112.8, 112.6 (t, J_{C-F} = 250.0 Hz), 111.9, 63.1, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): (E)-isomer: δ −103.38 (s, 2F). (Z)-isomer: δ −95.92(s, 2F).

(E)-Ethyl-2,2-difluoro-4-(thiophen-2-yl)-3-butenoate ***3u***. The product **3u** was purified with silica gel chromatography (PE/EA = 30:1) as a colorless oil (36.2 mg, 78% yield, E/Z > 99:1). Analytical data for **3u** was consistent with that previously reported.[6] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31 (d, J = 4.0 Hz, 1H), 7.21−7.15 (m, 2H), 7.03−7.02(m, 1H), 6.16−6.06 (m, 1H), 4.35(q, J = 8.0 Hz, 2H), 1.36 (t, J = 8.0 Hz, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 162.8 (t, J_{C-F} = 40.0 Hz), 137.9, 128.8 (t, J_{C-F} = 10.0 Hz), 128.4, 126.8, 126.2, 116.6 (t, J_{C-F} = 20.0 Hz), 111.4 (t, J_{C-F} = 250.0 Hz), 62.1, 12.9. ^{19}F NMR (376 MHz, $CDCl_3$): (E)-isomer: δ −102.92 (s, 2F). (Z)-isomer: δ −96.35 (s, 2F).

(E)-(3,3,4,4,5,5,6,6,7,7,8,8,8-Tridecafluoro-1-octen-1-yl)benzene ***5a***. The product **5a** was purified with silica gel chromatography (Petroleum ether) as a colorless oil (65.0 mg, 77% yield, E/Z > 99:1). Analytical data for **5a** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.51−7.48 (m, 2H), 7.42−7.41 (m, 3H), 7.22−7.18 (m, 1H), 6.28−6.18 (m, 1H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 139.7 (t, J_{C-F} = 10.0 Hz), 133.6, 130.2, 128.9, 127.6, 114.4 (t, J_{C-F} = 20.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.81 (t, J = 11.3 Hz, 3F), −111.07 (m, 2F), −121.56 (m, 2F), −122.84 (m, 2F), −123.20 (m, 2F), −126.12 (m, 2F).

(E)-1-Methoxy-4-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-1-octen-1-yl)benzene ***5b***. The product **5b** was purified with silica gel chromatography (petroleum ether) as a colorless oil (76.0 mg, 84% yield, E/Z > 99:1). Analytical data for **5b** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, J = 8.0 Hz, 2H), 7.10 (d, J = 16.0 Hz, 1H), 6.92 (d, J = 8.0 Hz, 2H), 6.10−6.00 (m, 1H), 3.84 (s, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 161.2, 139.2 (t, J_{C-F} = 10.0 Hz), 129.2, 126.3, 114.4, 111.8 (t, J_{C-F} = 20.0 Hz), 55.4. ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.81 (t, J = 11.3 Hz, 3F), −110.54 (m, 2F),-121.58 (m, 2F), −122.85 (m, 2F), −123.19 (m, 2F),- 126.14 (m, 2F).

(E)-1-Methyl-4-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-1-octen-1-yl)benzene ***5c***. The product **5c** was purified with silica gel chromatography (petroleum ether) as a colorless oil (70.7 mg, 81% yield, E/Z > 99:1). Analytical data for **5c** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 (d, J = 8.0 Hz, 2H), 7.25−7.11 (m, 3H), 6.19−6.09 (m, 1H), 2.37 (s, 3H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 140.5, 139.6 (t, J_{C-F} = 10.0 Hz), 130.8, 129.6, 127.6, 113.2 (t, J_{C-F} = 20.0 Hz), 21.3. ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.83 (t, J = 11.3 Hz, 3F), −110.83 (m, 2F), −121.57 (m, 2F), −122.84 (m, 2F), −123.21 (m, 2F), −126.12 (m, 2F).

(E)-1-Methyl-2-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-1-octen-1-yl)benzene ***5d***. The product **5d** was purified with silica gel chromatography (petroleum ether) as a colorless oil (66.3 mg, 76% yield, E/Z > 99:1). Analytical data for **5d** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.50−7.45 (m, 2H), 7.34−7.23 (m, 3H), 6.18−6.08 (m, 1H), 2.43 (s, 3H). $^{13}C\{^1H\}$-NMR (100 MHz, $CDCl_3$): δ 137.8 (t, J_{C-F} = 10.0 Hz), 137.0, 132.8, 130.7, 129.9, 126.5, 126.3, 115.7 (t, J_{C-F} = 20.0 Hz), 19.5. ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.83 (t, J = 11.3 Hz, 3F), −110.99 (m, 2F), −121.51 (m, 2F), −122.85 (m, 2F), −123.26 (m, 2F), −126.13 (m, 2F).

(E)-1-Chloro-4-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-1-octen-1-yl)benzene ***5e***. The product **5e** was purified with silica gel chromatography (petroleum ether) as a colorless oil (66.6 mg, 73% yield, E/Z > 99:1). Analytical data for **5e** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43−7.37(m, 4H), 7.16−7.11 (m, 1H), 6.23−6.13 (m, 1H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 138.5 (t, J_{C-F} = 10.0 Hz), 136.2, 132.0, 129.3, 128.8, 115.0 (t, J_{C-F} = 20.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.84 (t, J = 11.3 Hz, 3F), −111.16 (m, 2F), −121.59 (m, 2F), −122.82 (m, 2F), −123.16 (m, 2F), −126.14 (m, 2F).

(E)-1-Bromo-4-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-1-octen-1-yl)benzene ***5f***. The product **5f** was purified with silica gel chromatography (Petroleum ether) as a White solid (75.0 mg, 75% yield, E/Z > 99:1). Analytical data for **5f** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.56−7.53 (m, 2H), 7.36−7.34 (m, 2H), 7.15−7.10 (m, 1H), 6.25−6.15 (m, 1H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 138.6 (t, J_{C-F} = 10.0 Hz), 132.4, 132.2, 129.1, 124.5, 115.0 (t, J_{C-F} = 20.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −81.16 (m, 3F), −111.54 (m, 2F), −121.90 (m, 2F), −123.14 (m, 2F), −123.48 (m, 2F), −126.45 (m, 2F).

(E)-1-(3,3,4,4,5,5,6,6,7,7,8,8,8-Tridecafluoro-1-octen-1-yl)-4-(trifluoromethyl)benzene ***5g***. The product **5g** was purified with silica gel chromatography (petroleum ether) as a colorless oil (61.8 mg, 63% yield, E/Z > 99:1). Analytical data for **5g** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.67 (d, J = 8.0 Hz, 2H), 7.59 (d, J = 8.0 Hz, 2H), 7.26−7.20 (m, 1H), 6.35−6.25 (m, 1H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 138.3 (t, J_{C-F} = 10.0 Hz), 136.8, 127.9, 125.9 (q, J_{C-F} = 10.0 Hz), 125.1 (m), 118.6, 117.0 (t, J_{C-F} = 30.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −62.96 (t, 3F), −80.78 (t, J = 11.3 Hz, 3F), −111.54 (m, 2F), −121.54 (m, 2F), −122.80 (m, 2F), −123.13 (m, 2F), −126.09 (m, 2F).

(E)-2-(3,3,4,4,5,5,6,6,7,7,8,8,8-Tridecafluoro-1-octen-1-yl)-naphthalene ***5h***. The product **5h** was purified with silica gel chromatography (petroleum ether) as a white solid (78.0 mg, 80% yield, E/Z > 99:1). Analytical data for **5h** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88−78.5 (m, 4H), 7.63−7.52 (m, 3H), 7.36−7.32 (m, 1H), 6.37−6.27 (m, 1H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$): δ 139.8 (t, J_{C-F} = 10.0 Hz), 134.1, 133.3, 131.0, 129.3, 128.8, 128.5, 127.8, 127.3, 126.8, 123.1, 114.4 (t, J_{C-F} = 30.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.83 (t, J = 11.3

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Hz, 3F), −110.89 (m, 2F), −121.53 (m, 2F), −122.82 (m, 2F), −123.05 (m, 2F), −126.13 (m, 2F).

(E)-(3,3,4,4,5,5,6,6,6-Nonafluoro-1-hexen-1-yl)benzene ***5i***. The product **5i** was purified with silica gel chromatography (petroleum ether) as a colorless oil (45.8 mg, 71% yield, *E*/*Z* > 99:1). Analytical data for **5i** was consistent with that previously reported.[3k] ^{1}H NMR (400 MHz, $CDCl_3$): δ 750−7.48 (m, 2H), 7.43−7.41 (m, 3H), 7.27−7.17 (m, 1H), 6.27−6.11 (m, 1H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 139.8 (t, J_{C-F} = 10.0 Hz), 133.6, 130.2, 129.0, 127.6, 114.3 (t, J_{C-F} = 20.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −81.14 (m, 3F), −111.35 (m, 2F), −124.14 (m, 2F), −125.74 (m, 2F).

(E)-1-Methoxy-4-(3,3,4,4,5,5,6,6,6-nonafluoro-1-hexen-1-yl)-benzene ***5j***. The product **5j** was purified with silica gel chromatography (petroleum ether) as a colorless oil (56.3 mg, 80% yield, *E*/*Z* > 99:1). Analytical data for **5j** was consistent with that previously reported.[3k] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.0 Hz, 2H), 7.12−7.08 (m, 1H), 6.91 (d, *J* = 8.0 Hz, 2H), 6.09−5.99 (m, 1H), 3.84 (s, 3H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 161.3, 139.2 (t, J_{C-F} = 10.0 Hz), 129.3, 126.3, 114.4, 111.8(t, J_{C-F} = 20.0 Hz). 55.4. ^{19}F NMR (376 MHz, $CDCl_3$): δ −81.04 (t, *J* = 11.3 Hz, 3F), −110.76 (m, 2F), −124.08 (m, 2F), −125.68 (m, 2F).

(E)-1-Bromo-4-(3,3,4,4,5,5,6,6,6-nonafluoro-1-hexen-1-yl)-benzene ***5k***. The product **5k** was purified with silica gel chromatography (petroleum ether) as a colorless oil (57.6 mg, 72% yield, *E*/*Z* > 99:1). Analytical data for **5k** was consistent with that previously reported.[3k] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54 (d, *J* = 8.0 Hz, 2H), 7.34 (d, *J* = 8.0 Hz, 2H), 7.14−7.10 (m, 1H), 6.24−6.149 (m, 1H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 138.6 (t, J_{C-F} = 10.0 Hz), 132.4, 132.2, 129.1, 124.5, 115.0 (t, J_{C-F} = 20.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.03 (m, 3F), −111.44 (m, 2F), −124.05 (m, 2F), −125.66 (m, 2F).

(E)-(3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-Heptadecafluoro-1-decen-1-yl)benzene ***5l***. The product **5l** was purified with silica gel chromatography (petroleum ether) as a colorless oil (84.6 mg, 81% yield, *E*/*Z* > 99:1). Analytical data for **5l** was consistent with that previously reported.[3l] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.50−7.47 (m, 2H), 7.42−7.40 (m, 3H), 7.20−7.16 (m, 1H), 6.26−6.16 (m, 1H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 139.8 (t, J_{C-F} = 10.0 Hz), 133.6, 130.2, 129.0, 127.6, 114.4 (t, J_{C-F} = 20.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.83 (m, 3F), −111.10 (m, 2F), −121.38 (m, 2F), −121.92(m, 4F), −122.73 (m, 2F), −123.21 (m, 2F), −126.15(m, 2F).

(E)-1-Chloro-4-(3,3,4,4,5,5,6,6,6-nonafluoro-1-hexen-1-yl)-benzene ***5m***. The product **5m** was purified with silica gel chromatography (petroleum ether) as a colorless oil (50.6 mg, 71% yield, *E*/*Z* > 99:1). Analytical data for **5m** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43−7.37(m, 4H), 7.16−7.12 (m, 1H), 6.24−6.14 (m, 1H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 138.5 (t, J_{C-F} = 10.0 Hz), 136.2, 132.0, 129.3, 128.9, 115.0 (t, J_{C-F} = 20.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$): δ −81.01 (m, 3F), −111.29 (m, 2F), −124.03 (m, 2F), −125.66 (m, 2F).

(E)-1-(3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-Heptadecafluoro-1-decen-1-yl)-4-methoxybenzene ***5n***. The product **5n** was purified with silica gel chromatography (petroleum ether) as a colorless oil (91.7 mg, 83% yield, *E*/*Z* > 99:1). Analytical data for **5n** was consistent with that previously reported.[3j] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.0 Hz, 2H), 7.113−7.09 (m, 1H), 6.92 (d, *J* = 8.0 Hz, 2H), 6.10−6.00 (m, 1H), 3.84 (s, 3H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 161.2, 139.1 (t, J_{C-F} = 10.0 Hz), 129.2, 126.3, 114.4, 111.8 (t, J_{C-F} = 20.0 Hz), 55.4. ^{19}F NMR (376 MHz, $CDCl_3$): δ −80.85 (m, 3F), −110.56 (m, 2F), −121.38 (m, 2F), −121.91 (m, 4F), −122.73 (m, 2F), −123.18 (m, 2F), −126.13 (m, 2F).

Ethyl-2,2-difluoro-2-((2,2,6,6-tetramethyl-1-piperidinyl)oxy)-acetate ***7***. The product **7** was purified with silica gel chromatography (petroleum ether) as a colorless oil (42.5 mg, 76% yield). Analytical data for **7** was consistent with that previously reported.[3g] ^{1}H NMR (400 MHz, $CDCl_3$): δ 4.28 (q, *J* = 8.0 Hz, 2H), 1.52−1.46 (m, 6H), 1.30 (t, *J* = 4.0 Hz, 3H), 1.12−1.10 (m, 12H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 160.7 (t, J_{C-F} = 60.0 Hz), 115.5 (t, J_{C-F} = 270.0 Hz), 63.0, 61.4, 40.1, 33.4 (t, J_{C-F} = 10.0 Hz), 20.7, 16.9, 13.9. ^{19}F NMR (376 MHz, $CDCl_3$): δ −73.45.

Ethyl-2,2-difluoro-4,4-diphenyl-3-butenoate ***11***. The product **11** was purified with silica gel chromatography (petroleum ether) as a colorless oil (49.2 mg, 81% yield). Analytical data for **11** was consistent with that previously reported.[3g] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29−7.21 (m, 6H), 7.18−7.11 (m, 2H), 7.13−7.12 (m, 2H), 6.19 (t, *J* = 12.0 Hz, 1H), 3.83 (q, *J* = 8.0 Hz, 2H), 1.09 (t, *J* = 8.0 Hz, 3H). $^{13}C\{^{1}H\}$NMR (100 MHz, $CDCl_3$): δ 163.5 (t, J_{C-F} = 30.0 Hz), 151.0 (t, J_{C-F} = 10.0 Hz), 140.5, 137.1, 129.9 (t, J_{C-F} = 10.0 Hz), 129.1, 128.6, 128.4, 128.0, 127.9, 119.5 (t, J_{C-F} = 30.0 Hz), 112.6 (t, J_{C-F} = 250.0 Hz), 62.8, 13.7. ^{19}F NMR (376 MHz, $CDCl_3$): δ −91.00.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02613.

Experimental procedures and spectroscopic data (PDF)

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Notes

The authors declare no competing financial interest.

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