Synthesis of 5-(Trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphospholes by a One-Pot Three-Component Reaction

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Abstract: A series of trifluoromethyl-substituted 1,2λ^5-oxaphospholes were prepared in yields of up to 95% by a one-pot three-component reaction under mild conditions. The zwitterionic intermediate generated by attack of triphenylphosphine on an alkyl propiolate reacts with an aryl or styryl trifluoromethyl ketone to form the 1,2λ^5-oxaphosphole ring. All the new products were characterized by IR, NMR, and mass spectroscopy and the structure of one of them, ethyl 2,2,2-triphenyl-5-[(*E*)-2-phenylvinyl]-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate, was confirmed by X-ray single-crystal diffraction analysis.

Key words: heterocycles, phosphorus, fluorine, oxaphospholes, alkynes, ketones

Organophosphorus compounds are widely used in organic synthesis.[1] Recently, a great deal of attention has been paid to organophosphorus compounds because of their potential biological, industrial, and synthetic applications, and many novel methods have been developed for the synthesis of such compounds.[2–4]

The introduction of fluoro or fluoroalkyl groups into an organic molecule can profoundly affect its physical, chemical, and biological properties, and fluorine-containing heterocycles are now widely used in medicine and agriculture.[5] One of the most important strategies for the synthesis of fluorine-containing heterocycles involves the use of multicomponent reactions, which have long been recognized as effective, economic, convenient, and environmental benign.[6] Triphenylphosphine has been extensively studied as a nucleophilic species. As early as 1961, Tebby and co-workers found that the addition of triphenylphosphine to various activated alkynes, such as 1,4-diphenylbut-2-yne-1,4-dione, but-2-ynedinitrile, or dimethyl acetylenedicarboxylate, gave zwitterionic intermediates.[7,8] Recently, groups led by Esmaeili[9] and by Yavari[10] have reported that the reactions of acetylenic compound with triphenylphosphine in the presence of ketones give the corresponding 2,5-dihydro-1,2-oxaphospholes. However, to the best of our knowledge, there are few reports of preparations of fluorinated oxaphospholes.[11] As part of our current studies on the development of new routes to fluorinated heterocycles,[12] we now report a simple synthesis of 5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphospholes in good yields through the multicomponent one-pot reaction of triphenylphosphine, an alkyl propiolate, and an aryl or styryl trifluoromethyl ketone.

To test the reaction conditions, we selected the reaction of ethyl propiolate (**2a**) with (3*E*)-1,1,1-trifluoro-4-phenylbut-3-en-2-one (**3a**), and triphenylphosphine as a model reaction. When the reaction mixture was stirred in toluene at room temperature, thin-layer chromatography showed that the reaction was complete within 24 hours. The desired product **5a** was obtained in 71% yield (Table 1, entry 1). When the reaction was carried out at 100 °C, it was complete within three hours, but the yield was slightly lower (entry 2). A slightly lower yield was also obtained in xylene (entry 8) and similar yields were obtained in diethyl ether and in tetrahydrofuran (entries 9 and 10, respectively). Polar solvents such as acetonitrile or ethanol gave very low yields, even with longer reaction times (entries 11 and 12, respectively). Fortunately, when ethyl acetate was used as the solvent, the yield improved to 77% (entry 7). We therefore, conducted the remainder of the reactions in ethyl acetate at room temperature.

The product **5a** was fully characterized by means of NMR (^{1}H, ^{13}C, ^{19}F, and ^{31}P), IR, and mass spectroscopy, and its configuration was confirmed by X-ray crystallographic analysis (Figure 1).

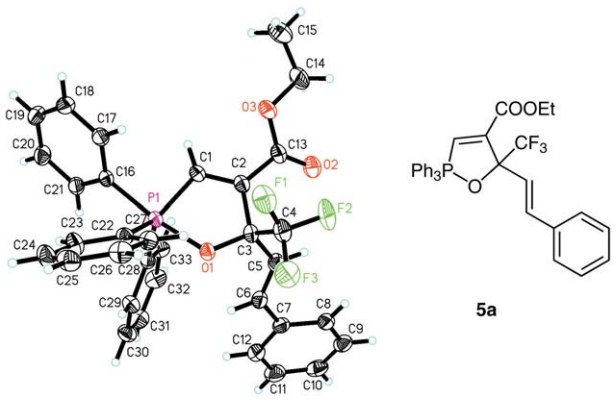

Figure 1 The structure of compound **5a**

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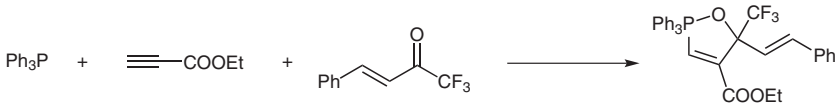
Table 1 Screening of Reaction Conditions for the Three-Component Reaction



1 **2a** **3a** **5a**

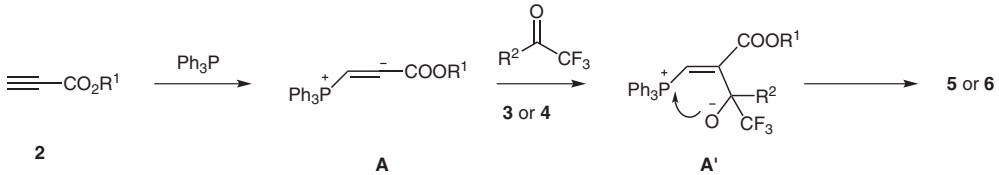
Entry[a]	Solvent	Temp (°C)	Time (h)	Yield[b] (%)
1	toluene	25	24	71
2	toluene	100	3	69
3[c]	toluene	25	24	66
4[d]	toluene	25	24	60
5	CH_2Cl_2	25	24	58
6	$CHCl_3$	25	24	60
7	EtOAc	25	10	77
8	xylene	25	24	69
9	THF	25	10	70
10	Et_2O	25	16	70
11	EtOH	25	40	30
12	MeCN	25	30	47

[a] Unless otherwise noted, the reaction was carried out with **1** (0.3 mmol), **2a** (0.25 mmol), and **3a** (0.2 mmol) in the appropriate solvent (1.0 mL).
[b] Isolated yield.
[c] The reaction was carried out with **1** (0.25 mmol), **2a** (0.25 mmol), and **3a** (0.2 mmol).
[d] The reaction was carried out with **1** (0.2 mmol), **2a** (0.2 mmol), and **3a** (0.2 mmol).

Having determined the optimized condition, we explored the scope of the reaction, and some of the results that we obtained are listed in Table 2. Generally, when the reaction was carried out with **1**, **2a**, and a styrenyl ketone **3a**–**h**, the corresponding product **5a**–**h** was obtained in about 80% yield, irrespective of the electronic nature of the substituents on the benzene ring (Table 2, entries 1–7). We then examined the reactions of various aryl trifluoromethyl ketones **4a**–**e** under similar reaction conditions. Both electron-donating and electron-withdrawing substituents on the benzene rings were tolerated and the desired products **6a**–**f** were obtained in high yields (entries 9–14). When other acetylenic compounds such as ethyl 3-phenylpropiolate or ethynylbenzene were investigated, no corresponding reaction was observed and the starting materials were recovered.

A possible reaction pathway is shown in Scheme 1. Initially, a 1,3-dipolar intermediate **A** is formed by the reaction of triphenylphosphine and the propiolate.[13] Subsequently, the carbonyl carbon of the trifluoromethyl ketone **3** or **4** is attacked by the intermediate **A** to form intermediate **A′** which then cyclizes to form the desired product **5** or **6**.

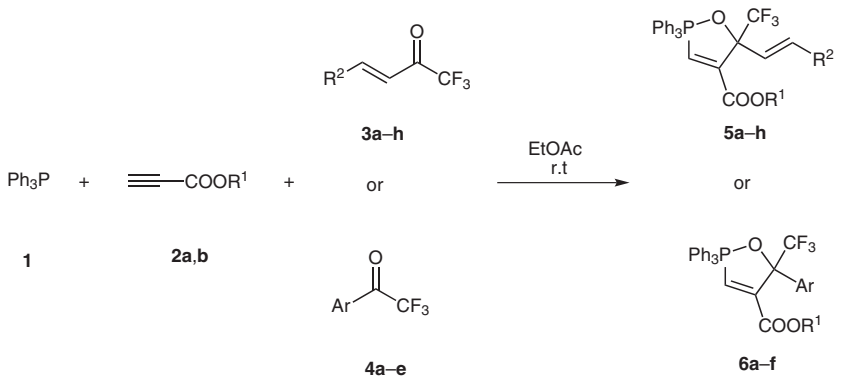
In summary, we have developed a simple method for synthesizing a series of 5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphospholes through the three-component reaction of triphenylphosphine, an alkyl propiolate, and an aryl or styryl trifluoromethyl ketone. The desired products were obtained in up to 95% yields under mild conditions. Further research on the reaction and its applications are in progress at our laboratories.



2 **A** **A'**

Scheme 1 Possible mechanism for the formation of the products

Table 2 Synthesis of a Series of Dihydro-1,2λ5-oxaphospholes



Entry[a]	R^1	R^2 or R^3	Time (h)	Product	Yield [b] (%)
1	Et (**2a**)	Ph (**3a**)	20	**5a**	77
2	Et (**2a**)	4-ClC_6H_4 (**3b**)	20	**5b**	81
3	Et (**2a**)	4-BrC_6H_4 (**3c**)	24	**5c**	79
4	Et (**2a**)	4-FC_6H_4 (**3d**)	24	**5d**	78
5	Et (**2a**)	4-$MeOC_6H_4$ (**3e**)	30	**5e**	82
6	Et (**2a**)	2-$MeOC_6H_4$ (**3f**)	30	**5f**	79
7	Et (**2a**)	3-$MeOC_6H_4$ (**3g**)	30	**5g**	79
8	Et (**2a**)	2-thienyl (**3h**)	20	**5h**	71
9	Et (**2a**)	Ph (**4a**)	8	**6a**	92
10	Et (**2a**)	4-ClC_6H_4 (**4b**)	8	**6b**	90
11	Et (**2a**)	4-BrC_6H_4 (**4c**)	8	**6c**	89
12	Et (**2a**)	4-FC_6H_4 (**4d**)	8	**6d**	92
13	Et (**2a**)	4-Tol (**4e**)	8	**6e**	93
14	Me (**2b**)	Ph (**4f**)	8	**6f**	95

[a] The reaction was carried out with **1** (0.3 mmol), **2** (0.25 mmol), and **3** (0.2 mmol) or **4** (0.2 mmol) in EtOAc (1.0 mL) at room temperature.
[b] Isolated yield.

Purifications were performed by flash chromatography with EtOAc and PE on silica gel. Melting points were measured on a Temp-Melt apparatus and are uncorrected. IR spectra were recorded on a Perkin-Elmer 983 spectrophotometer. ^1H and ^{19}F NMR spectra were recorded in $CDCl_3$ on a Bruker AM-300 instrument with TMS or $CFCl_3$ (upfield negative) as the internal and external standards, respectively. ^{13}C NMR spectra were recorded in $CDCl_3$ with a Bruker AMX spectrometer at 100 MHz, and chemical shifts are reported in ppm relative to TMS. High-resolution mass spectra were obtained with a Bruker Apex III 7.0 TESLA FTMS spectrometer. The single-crystal X-ray structure analysis was performed on a Bruker P4 instrument.

Alkyl 2,2,2-Triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ5-oxaphosphole-4-carboxylates 5 and 6; General Procedure

Ph_3P (0.3 mmol) was added to a soln of propiolate **2** (0.25 mmol) and styryl ketone **3** or aryl ketone **4** (0.2 mmol) in EtOAc (1.0 mL) at r.t. The mixture was stirred until the reaction was complete (TLC), then concentrated under reduced pressure. The resulting crude product was purified directly by column chromatography [silica gel, hexanes–EtOAc (30:1 to 20:1)].

Ethyl 2,2,2-Triphenyl-5-[(*E*)-2-phenylvinyl]-5-(trifluoromethyl)-2,5-dihydro-1,2λ5-oxaphosphole-4-carboxylate (5a)

Yield: 86.2 mg (77%); white solid; mp 161–162 °C. X-ray crystal data are summarized in Table 3.

IR (CH_2Cl_2, film): 1728, 1433, 1258, 1082, 972, 748 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.44–7.39 (m, 6 H), 7.27–7.25 (m, 9 H), 7.20–7.16 (m, 3 H), 7.06–7.01 (m, 3 H), 6.66 (d, *J* = 16 Hz, 1 H), 5.85 (d, *J* = 16 Hz, 1 H), 4.36 (q, *J* = 4.8 Hz, 2 H), 1.39 (t, *J* = 8.1 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4 (d, $^3J_{CP}$ = 28 Hz), 155.8 (d, $^2J_{CP}$ = 13 Hz), 143.9 (d, $^1J_{CP}$ = 106 Hz), 135.7 (d, $^1J_{CP}$ = 127 Hz), 133.6, 131.2 (d, $^2J_{CP}$ = 9 Hz), 128.6 (d, $^3J_{CP}$ = 3 Hz), 128.2, 128.0, 127.8, 127.6, 126.9, 124.3 (q, *J* = 289 Hz), 122.7, 81.3 (q, *J* = 29 Hz), 62.1, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –74.4 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –49.3 (s).

MS (ESI): *m/z* = 561 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{33}H_{29}F_3O_3P$: 561.1806; found: 561.1801.

Table 3 X-ray Data for Oxaphosphole **5a**

Empirical formula	$C_{33}H_{28}F_3O_3P$
Formula weight	560.52
Temperature	293(2) K
Wavelength	0.71073 Å
Crystal system, space group	triclinic, *P*1
Unit cell dimensions	a = 9.5067(6) Å, α = 97.1890(10)°
	b = 10.0271(6) Å, β = 91.5000(10)°
	c = 15.6189(10) Å, γ = 107.4710(10)°
Volume	1405.82(15) Å^3
Z, Calculated density	2, 1.324 Mg/m^3
Absorption coefficient	0.151 mm^{-1}
F(000)	584
Crystal size	0.450 × 0.387 × 0.301 mm
θ range for data collection	2.15–25.50°
Limiting indices	$-11 \le h \le 11$, $-11 \le k \le 12$, $-18 \le l \le 15$
Reflections collected/unique	7376/5136 [R(int) = 0.0238]
Completeness to θ = 25.50°	98.5%
Absorption correction	empirical
Max. and min. transmission	1.0000 and 0.8172
Refinement method	full-matrix least-squares on F^2
Data/restraints/parameters	5136/0/363
Goodness-of-fit on F^2	1.037
Final R indices [I > 2σ(I)]	$R1$ = 0.0416, $wR2$ = 0.1125
R indices (all data)	$R1$ = 0.0450, $wR2$ = 0.1159
Extinction coefficient	0.037(3)
Largest diff. peak and hole	0.372 and –0.268 e·Å^{-3}

Ethyl 5-[(*E*)-2-(4-Chlorophenyl)vinyl]-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (5b)

Yield: 96.2 mg (81%); white solid; mp 167–168 °C.

IR (CH_2Cl_2, film): 1724, 1433, 1265, 1082, 969, 739 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.43–7.37 (m, 6 H), 7.28–7.27 (m, 10 H), 7.17–7.14 (m, 2 H), 6.95–6.92 (m, 2 H), 6.65 (d, *J* = 15 Hz, 1 H), 5.85 (d, *J* = 15 Hz, 1 H), 4.36 (m, *J* = 6.9 Hz, 2 H), 1.39 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4 (d, *J* = 28 Hz), 155.7 (d, *J* = 13 Hz), 143.3 (d, *J* = 106 Hz), 135.7 (d, *J* = 128 Hz), 134.9, 133.3, 132.4, 131.2 (d, *J* = 9 Hz), 128.6 (d, *J* = 3 Hz), 128.4, 128.1, 127.9 (d, *J* = 12 Hz), 124.7 (q, *J* = 288 Hz), 123.4, 81.3 (q, *J* = 29 Hz), 62.1, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –75.1 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –46.4 (s).

MS (ESI): *m/z* = 595 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{33}H_{28}ClF_3O_3P$: 595.1417; found: 595.1411.

Ethyl 5-[(*E*)-2-(4-Bromophenyl)vinyl]-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (5c)

Yield: 100.8 mg (79%); white solid; mp 149–150 °C.

IR (CH_2Cl_2, film): 1731, 1438, 1260, 1072, 980, 738 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.43–7.38 (m, 6 H), 7.32–7.24 (m, 11 H), 7.10 (d, *J* = 40 Hz, 1 H), 6.87 (d, *J* = 8.4 Hz, 2 H), 6.65 (d, *J* = 15 Hz, 1 H), 5.85 (d, *J* = 16 Hz, 1 H), 4.36 (m, *J* = 3.6 Hz, 2 H), 1.38 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4 (d, *J* = 28 Hz), 155.6 (d, *J* = 13 Hz), 143.3 (d, *J* = 106 Hz), 135.7 (d, *J* = 128 Hz), 135.4, 132.5, 131.2 (d, *J* = 9 Hz), 128.6 (d, *J* = 3 Hz), 128.4, 128.0, 127.9, 124.2 (q, *J* = 288 Hz), 123.6, 121.5, 81.3 (q, *J* = 29 Hz), 62.1, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –75.1 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –48.3 (s).

MS (ESI): *m/z* = 641 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{33}H_{28}BrF_3O_3P$: 639.0912; found: 639.0906.

Ethyl 5-[(*E*)-2-(4-Fluorophenyl)vinyl]-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (5d)
Yield: 90.2 mg (78%); white solid; mp 165–166 °C.

IR (CH_2Cl_2, film): 1724, 1433, 1286, 1082, 970, 741 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.43–7.37 (m, 6 H), 7.28–7.27 (m, 10 H), 7.00–6.85 (m, 4 H), 6.59 (d, *J* = 15 Hz, 1 H), 5.78 (d, *J* = 15 Hz, 1 H), 4.36 (m, *J* = 7.2 Hz, 2 H), 1.39 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4 (d, *J* = 29 Hz), 162.8 (d, *J* = 245 Hz), 155.8 (d, *J* = 13 Hz), 143.3 (d, *J* = 106 Hz), 135.8 (d, *J* = 128 Hz), 132.6 (d, *J* = 3 Hz), 132.4, 131.2 (d, *J* = 9 Hz), 128.6 (d, *J* = 3 Hz), 128.4 (d, *J* = 8 Hz), 128.0, 127.8, 124.2 (q, *J* = 288 Hz), 115.1 (d, *J* = 22 Hz), 81.3 (q, *J* = 29 Hz), 62.1, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –75.1 (s, 3 F), –114.8 (s, 1 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –51.5 (s).

MS (ESI): *m/z* = 579 [M + H]$^+$.

HRMS: *m/z* calcd for $C_{33}H_{28}F_4O_3P$: 579.1712; found: 579.1707.

Ethyl 5-[(*E*)-2-(4-Methoxyphenyl)vinyl]-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (5e)
Yield: 96.8 mg (82%); white solid; mp 114–115 °C.

IR (CH_2Cl_2, film): 1731, 1437, 1251, 1081, 971, 741 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.45–7.37 (m, 6 H), 7.27–7.23 (m, 10 H), 6.97 (d, *J* = 8.7 Hz, 2 H), 6.73 (d, *J* = 8.7 Hz, 2 H), 6.52 (d, *J* = 15 Hz, 1 H), 5.78 (d, *J* = 15 Hz, 1 H), 4.36 (m, *J* = 6.9 Hz, 2 H), 3.75 (s, 3 H), 1.38 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4 (d, *J* = 29 Hz), 159.3, 156.0 (d, *J* = 13 Hz), 143.5 (d, *J* = 105 Hz), 135.7 (d, *J* = 128 Hz), 133.0, 131.2 (d, *J* = 8 Hz), 129.3, 128.6, 128.1, 127.9 (d, *J* = 12 Hz), 124.3 (q, *J* = 287 Hz), 120.3, 113.6, 81.3 (q, *J* = 29 Hz), 62.0, 55.2, 14.2.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –75.1 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –51.1 (s).

MS (ESI): *m/z* = 591 [M + H]$^+$.

HRMS: *m/z* calcd for $C_{34}H_{31}F_3O_4P$: 591.1912; found: 591.1907.

Ethyl 5-[(*E*)-2-(2-Methoxyphenyl)vinyl]-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (5f)
Yield: 93.2 mg (79%); white solid; mp 145–146 °C.

IR (CH_2Cl_2, film): 1729, 1435, 1276, 1080, 973, 741 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.44–7.38 (m, 6 H), 7.27–7.23 (m, 10 H), 7.17–7.08 (m, 2 H), 6.82–6.74 (m, 3 H), 6.33 (d, *J* = 15 Hz, 1 H), 4.36 (m, *J* = 6.9 Hz, 2 H), 3.73 (s, 3 H), 1.38 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.6 (d, *J* = 29 Hz), 157.1, 156.1 (d, *J* = 14 Hz), 143.7 (d, *J* = 106 Hz), 136.1 (d, *J* = 128 Hz), 131.2 (d, *J* = 9 Hz), 129.2, 128.7, 128.3 (d, *J* = 3 Hz), 128.2, 127.8 (d, *J* = 13 Hz), 125.5, 124.4 (q, *J* = 288 Hz), 123.7, 120.2, 110.7, 81.5 (q, *J* = 29 Hz), 62.0, 55.1, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –75.1 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.5 (s).

MS (ESI): *m/z* = 591 [M + H]$^+$.

HRMS: *m/z* calcd for $C_{34}H_{31}F_3O_4P$: 591.1912; found: 591.1907.

Ethyl 5-[(*E*)-2-(3-Methoxyphenyl)vinyl]-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (5g)
Yield: 93.2 mg (79%); white solid; mp 146–147 °C.

IR (CH_2Cl_2, film): 1732, 1436, 1248, 1083, 963, 721 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.44–7.38 (m, 6 H), 7.27–7.23 (m, 9 H), 7.18–7.05 (m, 2 H), 6.73–6.64 (m, 3 H), 6.53 (s, 1 H), 5.80 (d, *J* = 15 Hz, 1 H), 4.36 (m, *J* = 6.9 Hz, 2 H), 3.76 (s, 3 H), 1.39 (t, *J* = 6.9 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4 (d, *J* = 28 Hz), 159.5, 155.8 (d, *J* = 14 Hz), 143.5 (d, *J* = 106 Hz), 137.9, 135.9 (d, *J* = 128 Hz), 133.5, 131.2 (d, *J* = 9 Hz), 129.1, 128.6 (d, *J* = 3 Hz), 127.9 (d, *J* = 13 Hz), 124.3 (q, *J* = 288 Hz), 123.1, 119.5, 113.4, 112.3, 81.3 (q, *J* = 29 Hz), 62.0, 55.2, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –75.0 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.3 (s).

MS (ESI): *m/z* = 591 [M + H]$^+$.

HRMS: *m/z* calcd for $C_{34}H_{31}F_3O_4P$: 591.1912; found: 591.1907.

Ethyl 2,2,2-Triphenyl-5-[(*E*)-2-(2-thienyl)vinyl]-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (5h)
Yield: 80.4 mg (71%); white solid; mp 161–162 °C.

IR (CH_2Cl_2, film): 1727, 1436, 1259, 1080, 963, 739 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.45–7.37 (m, 7 H), 7.28–7.23 (m, 9 H), 7.08–7.04 (m, 1 H), 6.85–6.82 (m, 1 H), 6.53–6.52 (m, 1 H), 6.47 (d, *J* = 15 Hz, 1 H), 5.87 (d, *J* = 15 Hz, 1 H), 4.36 (m, *J* = 7.2 Hz, 2 H), 1.39 (t, *J* = 7.8 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4 (d, *J* = 28 Hz), 155.8 (d, *J* = 13 Hz), 142.3 (d, *J* = 106 Hz), 141.6, 135.8 (d, *J* = 129 Hz), 131.2 (d, *J* = 9 Hz), 128.6 (d, *J* = 3 Hz), 128.0, 127.1, 126.8, 126.3, 124.6, 123.9 (q, *J* = 288 Hz), 122.2, 81.1 (q, *J* = 29 Hz), 62.1, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –75.1 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –50.3 (s).

MS (ESI): *m/z* = 567 [M + H]$^+$.

HRMS: *m/z* calcd for $C_{31}H_{27}F_3O_3PS$: 567.1371; found: 567.1365.

Ethyl 2,2,2,5-Tetraphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (6a)
Yield: 98.3 mg (92%); white solid; mp 176–177 °C.

IR (CH_2Cl_2, film): 1731, 1438, 1259, 1072, 980, 738 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.35–7.31 (m, 7 H), 7.23–7.10 (m, 12 H), 7.04–6.99 (m, 2 H), 4.41 (m, *J* = 6.9 Hz, 2 H), 1.39 (t, *J* = 6.9 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.3 (d, *J* = 28 Hz), 156.9 (d, *J* = 12 Hz), 143.5 (d, *J* = 106 Hz), 138.5 (d, *J* = 127 Hz), 136.9, 131.3 (d, *J* = 9 Hz), 128.4 (d, *J* = 3 Hz), 127.8, 127.7, 127.6, 127.4, 122.0 (q, *J* = 286 Hz), 82.0 (q, *J* = 30 Hz), 62.2, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –72.4 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.8 (s).

MS (ESI): *m/z* = 535 [M + H]$^+$.

HRMS: *m/z* calcd for $C_{31}H_{27}F_3O_3P$: 535.1650; found: 535.1644.

Ethyl 5-(4-Bromophenyl)-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (6b)
Yield: 102.3 mg (90%); white solid; mp 194–195 °C.

IR (CH_2Cl_2, film): 1731, 1436, 1260, 1101, 930, 703 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.33–7.17 (m, 16 H), 7.09–7.00 (m, 4 H), 4.38 (m, *J* = 7.2 Hz, 2 H), 1.35 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.2 (d, *J* = 28 Hz), 156.5 (d, *J* = 12 Hz), 143.0 (d, *J* = 106 Hz), 138.5 (d, *J* = 127 Hz), 136.1, 131.3 (d, *J* = 9 Hz), 130.4, 129.6, 128.5 (d, *J* = 3 Hz), 127.8 (d, *J* = 13 Hz), 124.2 (q, *J* = 288 Hz), 122.0, 81.6 (q, *J* = 30 Hz), 62.3, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –72.2 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.1 (s).

MS (ESI): *m/z* = 613 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{31}H_{26}BrF_3O_3P$: 613.0755; found: 613.0750.

Ethyl 5-(4-Fluorophenyl)-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (6c)
Yield: 108.9 mg (89%); white solid; mp 174–175 °C.

IR (CH_2Cl_2, film): 1731, 1438, 1260, 1081, 930, 744 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.33–7.10 (m, 18 H), 6.64 (t, *J* = 8.7 Hz, 2 H), 4.38 (m, *J* = 7.5 Hz, 2 H), 1.37 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.3 (d, *J* = 29 Hz), 161.7 (d, *J* = 245 Hz), 156.7 (d, *J* = 13 Hz), 143.1 (d, *J* = 106 Hz), 138.6 (d, *J* = 126 Hz), 132.8, 131.2 (d, *J* = 9 Hz), 129.7 (d, *J* = 8 Hz), 128.5 (d, *J* = 3 Hz), 127.7 (d, *J* = 12 Hz), 124.2 (q, *J* = 286 Hz), 114.1 (d, *J* = 21 Hz), 81.5 (q, *J* = 30 Hz), 62.3, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –73.0 (s, 3 F), –115.3 (s, 1 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.5 (s).

MS (ESI): *m/z* = 553 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{31}H_{26}F_4O_3P$: 553.1556; found: 553.1550.

Ethyl 5-(4-Chlorophenyl)-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (6d)
Yield: 101.6 mg (92%); white solid; mp 179–180 °C.

IR (CH_2Cl_2, film): 1731, 1436, 1298, 1081, 971, 738 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.36–7.24 (m, 16 H), 7.10 (d, *J* = 8.1 Hz, 2 H), 6.94 (d, *J* = 8.4 Hz, 2 H), 4.39 (m, *J* = 6.9 Hz, 2 H), 1.37 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.2 (d, *J* = 28 Hz), 156.6 (d, *J* = 12 Hz), 143.0 (d, *J* = 106 Hz), 138.6 (d, *J* = 127 Hz), 135.6, 133.7, 131.3 (d, *J* = 9 Hz), 129.3, 128.5 (d, *J* = 3 Hz), 127.8, 127.4, 124.2 (q, *J* = 287 Hz), 81.6 (q, *J* = 30 Hz), 62.3, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –72.9 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.2 (s).

MS (ESI): *m/z* = 569 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{31}H_{26}ClF_3O_3P$: 569.1260; found: 569.1255.

Ethyl 5-(4-Methylphenyl)-2,2,2-triphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (6e)
Yield: 102.0 mg (93%); white solid; mp 173–174 °C.

IR (CH_2Cl_2, film): 1731, 1437, 1256, 1099, 931, 702 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.36–7.22 (m, 16 H), 7.03 (d, *J* = 8.1 Hz, 2 H), 6.82 (d, *J* = 7.2 Hz, 2 H), 4.39 (m, *J* = 6.9 Hz, 2 H), 2.24 (s, 3 H), 1.37 (t, *J* = 6.9 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.3 (d, *J* = 29 Hz), 159.9 (d, *J* = 13 Hz), 143.5 (d, *J* = 106 Hz), 138.1 (d, *J* = 127 Hz), 137.4, 134.0, 131.3 (d, *J* = 8 Hz), 128.3 (d, *J* = 3 Hz), 128.1, 127.7 (d, *J* = 13 Hz), 127.5, 124.4 (q, *J* = 287 Hz), 81.9 (q, *J* = 30 Hz), 62.1, 21.0, 14.1.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –72.5 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.4 (s).

MS (ESI): *m/z* = 549 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{32}H_{29}F_3O_3P$: 549.1806; found: 549.1801.

Methyl 2,2,2,5-Tetraphenyl-5-(trifluoromethyl)-2,5-dihydro-1,2λ^5-oxaphosphole-4-carboxylate (6f)
Yield: 98.8 mg (95%); white solid; mp 163–164 °C.

IR (CH_2Cl_2, film): 1736, 1435, 1256, 1081, 943, 745 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.72–7.63 (m, 7 H), 7.59–7.54 (m, 10 H), 7.50–7.45 (m, 3 H), 7.35–7.33 (m, 1 H), 4.27 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.5 (d, *J* = 28 Hz), 156.9 (d, *J* = 13 Hz), 143.3 (d, *J* = 106 Hz), 139.2 (d, *J* = 127 Hz), 136.8, 131.3 (d, *J* = 10 Hz), 128.4, 127.8, 127.7, 127.6, 127.5 (d, *J* = 15 Hz), 124.4 (q, *J* = 287 Hz), 82.0 (q, *J* = 30 Hz), 52.9.

^{19}F NMR (282 MHz, $CDCl_3$): δ = –71.7 (s, 3 F).

^{31}P NMR (75 MHz, $CDCl_3$): δ = –52.7 (s).

MS (ESI): *m/z* = 521 $[M + H]^+$.

HRMS: *m/z* calcd for $C_{30}H_{25}F_3O_3P$: 521.1493; found: 521.1488.

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