JOC*Note*

Electrochemical Partial Fluorination of Organic Compounds. 80. Synthesis of Cyclic α-Arylthio-α-monofluorophosphonate Esters

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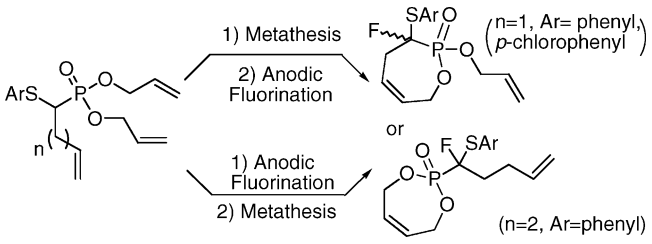

Seven-membered cyclic α-monofluorophosphonate esters such as 2-allyloxy-3-fluoro-3-phenylthio-4,7-dihydro-[1, 2]-oxaphosphinine-2-oxide were successfully synthesized in moderate total yield as 41% from open-chain allyl phosphonates having an α-arylthio group as an electroauxiliary using an alternative sequence of anodic fluorination and ring-closing olefin metathesis (RCM). On the other hand, in an attempt to synthesize an eight-membered analogue, a different type of seven-membered fluorinated cyclic product was formed predominantly by the RCM reaction between the allyloxy groups.

Cyclic phosphonates play critical roles in a wide variety of biochemical processes such as carbohydrate-linked biological process (e.g. cellular recognition).[1,2] On the other hand, cyclic allylic phosphonates have enormous potential in the development of novel phosphonates, phosphonic acids, phosphinates, phosphonosugars, and conformationally restricted phosphonic acid.[3]

Many studies indicated that the presence of the fluorine atoms at the α-position of phosphorus in phosphonate increased both the structural and electronic similarities to the parent phosphate groups.[4] Moreover, several analogues of phosphates encompassing the difluoromethylene-phosphonate moiety have been shown to exhibit better bioactivity than the corresponding nonfluorinated phosphonates.[5] It has also been suggested that the α-monofluorophosphonates gave superior results to α,α-difluorination in phosphonate mimics of biological phosphates.[6] Therefore, in recent years, many efforts have been devoted to construct phosphonate mimics with α-fluoro- and α,α-difluoromethylene groups as an isoelectronic and isosteric replacement for oxygen in phosphate groups. On the other hand, compounds having an ArSCHF moiety are considered to be fluoropeptido mimetics, and they show protease inhibition.[7]

FIGURE 1. First- (**A**) and second-generation (**B**) Grubbs' catalysts.

N,*N*-Diethylaminosulfurtrifluoride (DAST) has been mainly used for the preparation of α-mono- and α,α-difluorophosphonates from α-hydroxy- and α-ketophosphonates, respectively.[6,8] However, a serious drawback of DAST is that it is expensive and sometimes explosive. On the other hand, selective electrochemical fluorination has been shown to be a highly efficient tool for the synthesis of various fluorinated organic sulfur compounds[9] with the advantage of mild conditions and avoidance of hazardous and explosive reagents.

The ring-closing olefin metathesis (RCM) reaction has been recognized as a powerful method for the preparation of medium- or large-sized rings to create heterocycles, constrained peptides, and complex natural products.[10] Grubbs' ruthenium catalysts **A**[11a] and **B**,[11b] as shown in Figure 1, have been used most widely in RCM reactions because of their high reactivity, air stability, and re-

(1) (a) Darrow, J. W.; Drueckhammer, D. G. *J. Org. Chem.* **1994**, *59*, 2976−2985. (b) Hannessian, S.; Galeotti, N.; Rosen, P.; Olva, G.; Babu, S. *Bioorg. Med. Chem.* **1994**, *23*, 2763.

(2) Rademacher, T. W.; Parekh, R. B.; Dwek, R. A. *Annu. Rev. Biochem.* **1998**, *57*, 785.

(3) (a) Hanson, P. R.; Stoianova, D. S. *Tetrahedron Lett.* **1998**, *39*, 3939−3942. (b) Wang, Q.; Pfeiffer, B.; Tucker, G. C.; Royer, J.; Husson, H.-P. *Bioorg. Med. Chem. Lett.* **1997**, *7*, 2477 (c) Gao, J.; Martichonok, V.; Whitesides, G. M. *J. Org. Chem.* **1996**, *61*, 9538. (d) Natchev, I. A. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 3705 and 3711. (e) Natchev, I. A. *J. Chem. Soc., Perkin Trans. 1* **1989**, 125.

(4) See, for example: (a) Burke, T. R., Jr.; Kole, H. K.; Roller, P. P. *Biochem. Biophys. Res. Commun.* **1994**, *204*, 129−134. (b) Halazy, S.; Ehrhard, A.; Eggenspiller, A.; Berges-Gross, V.; Danzin, C. *Tetrahedron* **1996**, *52*, 172−184. (c) Higashimoto, Y.; Saito, S.; Tong, X.-H.; Hong, A.; Sakaguchi, K.; Appella, E.; Anderson, C. W. *J. Biol. Chem.* **2000**, *275*, 23199−23203.

(5) (a) Lequeux, T.; Lebouc, F.; Lopin, C.; Yang, H.; Gouhier, G.; Piettre, S. R. *Org. Lett.* **2001**, *3*, 185−188. (b) Taylor, S. D.; Kotoris, C. C.; Dinaut, A. N.; Chen, M. J. *Tetrahedron* **1998**, *54*, 1691−1714.

(6) See, for example: (a) Berkowitz, D. B.; Bose, M.; Pfannenstied, T. J.; Doukov, T. *J. Org. Chem.* **2000**, *65*, 4498−4508. (b) Berkowitz, D. B.; Bose, M. *J. Fluorine Chem.* **2001**, *112*, 13−33.

(7) Annedi, S. C.; Majumder, K.; Wei, L.; Oyiliagu, C. E.; Samson, S.; Kotra, L. P. *Bioorg. Med. Chem.* **2005**, *13*, 2943−2958.

(8) (a) Smith, M. S.; Burke, T. R. *Tetrahedron* **1994**, *35*, 551−554. (b) Solas, D.; Hale, R. D.; Patel, D. V. *J. Org. Chem.* **1996**, *61*, 1537−1539.

(9) (a) Fuchigami, T. *Organic Electrochemistry*, 4th ed.; Lund, H., Hammerich, O., Eds.; Marcel Dekker: New York, 2000; Chapter 25. (b) Suzuki, K.; Fuchigami, T. *J. Org. Chem.* **2004**, *69*, 1276−1282. (c) Dawood, K. M.; Fuchigami, T. *J. Org. Chem.* **2004**, *69*, 5302−5306. (d) Hasegawa, M.; Ishii, H.; Fuchigami, T. *Green Chem.* **2003**, *5*, 512−515.

(10) For recent reviews on RCM, see: (a) Furstner, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 3012−3043. (b) Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18−29. (c) Love, J. A.; Sanford, M. S.; Day, M. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2003**, 10103−10109. (d) Grubbs, R. H. *Tetrahedron* **2004**, *60*, 7117−7140.

(11) (a) Nguyen, S. T.; Grubbs, R. H. *J. Am. Chem. Soc.* **1993**, *115*, 9858−9859. (b) Scholl, M.; Ding, S.; Lee, C. W.; Grubbs, R. H. *Org. Lett.* **1999**, *1*, 953−956.

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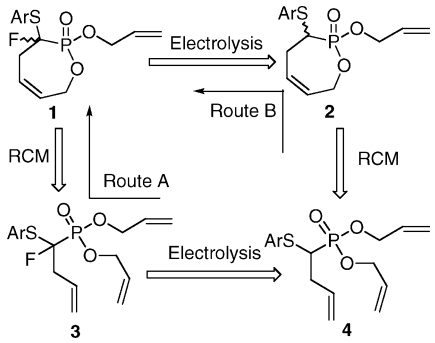
SCHEME 1. Retrosynthetic Analysis of Fluorinated Cyclic Phosphonate Esters



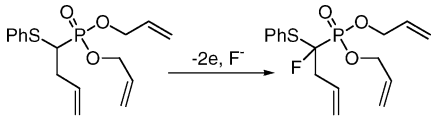
markable functional group tolerance. Recently, it was shown that the RCM reaction by using Grubbs' catalyst **A** is an effective method for the construction of phosphorus-containing cyclic compounds.[3a,12] It has also been found that Grubbs' catalyst **B** was more efficient in the RCM reaction of sulfur-containing compounds.[13] Although there has been only one report on the synthesis of cyclic α,α-difluorophosphonates using bromodifluorophosphonate as a building block,[14] a combination of the RCM reaction and anodic fluorination has never been used, to our knowledge, for the preparation of α-monofluorinated cyclic phosphonates.

In this Note, we describe the synthesis of 2-allyoxy-3-fluoro-3-arylthiocyclic phosphonate esters using both electrolysis and the RCM reaction. The retrosynthetic analysis of our strategy is shown in Scheme 1. Two possible synthetic routes, namely, an alternative sequence of electrolysis and the RCM reaction from open-chain diallyl (1-arylthio-3-butenyl) phosphonate **4**, were considered. It is of much interest to compare the RCM reactivity of the fluorinated and nonfluorinated open-chain diallyl phosphonate derivatives and also the anodic fluorination of open-chain and the corresponding cyclic phosphonate derivatives.

The starting material, diallyl α-arylthio-olefinic phosphonates **4**, was prepared by allylation of diethyl (α-arylthio)-methylphosphonate, followed by the three-step transesterification procedure outlined in the literature.[15]

Initially, anodic fluorination of diallyl 1-phenylthio-3-butenylphosphonate (**4a**) was investigated at a constant current by using an undivided cell and platinum electrodes. Various quaternary ammonium fluorinate salts were used as a supporting electrolyte and a fluoride ion source, as shown in Table 1. The monofluorination of **4a** proceeded smoothly in Et_4NF-3HF/dimethoxyethane (DME) to give the maximum yield (64%) of the monofluorinated product **3a** (Table 1, entry 1). The use of other supporting electrolytes resulted in much lower yields of **3a**, and the starting material **4a** was recovered considerably (Table 1, entries 2 and 3). The fluorination of **4a** did not proceed at all in CH_3CN.

TABLE 1. Anodic Fluorination of Diallyl α-Phenylthio-3-butenylphosphonate (4a)[a]

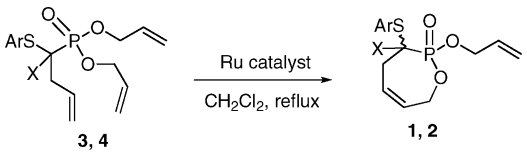


E_p^{ox} =1.69 V *vs* SCE

entry	solvent	supporting electrolyte (1 M)	yield (%)[b]
1	DME	Et_4NF-3HF	64 (53)
2	DME	Et_3N-3HF	21[c]
3	DME	Et_3N-5HF	4[c]
4	CH_3CN	Et_4NF-3HF	0[c]

[a] Constant current: 20 mA/cm^2; electricity: 12 F/mol. [b] Determined by ^{19}F NMR. The number in parentheses is the isolated yield. [c] The starting material was mostly recovered.

TABLE 2. RCM Reaction of Open-Chain Phosphonates 3 and 4



entry	substrate Ar	X	No.	catalyst	reaction time (h)	yield (%)[a]	
1	C_6H_5	H	**4a**	**A**	4	0[b]	**2a**
2	C_6H_5	F	**3a**	**A**	0.5	45 (1:2.7)	**1a**
3	ClC_6H_4	H	**4b**	**A**	4	0[b]	**2b**
4	C_6H_5	H	**4a**	**B**	4	71 (1:1.4)	**2a**
5	C_6H_5	F	**3a**	**B**	0.5	42 (1:3)	**1a**
6	ClC_6H_4	H	**4b**	**B**	4	77 (1:1)	**2b**

[a] Isolated yield. Numbers in parentheses are diastereoisomeric ratios. [b] The starting material was mostly recovered.

Next, the RCM reaction was carried out in refluxing CH_2Cl_2 containing 5 mol % Grubbs' catalyst. As shown in Table 2, the ring-closing reaction of **4a** did not proceed at all by using catalyst **A** (Table 2, entry 1). This is probably because of the deactivation of the catalyst by complexation of the Ru metal with a sulfur atom of **4a**.[16] To suppress such complexation, diallyl 3-butenylphosphonate having an electron-withdrawing *p*-chlorophenylthio group at the α-position of **4b** was used for the RCM reaction. However, the RCM reaction did not proceed at all, and the starting **4b** was mostly recovered (Table 2, entry 3).

In sharp contrast, monofluorinated phosphonate **3a** provided the target cyclic fluorinated product **1a** as a diastereoisomeric mixture in moderate yield (Table 2, entry 2). This can be explained in terms of the suppression of the formation of a complex of the catalyst metal with the sulfur atom of **3a** owing to the decrease of the electron density of the sulfur atom by the strongly electron-withdrawing fluorine atom at the α-position of **3a**. Hanson and co-workers found a similar effect of an α-electron-withdrawing ester group on the RCM reaction of sulfides.[16] On the other hand, even nonfluorinated phosphonates **4a** and **4b** underwent the RCM reactions

(12) (a) Hetherington, L.; Greedy, B.; Gouverneur, V. *Tetrahedron* **2000**, *56*, 2053−2060. (b) Stoianova, D. S.; Hanson, P. R. *Org. Lett.* **2001**, *3*, 3285−3288.

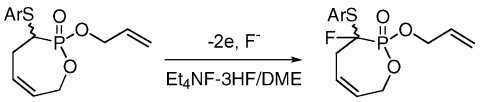
(13) Spagnol, G.; Heck, M.-P.; Nalan, S. P.; Mioskowski, C. *Org. Lett.* **2002**, *4*, 1767−1770.

(14) Butt, A. H.; Percy, J. M.; Spencer, N. S. *Chem. Commun.* **2000**, 1691−1692.

(15) Skropeta, D.; Schmidt, R. R. *Tetrahedron: Asymmetry* **2003**, *14*, 265−273.

(16) Moore, J. D.; Sprott, K. T.; Hanson, P. R. *Synlett* **2001**, 605−608.

TABLE 3. Anodic Fluorination of Cyclic Phosphonates 2[a]



2 1

	substrate			
entry	Ar	No.	yield (%)[b]	
1	C_6H_5	**2a**	58 (45)[c]	**1a**
2	ClC_6H_4	**2b**	45 (38)[d]	**1b**

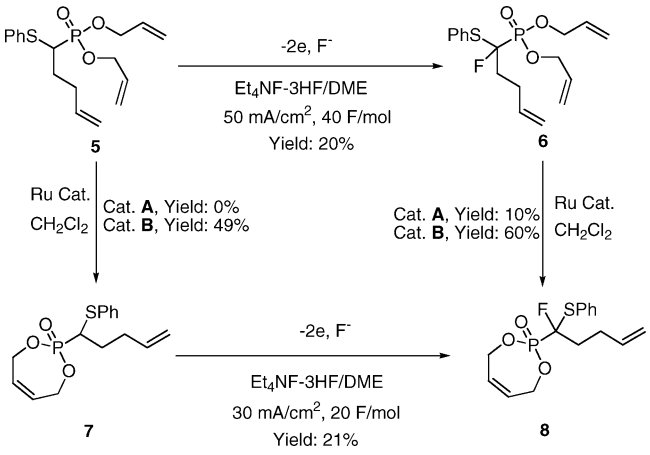
[a] Constant current: 20 mA/cm^2; electricity: 12 F/mol. [b] Determined by ^{19}F NMR. Numbers in parentheses are isolated yields. [c] Diastereoisomeric ratio = (1:2.3). [d] Diastereoisomeric ratio = (1:2.2).

in the presence of the second-generation Grubbs' catalyst **B** to provide the cyclic products **2a** and **2b** in relatively good yields (Table 2, entries 4 and 6). It was expected that the fluorinated phosphonate **3a** would provide similarly high yield of cyclic product **1a** in the presence of catalyst **B**. However, the yield was not increased and was almost the same as that obtained in the presence of catalyst **A** (Table 2, entry 5). Although diastereoselectivity was not observed in the RCM reaction of nonfluorinated phosphonates **4a** and **4b**, the α-fluorine atom of the phosphonate **3a** affected the diastereoselectivity of the RCM reaction appreciably. Almost the same diastereomeric ratio (ca. 1:3) was obtained regardless of the catalysts.

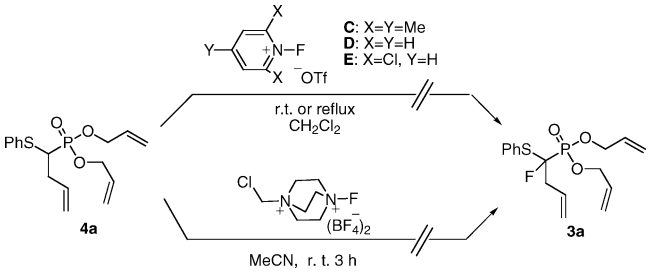
Next, an alternative synthesis of α-fluorinated cyclic phosphonates **1** was attempted according to route B in Scheme 1. Anodic fluorination of the cyclic phosphonates **2** was carried out under the optimum electrolytic conditions for the case of **4a** (Table 1, entry 1). The target products **1** were obtained in moderate yields regardless of the substituents on the benzene ring of the arylthio groups as shown in Table 3. The diastereoisomeric ratios of products **1a** and **1b** were almost the same and also were similar to that of **1a** derived from **3a** (Table 2, entries 2 and 5). The total yield (41%) of cyclic α-fluorophosphonate **1a** from **4a** by route B was found to be higher than that obtained by route A (29% yield). Therefore, route B is more efficient than route A due to the higher reactivity of nonfluorinated open-chain phosphonate in the RCM reaction compared with fluorinated phosphonate. In addition, it was also found that the diastereoisomeric ratio was similar in both routes.

Furthermore, the preparation of eight-membered cyclic α-fluorophosphonate ester was also attempted in a similar manner. The anodic fluorination of diallyl α-phenylthio-4-pentenylphosphonate (**5**) gave extremely low yield. After many attempts under various electrolytic conditions, the fluorinated product **6** was obtained in 20% yield as the maximum yield in Et_4NF-3HF/DME at a higher current density after an extremely large excess amount of electricity was passed owing to its high oxidation potential [decomposition potential (E_d^{ox}): ca. 2.2 V versus SCE] as shown in Scheme 2. The reason for the extremely higher oxidation potential of **5** compared with that of **4a** is not clear. However, such a high oxidation potential of **5** may be attributable to the steric hindrance of a 4-pentenyl group.

SCHEME 2. Anodic Oxidation and RCM Reaction of Diallyl α-Phenylthio-3-pentenylphosphonate (5)



SCHEME 3. Chemical Fluorination of Diallyl α-Phenylthio-3-butenylphosphonate (4a)



The RCM reaction of **6** thus obtained was carried out as shown in Scheme 2. In sharp contrast to **4a**, the RCM reaction took place between two allyloxy chains to provide seven-membered cyclic phosphonate ester **8** instead of the expected eight-membered analogue to **1a**. Boom and coworkers also reported that the formation of a smaller size cycle was first favored among five-, six-, and seven-membered cycles in the synthesis of phosphorus bicycles by RCM reaction.[17] The use of catalyst **A** resulted in low yield of **8**, and a large amount of starting **6** was recovered. However, the yield was increased considerably to 60% by using catalyst **B**. Alternatively, the RCM reaction of nonfluorinated substrate **5** was also carried out. In the presence of catalyst **A**, the RCM reaction did not proceed and the starting material **5** was mostly recovered similar to the case of **4a**. On the other hand, the RCM reaction proceeded by using catalyst **B**; however, the cyclization took place between two allyloxy chains in a manner similar to the case of fluorinated substrate **6** to provide **7** in moderate yield (49%). The RCM product **7** was subjected to anodic fluorination in the same electrolytic solution as used for **5**, and the corresponding fluorinated product **8** was obtained in reasonable yield (21%).

Finally, we attempted the chemical fluorination of **4a** using various selecfluor[18] and *N*-fluoropyridinium salts **C**−**E**[19] as shown in Scheme 3, since these fluorinating reagents are well-known to be effective for the α-fluori-

(17) Timmer, M. S. M.; Ovaa, H.; Filippov, D. V.; Marel, G. A.; Boom, J. H. *Tetrahedron Lett.* **2001** *42*, 8231−8233.
(18) Lal, G. S. *J. Org. Chem.* **1993**, *58*, 2791−2796.
(19) (a) Umemoto, T.; Tomizawa, G. *Bull. Chem. Soc. Jpn.* **1986**, *59*, 3625−3629. (b) Umemoto, T.; Tomizawa, G. *J. Org. Chem.* **1995**, *60*, 6563−6570.

nation of sulfides. However, the fluorination did not proceed at all. In all cases, the starting material was mostly recovered.

In conclusion, seven-membered cyclic monofluorophosphonate esters were successfully synthesized from open-chain allyl phosphonates having an α-arylthio group using anodic fluorination, followed by ring-closing olefin metathesis with the first-generation Grubbs' catalyst **A**. Alternatively, allyl phosphonates having an α-arylthio group were transformed to cyclic phosphonates using the second-generation Grubbs' catalyst **B**, and subsequently the cyclic phosphonates were subjected to anodic fluorination to provide the desired same fluorinated products. The latter route was found to be more efficient. However, in an attempt to synthesize an eight-membered analogue, the RCM reaction proceeded in a different manner and the allyloxy ring-closing product was obtained solely instead of the expected analogue of **1**. The fluorinated cyclic phosphonates **1** and **8** thus prepared are expected to have unique biological activity.

Experimental Section

General experimental details can be found in Supporting Information.

Electrolytic Procedure for Fluorination. A typical procedure is as follows. Anodic fluorination of phosphonates (0.2 mmol) was carried out with platinum plate electrodes (2 × 2 cm^2) in a solvent (10 mL) containing a fluoride salt (1 M) using an undivided cell at room temperature. Constant current (20 mA/cm^2) was passed until the starting material was consumed (monitored by TLC). The cell voltage during the electrolysis was ca. 10 V. After the electrolysis, the resulting electrolytic solution was passed through a short column of silica gel eluting with AcOEt to remove the fluoride salt. The eluent was evaporated under vacuum, and the residue was purified by silica gel column chromatography using AcOEt and hexane (5:1−1:1) to give pure fluorinated products. The products were identified by spectral data.

Ring-Closing Metathesis Reaction. Under a nitrogen atmosphere to a solution of diallyl phosphonate in dry CH_2Cl_2 (0.02 M) was added dropwise the Grubbs' catalyst **A** or **B** (5 mol %). The solution was refluxed until maximum conversion as shown by TLC. The solvent was removed under vacuum and purified by column chromatography eluting with AcOEt and hexane (10:1−5:1).

2-Allyloxy-3-fluoro-3-phenylthio-4,7-dihydro-[1,2]oxaphosphinine-2-oxide (1a): yellow oil; diastereomer mixture; ^{1}H NMR ($CDCl_3$) δ 2.59−2.95 (m, 2H), 4.50−4.83 (m, 4H), 5.22−5.46 (m, 2H), 5.65 (m, 1H), 5.93 (m, 2H), 7.34−7.65 (m, 5H); ^{19}F NMR ($CDCl_3$) δ −53.1 (dd, J_{PF} = 82.6 Hz, J_{HF} = 20.3 Hz, major), −51.8 (dd, J_{PF} = 92.5 Hz, J_{HF} = 18.5 Hz, minor), MS *m/z* 314 (M^+), 294 (M^+ − HF), 185 (M^+ − HF/SC_6H_5); HRMS *m/z* calcd for $C_{14}H_{16}FO_3PS$: 314.0541. Found: 314.0542

2-Allyloxy-3-fluoro-3-(*para*-chlorophenyl)thio-4,7-dihydro-[1,2]oxaphosphinine-2-oxide (1b): yellow oil; diastereomer mixture; ^{1}H NMR ($CDCl_3$) δ 2.34−2.97 (m, 2H), 4.50−4.86 (m, 4H), 5.23−5.45 (m, 2H), 5.67−6.01 (m, 3H), 7.26−7.64 (m, 4H); ^{13}C NMR δ 29.62, 63.56 (d, J_{CP} = 5.02 Hz, major), 64.48 (d, J_{CP} = 5.56 Hz, minor), 67.09 (d, J_{CP} = 6.64 Hz, major), 68.36 (d, J_{CP} = 6.64 Hz, minor), 118.5, 126.0, 129.0, 130.8, 131.8 (d, J_{CP} = 6.17 Hz), 137.5; ^{19}F NMR ($CDCl_3$) −54.2 (dd, J_{PF} = 81.3 Hz, J_{HF} = 18.5 Hz, major), −53.1 (dd, J_{PF} = 92.5 Hz, J_{HF} = 18.5 Hz, minor); MS *m/z* 348 (M^+), 330 (M^+ + H − F); HRMS *m/z* calcd for $C_{14}H_{15}ClFO_3PS$: 348.0152. Found: 348.0146.

2-Allyloxy-3-phenylthio-4,7-dihydro-[1,2]oxaphosphinine-2-oxide (2a): yellow oil; diastereomer mixture; ^{1}H NMR ($CDCl_3$) δ 2.56−2.80 (m, 2H), 3.36−3.60 (m, 1H), 4.43−4.76 (m, 4H), 5.22−5.42 (m, 2H), 5.89 (m, 3H), 7.27−7.52 (m, 5H); ^{13}C NMR δ 29.72 (major), 30.18 (minor), 44.38 (d, J_{CP} = 136.1 Hz, major), 44.88 (d, J_{CP} = 133.9 Hz, minor), 63.05 (d, J_{CP} = 5.56 Hz, major), 63.46 (d, J_{CP} = 5.02 Hz, minor), 67.19 (d, J_{CP} = 6.71 Hz, major), 67.36 (d, J_{CP} = 6.17 Hz, minor), 118.2, 127.6, 128.5, 129.0, 130.5, 132.2 (d, J_{CP} = 17.3 Hz), 132.5; MS *m/z* 296 (M^+), 255 (M^+ − CH_2CHCH_2), 187 (M^+ − SC_6H_5); HRMS *m/z* calcd for $C_{14}H_{17}O_3PS$: 296.0636. Found: 296.0631.

2-Allyloxy-3-(*para*-chlorophenyl)thio-4,7-dihydro-[1,2]-oxaphosphinine-2-oxide (2b): yellow oil; diastereomer mixture; ^{1}H NMR ($CDCl_3$) δ 2.53−2.79 (m, 2H), 3.30−3.41 (m, 1H), 4.43−4.76 (m, 4H), 5.24−5.39 (m, 2H), 5.84−6.01 (m, 3H), 7.27−7.48 (m, 4H); ^{13}C NMR δ 28.84 (0.5C), 29.30 (0.5C), 44.42 (d, J_{CP} = 136 Hz, 0.5C), 44.99 (d, J_{CP} = 134 Hz, 0.5C), 63.06 (d, J_{CP} = 5.01 Hz, 0.5C), 63.40 (d, J_{CP} = 5.02 Hz, 0.5C), 67.05 (d, J_{CP} = 6.71 Hz, 0.5C), 67.18 (d, J_{CP} = 6.64 Hz, 0.5C), 118.3, 128.6, 129.1, 130.7, 132.2 (d, J_{CP} = 11.7 Hz), 133.9 MS *m/z* 330 (M^+), 187 (M^+ − SC_6H_4Cl); HRMS *m/z* calcd for $C_{14}H_{16}ClO_3PS$: 330.0246. Found: 330.0237.

Diallyl α-fluoro-(α-phenylthio)-3-butenylphosphonate (3a): yellow oil; ^{1}H NMR ($CDCl_3$) δ 2.86 (m, 2H), 4.57 (m, 4H), 5.08−5.36 (m, 6H), 5.88 (m, 3H), 7.27−7.63 (m, 5H); ^{13}C NMR δ 34.30, 67.19 (dd, J_{CP} = 17.90, J_{CF} = 6.71 Hz), 69.9 (dd, J_{CP} = 17.90, J_{CF} = 6.71 Hz), 103.9 (d, J_{CF} = 175 Hz) 117.8, 119.4, 127.4, 128.7, 131.9, 132.2 (d, J_{CP} = 6.10 Hz), 132.7 (d, J_{CP} = 6.10 Hz) 134.1 (d, J_{CP} = 11.7 Hz), 136.3; ^{19}F NMR ($CDCl_3$) δ −62.9 (dt, J_{PF} = 98.1 Hz, J_{HF} = 16.6 Hz); MS *m/z* 342 (M^+), 322 (M^+ − HF), 281 (M^+ − CH_2CHCH_2/HF); HRMS (*m/z*) calcd for $C_{16}H_{20}FO_3PS$: 342.0855. Found: 324.0860.

Diallyl α-fluoro-(α-phenylthio)-4-pentenylphosphonate (6): yellow oil; ^{1}H NMR ($CDCl_3$) δ 2.00−2.18 (m, 2H) 2.34−2.40 (m, 2H), 4.58 (m, 4H), 4.92−5.00 (m, 2H), 5.22−5.37 (m, 4H), 5.62−5.93 (m, 3H), 7.26−7.63 (m, 5H); ^{13}C NMR δ 28.20, 35.18 (d, J_{CP} = 5.02 Hz), 67.96 (dd, J_{CP} = 15.1 Hz, J_{CF} = 5.01 Hz), 68.05 (dd, J_{CP} = 15.2 Hz, J_{CF} = 5.02 Hz), 102.2 (J_{CF} = 241 Hz), 115.2, 118.4, 128.7, 128.8, 131.8, 132.2 (d, J_{CP} = 6.78 Hz), 132.3 (d, J_{CP} = 6.67 Hz) 135.8 (d, J_{CP} = 2.32 Hz), 136.4; ^{19}F NMR ($CDCl_3$) δ −63.0 (dt, J_{PF} = 99.0 Hz, J_{HF} = 16.8 Hz); MS *m/z* 356 (M^+), 236 (M^+ − HF), 172 (M^+ − HF/SC_6H_5/$CH_2CH_2CHCH_2$); HRMS (*m/z*) calcd for $C_{17}H_{22}FO_3PS$: 356.1011. Found: 356.1013.

2-(1-Phenylthio-4-pentenyl)-4,7-dihydro-[1,3,2]dioxaphosphepine-2-oxide (7): yellow oil; ^{1}H NMR ($CDCl_3$) δ 1.87 (m, 1H), 1.97−2.19 (m, 1H), 2.27−2.49 (m, 2H), 3.30 (m, 1H), 4.46−5.04 (m, 6H), 5.70−5.85 (m, 3H), 7.27−7.54 (m, 5H); ^{13}C NMR δ 28.84, 30.57 (J_{CP} = 11.7 Hz), 42.65 (d, J_{CP} = 145 Hz), 64.44 (d, J_{CP} = 7.80 Hz), 64.85 (d, J_{CP} = 8.41 Hz), 116.1, 127.2, 127.3, 127.5, 128.8, 130.5, 132.1, 134.2 (d, J_{CP} = 2.85 Hz), 136.5; MS *m/z* 310 (M^+), 256 (M^+ − $CH_2CHCHCH_2$), 201 (M^+ − SC_6H_5); HRMS *m/z* calcd for $C_{15}H_{19}O_3PS$: 310.0793. Found: 310.0789.

2-(1-Fluoro-1-phenylthio-4-pentenyl)-4,7-dihydro-[1,3,2]-dioxaphosphepine-2-oxide (8): yellow oil; ^{1}H NMR ($CDCl_3$) δ 2.16−2.46 (m, 4H), 4.08−4.30 (m, 2H), 4.47−5.05 (m, 4H), 5.60−5.85 (m, 3H), 7.26−7.68 (m, 5H); ^{13}C NMR δ 23.06, 29.77, 65.05 (d, J_{CP} = 6.71 Hz), 65.19 (d, J_{CP} = 2.77 Hz), 105.2 (d, J_{CF} = 237 Hz) 115.4, 126.9, 127.0, 128.7, 129.7, 136.6, 136.8 (d, J_{CP} = 1.15 Hz); ^{19}F NMR ($CDCl_3$) −63.37 (dd, J_{PF} = 92.5 Hz, J_{HF} = 18.3 Hz), MS *m/z* 328 (M^+), HRMS *m/z* calcd for $C_{15}H_{18}FO_3PS$: 328.0698. Found: 328.0702.

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Supporting Information Available: General part and general experimental method; synthetic procedures for the starting materials **4a**, **4b**, and **5**; spectroscopy data and analytical data of compounds **4a**, **4b**, **5**, and the unknown compounds of intermediates in the synthesis of the starting materials; NMR spectra of **1**−**8** and other unknown compounds without elemental analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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