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vic-Diphosphination of Alkenes with Silylphosphine under Visible-Light-Promoted Photoredox Catalysis

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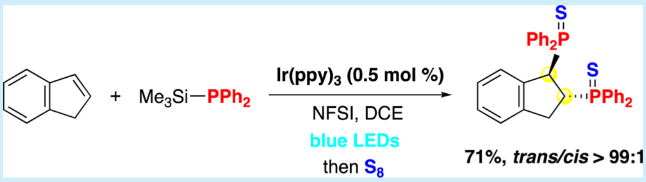
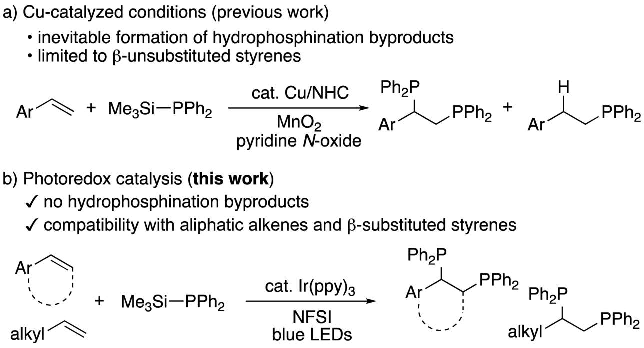
Supporting Information

ABSTRACT: An Ir(ppy)$_3$-catalyzed *vic*-diphosphination of styrenes with Me$_3$Si-PPh$_2$ and NFSI proceeds under blue LED irradiation to afford the corresponding bis(diphenylphosphino)ethane derivatives without any formation of hydrophosphination byproducts, which are inevitable and problematic under the previous Cu/NHC catalysis. Additionally, the visible-light-promoted photoredox catalysis enables the diphosphination of relatively challenging aliphatic alkenes and *β*-substituted styrene.



Diphosphines are now one of the indispensable organophosphorus compounds in chemical synthesis since they are prevalent ancillary ligands for transition metal catalysis.[1] Particularly, bis(diphenylphosphino)ethane (DPPE)-type bidentate ligands are frequently employed because of their uniquely rigid chelating nature. Thus, the development of a synthetic strategy for the efficient preparation of DPPEs is of great importance in modern organic chemistry. In addition to the classical nucleophilic substitution reaction with phosphide nucleophiles, an addition reaction of phosphino groups to C−C multiple bonds has received significant attention because relatively simple hydrocarbon materials can be used as the starting substrates. To date, synthesis of DPPEs from alkynes was achieved via metal-catalyzed double hydrophosphination[2] or radical diphosphination with diphosphanes (R_2P-PR_2) followed by reduction of the resulting double bond.[3] Additionally, a good alternative is a stepwise phosphine introduction approach including phosphination of terminal alkynes, metal-promoted hydrophosphination, and alkene hydrogenation.[4] On the other hand, the direct diphosphination of more robust and abundant alkenes still remains largely elusive.[5] In this context, we recently reported the Cu/NHC-catalyzed *vic*-diphosphination of styrenes with silylphosphine,[6] in conjunction with MnO$_2$/pyridine *N*-oxide combined oxidant (Scheme 1a).[7] The copper catalysis can convert the simple styrenes to the promising DPPE-type bidentate ligands in one synthetic operation. However, there are two large drawbacks: one is the inevitable formation of hydrophosphination byproducts, which often hampered rapid purification of desired diphosphination products. Another is the relatively limited substrate scope: only electronically activated and sterically accessible *β*-unsubstituted styrenes could be used. Around the same time, Ogawa developed the related radical phosphinylphosphination of aliphatic terminal alkenes with Ph$_2$(O)P−PPh$_2$, but attempts to apply styrenes and internal alkenes remained unsuccessful.[8] Thus, further improvements of catalytic systems directed toward olefin diphosphination are greatly appealing. Herein, we report the second generation system based on photoredox catalysis: Ir(ppy)$_3$-catalyzed *vic*-diphosphination of alkenes with silylphosphine, and NFSI proceeds under blue LED irradiation to deliver the corresponding DPPE derivatives in good yields (Scheme 1b). The photoredox catalysis avoids the formation of hydrophosphination byproducts and allows relatively challenging aliphatic terminal alkenes and *β*-substituted styrenes to be adopted in the diphosphination reaction.

Scheme 1. Direct *vic*-Diphosphination of Alkenes with Silylphosphine



On the basis of our previous mechanistic studies that a phosphinyl radical is considered to be the key intermediate in the alkene diphosphination,[7] we envisioned that if such a highly reactive radical species was generated under much milder conditions, drawbacks of the first generation Cu catalysis, such as the formation of hydrophosphination byproducts, could be addressed. We thus focused on recently greatly developed visible-light-promoted photoredox catalysis, in which the radical process can be operative under visible light irradiation at ambient temperature.[9] Actually, in an early experiment, treatment of styrene (**1a**) with trimethylsilyldiphenylphosphine (Me$_3$Si−PPh$_2$; **2**) and *N*-fluorobenzenesulfonimide (NFSI) in

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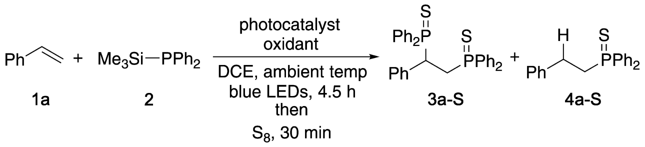
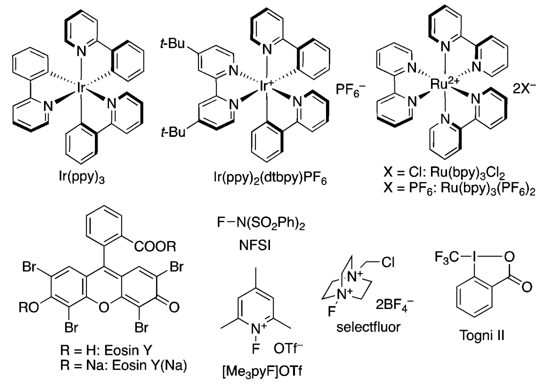
the presence of 10 mol % Ir(ppy)$_3$ in DCE solvent under blue LED irradiation was followed by the addition of elemental sulfur (S$_8$) for ease of handling to afford the corresponding diphosphinated product **3a-S** in 44% NMR yield, along with 12% of the undesired hydrophosphination byproduct **4a-S** (Table 1, entry 1). Although we tested other photosensitizers including Ir(ppy)$_2$(dtbpy)PF$_6$, Ru(bpy)$_3$Cl$_2$, Ru(bpy)$_3$(PF$_6$)$_2$, and Eosin Y, Ir(ppy)$_3$ showed better activity (entries 2–6). A decrease in the amount of Ir(ppy)$_3$ (10 to 0.5 mol %) increased the yield of **3a-S** to 65% (entry 7). Notably, the addition order of reagents had a large influence on the diphosphination/hydrophosphination selectivity: the undesired **4a-S** was completely suppressed by initially mixing Ir(ppy)$_3$, NFSI, and silylphosphine **2** followed by drop of styrene (entry 8). Additionally, the choice of oxidant was also critical: *N*-fluoro-2,4,6-trimethylpyridinium triflate ([Me$_3$pyF]OTf) afforded the diphosphinated product **4a-S** in a slightly lower yield (entry 9), but other F$^+$-based and I(III) oxidants gave no or negligible amount of **4a-S** (entries 10–12). We also confirmed the necessity of both photosensitizer and light for the satisfactory conversion (entries 13 and 14).

Table 1. Optimization for *vic*-Diphosphination of Styrene (1a) with Trimethylsilyldiphenylphosphine (2) under Visible-Light-Promoted Photoredox Catalysis[a]



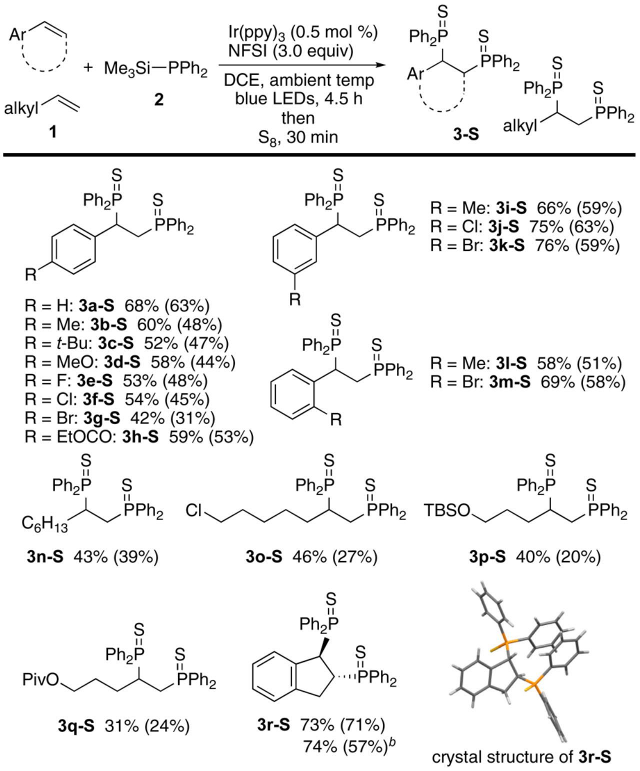
entry	photocatalyst (mol %)	oxidant	yield (%)[b]	
			3a-S	4a-S
1	Ir(ppy)$_3$ (10)	NFSI	44	12
2	Ir(ppy)$_2$(dtbpy)PF$_6$ (10)	NFSI	42	0
3	Ru(bpy)$_3$Cl$_2$ (10)	NFSI	7	0
4	Ru(bpy)$_3$(PF$_6$)$_2$ (10)	NFSI	8	trace
5[c]	Eosin Y (10)	NFSI	8	0
6[c]	Eosin Y (Na) (10)	NFSI	19	0
7	Ir(ppy)$_3$ (0.5)	NFSI	65	13
8[d]	Ir(ppy)$_3$ (0.5)	NFSI	68	0
9[d]	Ir(ppy)$_3$ (0.5)	[Me$_3$pyF]OTf	53	0
10[d]	Ir(ppy)$_3$ (0.5)	selectfluor	0	40
11[d]	Ir(ppy)$_3$ (0.5)	PhI(OAc)$_2$	3	0
12[d]	Ir(ppy)$_3$ (0.5)	Togni II	0	7
13	none	NFSI	4	0
14[e]	Ir(ppy)$_3$ (0.5)	NFSI	0	0

[a] Reaction conditions: **1a** (0.25 mmol), **2** (0.60 mmol), photocatalyst, oxidant (0.60 mmol), DCE (3.0 mL), 4.5 h, N$_2$, blue LED irradiation, ambient temp then S$_8$, 30 min, N$_2$. [b] ^{1}H NMR yield. [c] Green LED irradiation. [d] Initial mixing Ir(ppy)$_3$, **2** (0.75 mmol), and oxidant (0.75 mmol) followed by addition of **1a** (0.25 mmol). [e] In the dark.



Under conditions of entry 8 in Table 1, we investigated the scope of alkene substrates. The representative products are summarized in Scheme 2. The photoredox catalysis was compatible with electronically diverse functions at the *ortho*-, *meta*-, and *para*-positions of styrene, including methy, *tert*-butyl, methoxy, fluoro, chloro, bromo, and ester groups, and the corresponding diphosphinated products were formed in moderate to good yields (**3a-S** to **3m-S**). In general, the reaction efficiency was somewhat lower than that of the previous copper-based system,[7] but in all cases no hydrophosphination byproduct was detected, which makes the purification easier. Additionally, the protodebromination of the C−Br bond, which competitively occurred under Cu/NHC catalysis,[7] was completely avoided (**3g-S**, **3k-S**, and **3m-S**). Moreover, the aliphatic terminal alkenes also underwent the diphosphination to furnish **3n-S** to **3q-S** albeit with moderate yields. Some starting materials were recovered unchanged while styrene derivatives were fully consumed probably via a competitive radical polymerization. Particularly notable is the successful *trans*-selective diphosphination of *β*-substituted styrene, indene (**3r-S**): its structure including the stereochemistry was unambiguously determined by NMR, HRMS, and X-ray analysis.[10] The above tolerance with aliphatic

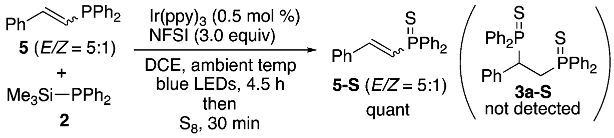
Scheme 2. *vic*-Diphosphination of Alkenes 1 with Trimethylsilyldiphenylphosphine (2) under Visible-Light-Promoted Photoredox Catalysis[a]



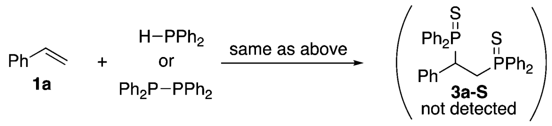
[a] Reaction conditions: **1** (0.25 mmol), **2** (0.75 mmol), Ir(ppy)$_3$ (0.0013 mmol), NFSI (0.75 mmol), DCE (3.0 mL), 4.5 h, N$_2$, blue LED irradiation, ambient temp then S$_8$, 30 min, N$_2$. ^{1}H NMR yields are shown. Isolated yields are in parentheses. [b] 1.0 mmol scale.

terminal alkenes and β-substituted styrene deserves significant attention because they are inaccessible substrates in the previous Cu catalyst.[7,11]

To get mechanistic insight, we performed several control experiments. When the independently prepared styrylphosphine **5** was subjected to the standard reaction conditions, **3a-S** was not formed and the corresponding phosphine sulfide **5-S** was exclusively observed, indicating that the oxidative phosphination/hydrophosphination sequence is unlikely (eq 1). The present photoredox catalysis was operative uniquely with the silylphosphine **2**: neither diphenylphosphine nor tetraphenyldiphosphane, which was observed as the main byproduct under identical conditions, gave the diphosphinated **3a-S** (eq 2). We thus checked the stability of silylphosphine **2** and NFSI by ^{31}P and ^{19}F NMR. When mixing **2** and NFSI in DCE-d_4, their original signals immediately disappeared, and several new signals appeared. The major ones had large coupling constants about 1000 Hz, which are characteristic of $^{1}J_{PF}$. Although we could not completely assign all signals, the major species may be fluorophosphoniums.[12−14]



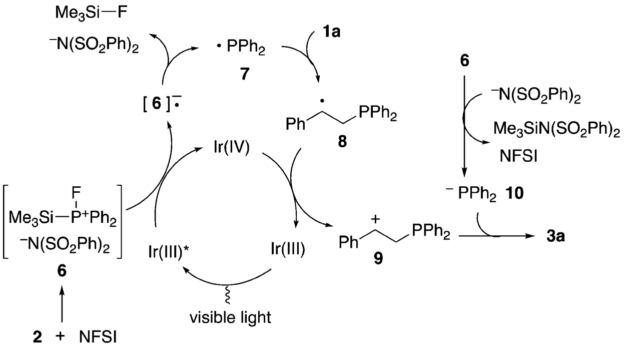
(1)

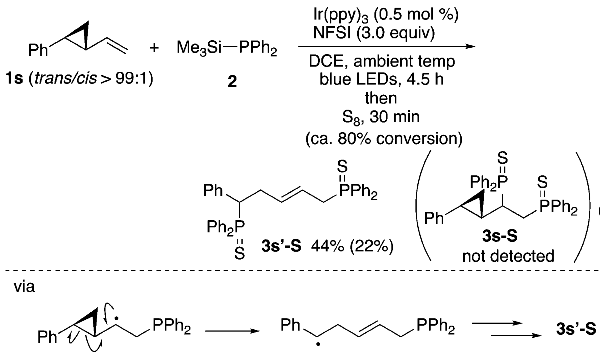


(2)

Although the detail is unclear, on the basis of the above findings and literature information,[9] we are tempted to assume the reaction mechanism of **1a** with **2** as follows (Scheme 3). Initial visible light irradiation excites the starting Ir(III) catalyst to the active Ir(III)* species. Subsequent single electron transfer (SET) from Ir(III)* to the in situ generated fluorophosphonium species **6** delivers Ir(IV) of the higher oxidation state and anion radical species of **6**, which then undergoes fragmentation to the corresponding diphenylphosphinyl radical **7**. The radical addition of **7** to styrene (**1a**) is followed by the back electron transfer to Ir(IV) to complete the Ir photoredox catalytic cycle along with the generation of phosphinated benzylic cation **9**. Finally, the cation **9** is trapped with diphenylphosphide **10** arising from the fluorophosphonium **6** and imide anion $^{-}N(SO_2Ph)_2$ to form the observed diphosphinated product **3a**.[15] The exclusive ring-opening diphosphination of vinylcyclopropane **1s** also suggests the radical intermediacy (eq 3). An alternative radical chain mechanism cannot be completely excluded, but a light on/off experiment supports the proposed Ir catalytic cycle.[16]

Scheme 3. Plausible Mechanism





(3)

In conclusion, we have developed visible-light-promoted photoredox catalysis for the *vic*-diphosphination of styrenes with silylphosphine and NFSI. The reaction proceeds under mild conditions (visible light irradiation, ambient temperature) and avoids the formation of undesired hydrophosphination byproducts, which are inevitable under the previous Cu catalysis. Additionally, the photoredox catalysis is compatible with relatively challenging aliphatic alkenes and β-substituted styrene. Thus, the present reaction system enables the rapid preparation of DPPE-type bidentate ligands from readily accessible and simple alkenes.[17] Further development of related photoredox catalysis and mechanistic investigation are ongoing in our laboratory.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b02223.

^{1}H, ^{13}C{^{1}H}, ^{19}F{^{1}H}, and ^{31}P{^{1}H} NMR spectra, ORTEP drawing, and NMR studies (PDF)
CIF file of **3r-S** (CIF)

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Notes

The authors declare no competing financial interest.

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(10) Crystallographic data for the structure have been deposited with the Cambridge Crystallographic Data Centre (CCDC 1562909). See the Supporting Information for details.

(11) Unfortunately, attempts to apply aliphatic internal alkenes such as cyclohexene remained unsuccessful. The reaction with Me_3Si-PCy_2 also formed no corresponding phosphinated product.

(12) Only a trace amount of free $F-PPh_2$ was also observed, but it gradually disappeared. See the Supporting Information for details.

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(14) We also monitored the stoichiometric reaction of H-PPh_2 or Ph_2P-PPh_2 with NFSI in DCE-d_4 by ^{19}F and ^{31}P NMR. The reaction of H-PPh_2 and NFSI formed a large amount of free F-PPh_2 and Ph_2P-PPh_2, which are inactive species toward the desired *vic*-diphosphination. On the other hand, the mixture of Ph_2P-PPh_2 and NFSI showed ^{19}F and ^{31}P NMR spectra similar to those from Me_3Si-PPh_2 and NFSI. Thus, we cannot provide conclusive statements at present. See the Supporting Information for details.

(15) The formed diphosphinated species **3a** can coordinate to the regenerated NFSI: actually, upon treatment of bis(diphenylphosphono)ethane (DPPE) with NFSI in $CDCl_3$, the corresponding $^1J_{PF}$ coupling (ca. 1000 Hz) was observed by ^{31}P and ^{19}F NMR. See the Supporting Information for details.

(16) See the Supporting Information for details.

(17) The obtained phosphine sulfides can be readily desulfidated to the corresponding phosphines (a) Zablocka, M.; Delest, B.; Igau, A.; Skowronska, A.; Majoral, J.-P. *Tetrahedron Lett.* **1997**, *38*, 5997. (b) Saito, M.; Nishibayashi, Y.; Uemura, S. *Organometallics* **2004**, *23*, 4012. Aso see refs 4c and 7.