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P–alkene bidentate ligands: an unusual ligand effect in Pd-catalysed Suzuki reactions

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Abstract—The versatile reagent bis(diphenylphosphino)benzaldehyde was used to prepare a variety of electronically and sterically varied ligands using Wittig or aldol methodology in high yields. Pd-catalysed Suzuki reactions were evaluated using these ligands. The influence of the functional group on the alkene, which is in direct conjugation with the phosphorus centre of the ligand, was visible in the activity profiles of the reactions. In general, the activity and stability of the Pd–ligand system increased as electron deficiency and steric bulk increased at the alkene. Furthermore, the ligands could be used at decreased catalyst loadings with improved yields and did not themselves participate in the reactions as substrates.

1. Introduction

Despite the existence of several 'ligandless' transition metal-mediated reactions,[1] ligands play pivotal roles in directing the outcome of the overwhelming majority of such catalysed transformations. For example, unactivated aryl halides such as chlorides or electron-rich bromides may usually only be used in Pd-catalysed reactions when a very electron-rich ligand is used to modify the metal.[2] Similarly, workers at Sasol have recently very elegantly shown the ligand-dependent effect of the co-catalysed oligomerisation of ethylene to form 1-hexene or 1-octene, depending on the type of ligand employed.[3] Furthermore, the hydroformylation reaction has been shown to be highly dependent upon the presence of a ligand and very specifically its bite angle.[4] It is therefore clear that various characteristics of ligands modify the outcomes of reactions.

In the instance of Pd-mediated chemistry, electron-deficient alkenes have been shown to be useful as *reagents* in Heck reactions.[5] Conversely, several workers have employed succinic anhydride and similar electron-deficient alkenes not as substrates but as added *ligands* to prove the intermediacy of $L_2Pd(0)$ type materials, the complexes of which provide not only characteristic NMR data arising from substantial π-back donation from the electron-rich Pd to the π-acidic alkene,[6] but also allow X-ray structural determinations to be carried out.[7] Scrivanti has recently reported on the stabilisation of catalyst systems in the presence of electron-deficient alkenes.[8] On the other hand, earlier work by Amatore et al.[9] has indicated that dba (as originating from $Pd(dba)_2$ catalyst precursors) strongly competes with PPh_3 for complexation to co-ordinatively unsaturated $Pd(PPh_3)_2$, slowing the overall rate of the oxidative addition step (using PhI) in the catalytic cycle[9a] and exerting a controlling effect on the apparent rate of the overall reaction.[9b] Furthermore, the alkene reactant present in Heck reactions has been shown to decelerate the oxidative addition step, with methyl acrylate retarding that step more than styrene does.[9c] Fairlamb has broadened the scope of the prior work by employing a range of functionalised dba ligands, indicating that the more electron-rich the dba ligand in the catalyst precursor (by virtue of aryl substitution on the dba ligand), the higher the overall rate of the oxidative addition reaction.[10] This is because the functionalised dba ligand competes less efficiently for the catalytically active $Pd(PPh_3)_2$ species when it is electron-rich, allowing higher concentrations of this species to exist. With this as a background, we were motivated to report our work on the synthesis and evaluation of 'bidentate' phosphine–alkene ligands derived from the readily available bis(diphenylphosphino)benzaldehyde.

2. Results and discussion

Bis(diphenylphosphino)benzaldehyde **1** was converted in high yields into several alkenes with varying electronic properties at the alkene moiety, using Wittig or aldol-type technology (Scheme 1).

Keywords: Suzuki; Sterics; Ligand effects; Palladium.
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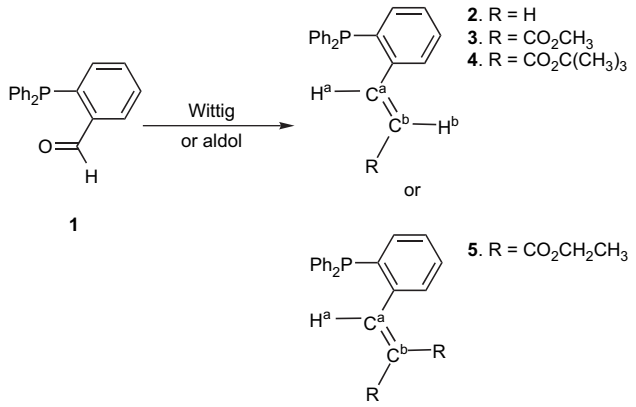
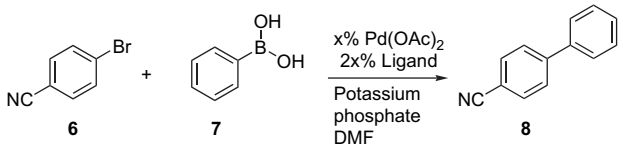


Scheme 1.

Accordingly, reaction of **1** with methyltriphenylphosphonium bromide in the presence of sodium amide afforded the styrene derivative **2** in 81% yield, while the enoate derivatives **3** and **4** were prepared making use of (methoxycarbonylmethylene) triphenylphosphorane and (*tert*-butoxycarbonylmethylene) triphenylphosphorane in yields of 92% and 80%, respectively. Diester **5** was prepared using a base-promoted Knoevenagel reaction in a yield of 66%.

Each of the new ligands (2 equiv) was complexed in situ with $Pd(dba)_2$ by simply mixing the ligand and $Pd(dba)_2$ in deuterated chloroform. NMR spectroscopy unambiguously showed complexation of the Pd metal to the P(III) atom by a substantial (ca. 40 ppm) down-field shift as detected in the ^{31}P NMR spectrum for each of the Pd complexes of ligands **2**, **3**, **4** and **5** (Table 1), which is consistent with published data.[6] Here, the signals manifested as one sharp singlet for each ligand with only very little or no free ligand being detected. This indicated that the complex, whatever its actual constitution and geometry be, gave rise to equivalent phosphines. This is in contradistinction to prior observations on the complexation behaviour of $Pd(dba)_2$ towards PPh_3, where non-equivalent phosphines were observed.[9a] Additionally, the NMR spectra also clearly proved that the alkene forms a chelate structure to the Pd centre by strong up-field shifts of the signals characteristic of the unsaturated moiety in both the ^1H and ^{13}C NMR spectra for Pd complexes of **3**, **4** and **5**, also consistent with the literature.[6] In the case of styrene derivative **2**, only the shift in the ^{31}P NMR spectrum was observed; no concomitant shifts in the other spectra were seen. This situation is readily explained by the fact that the extent of π-back donation from a metal onto a ligand is strongly dependent on the ability of that ligand to accept additional electron density. In the cases of the ligands and complexes of this study, it is the ability of the alkene to accept this electron density that allows such π-back donation to take place. 'Unactivated' alkenes are electron-rich, while enoate esters are electron-deficient, the latter being better able to accommodate π-back donation into their lower lying[11] π* (LUMO) orbitals. Alkene complexation is also witnessed by changes in the C=O IR stretching frequencies.

Application of the complexes to a Pd-catalysed Suzuki reaction (Scheme 2) making use of bromobenzonitrile (**6**) and phenylboronic acid (**7**) yielded exciting and intriguing results, which are summarised in Tables 2–4. The results of reactions performed at 110 °C show a clear trend of enhanced catalyst activity and stability that mimics the series of ligands from most electron-rich to most electron-poor, the latter providing the best results (rate, yield and catalyst stability). The stability of the catalyst was gauged by the formation or not of Pd black, the formation of which corresponded with a dramatic slowing in the progress of the reaction if the reaction was not already essentially complete, also indicative of a less stable catalyst.



Scheme 2.

It is clear from the results in Table 2 that all of the reactions are fast, with the exception of those involving styrene ligand **2** and, to a lesser extent, PPh_3. It is also evident that the ligands containing electron-withdrawing groups provide an enhanced rate of reaction, which is further increased with additional steric bulk. Saturated versions of ligands **3** and **4** showed poor activity in these reactions, highlighting the need for and the effect of the unsaturation in enhancing the activity of catalysts derived from our ligands.

Table 2. Yields of biphenyl **8** with varying ligands[a]

Time (h)	PPh_3 (%)	Ligand **2** (%)	Ligand **3** (%)	Ligand **4** (%)	Ligand **5** (%)
1	50	14	64	63	79
2	56	16	70	71	82
4	61	17	74	76	86
8	67	21	83	83	88
12	69	22	84	86	91
24	71	26	85	87	93

[a] $Pd(OAc)_2$ (5%), 10% ligand, 110 °C, DMF, isolated yield.

Table 1. Selected physical data for free versus Pd(0)-complexed ligands **2**–**5**

Ligand	^{31}P (ppm)	H^a (ppm)	H^b (ppm)	C^a (ppm)	C^b (ppm)	ν_{CO} (cm^{-1})
Free ligand **2**	−12.9	7.34	5.40	129.0	116.0	n/a
Pd complex of **2**	32.9	7.35	5.36	129.7	116.9	n/a
Free ligand **3**	−14.0	8.44	6.27	139.1	119.7	1713
Pd complex of **3**	29.3	5.95	4.44	95.5	72.8	1695
Free ligand **4**	−13.1	8.28	6.17	139.1	121.9	1700
Pd complex of **4**	31.0	4.40	4.40	94.8	73.2	1683
Free ligand **5**	−12.5	8.25	n/a	142.0	127.8	1727
Pd complex of **5**	28.6	7.34	n/a	112.7	97.4	1697

Table 3. Yields of biphenyl **8** in reactions performed at 82 °C[a]

Time (h)	Ligand **2** (%)	Ligand **3** (%)	Ligand **4** (%)	Ligand **5** (%)
1	14	13	16	14
2	21	31	43	35
4	25	43	56	59
8	28	57	66	73
12	29	63	69	81
24	29	68	72	83

[a] $Pd(OAc)_2$ (5%), 10% ligand, 82 °C, DMF, isolated yield.

Table 4. Yields of biphenyl **8** at lower catalyst loading (1% Pd) in reactions performed at 82 °C[a]

Time (h)	Ligand **2** (%)	Ligand **3** (%)	Ligand **4** (%)	Ligand **5** (%)
1	13	25	25	29
2	18	28	35	43
4	22	34	43	52
8	31	44	54	62
12	36	53	62	72
24	51	73	75	84

[a] $Pd(OAc)_2$ (1%), 2% ligand, DMF, isolated yield.

Table 5. Yields of biphenyl **8** at lower catalyst loading (1% Pd) in reactions performed at 110 °C[a]

Time (h)	Ligand **2** (%)	Ligand **3** (%)	Ligand **4** (%)	Ligand **5** (%)
1	56	84	82	85
2	65	87	86	87
4	74	89	88	88
8	80	91	90	93
12	87	92	94	97

[a] $Pd(OAc)_2$ (1%), 2% ligand, DMF, isolated yield.

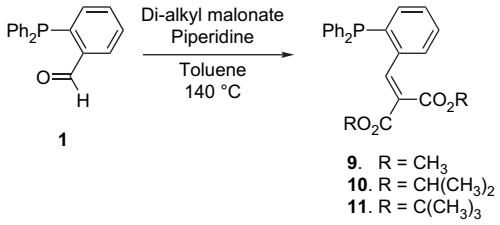
A similar reactivity trend was obtained when carrying out the reactions at 82 °C (Table 3). Here too, the activity increased with increasing electron deficiency. For PPh_3 and ligand **2** rapid deactivation of the catalyst and concomitant precipitation of Pd black were observed at both temperatures (110 °C and 82 °C).

Having experienced success at the relatively high catalyst loading of 5% Pd, we reduced the loading to 1% Pd (Tables 4 and 5). At the lower catalyst loading of 1% Pd at 82 °C, slight rate enhancements were observed over the first hour in otherwise similar yielding reactions. Most of the benefit was seen for ligand **2** (Table 3 vs Table 4).

When repeating the reactions at 110 °C, extremely fast reactions were observed for all of the ligands employed and very high yields were obtained (Table 5). The reactions were essentially complete within the first hour, with slow increases in yields being observed up to 12 h. The higher activity at the lower catalyst loading may be ascribable to lower levels of aggregation of the homogeneous catalyst. Notwithstanding the overall high rates and yields of these reactions, the overall relative catalyst activity followed the same pattern previously observed.

The ligands themselves did not participate in Pd-mediated reactions of the Heck-type (to which they are activated), and could be isolated intact in yields of >80% from large-scale reactions. This negated the possibility of the ligands being subject to such Pd-mediated reactions, the products of which might have been argued to be the actual and active ligands for the Pd metal.

A second series of ligands was synthesised using the Knoevenagel reaction, producing malonate-derived ligands **9**, **10** and **11** that were structurally similar to **5** (Scheme 3), in an effort to probe the stereoelectronic influence of the ligands more fully.



Scheme 3.

The Knoevenagel products were evaluated as ligands in the Suzuki reaction (Scheme 2) making use of 5% catalyst and 1% catalyst (Table 6). As before, the lower catalyst loading afforded improved reactions, and at both catalyst loadings there was a distinct trend of increasing yield in response to increased steric hindrance of the ligand. Catalysts derived from the latter set of ligands proved more efficient and robust than the analogous monoester ligands **2**–**4**.

Rate enhancements in otherwise identical catalysed reactions usually imply that the particular ligand speeds up the rate-limiting step in the reaction. The now-accepted three-step mechanism of the Suzuki reaction[12] involves oxidative addition of the aryl halide to the active Pd(0) catalyst, transmetallation from the boronic acid or ester to form an Ar–Pd–R species and reductive elimination as the final (C–C bond-forming) step. Electron-rich ligands tend to enhance the rate of the oxidative addition step,[2] since these ligands destabilise the Pd(0) oxidation state and render the metal centre more nucleophilic and susceptible to oxidation. In contrast, electron-deficient ligands tend to destabilise the higher Pd(II) oxidation state, thereby promoting the reductive elimination step. For the present set of ligands, we believe that it is the rate of the transmetallation step or the reductive elimination step that is being enhanced, and not the oxidative addition step, argued as follows.

If one assumes a P-only co-ordination mode of the ligand onto the metal during the catalytic cycle, then the complex of ligand **2** would oxidatively add fastest, followed by the catalyst generated from enoate esters **3** and **4**, with those of diesters **5** and **9**–**11** being slowest, since the alkene is in conjugation with the P-atom. This conjugation would

Table 6. Yields of **8** using Knoevenagel products as ligands

9 (R=Me)	**5** (R=Et)	**10** (R=^{i}Pr)	**11** (R=^{t}Bu)
80[a]	81[a]	86[a]	88[a]
84[b]	85[b]	94[b]	97[b]

[a] $Pd(OAc)_2$ (5%), 10% ligand, 82 °C, 12 h, isolated yield of **8**.
[b] $Pd(OAc)_2$ (1%), 2% ligand, 82 °C, 12 h, isolated yield of **8**.

decrease the electron density of the P-atom along this general series, leading to slower oxidative addition reactions. If one assumes a chelated binding mode, as has been demonstrated to be the case for these ligands, then a scenario in which the oxidative addition step is rate-limiting would also follow the order **2**>**3**,**4**>**5**,**9**,**10**,**11** since the extent of π-back donation is expected to increase along this series, thereby decreasing the electron density on the Pd atom. That this is *not* the observed order of activity eliminates the oxidative addition step as rate-limiting in these reactions (in fact, the ligands may well slow the rate of this step). By default, therefore, it is either the transmetallation or the reductive elimination step that is rate-limiting and is enhanced by our P–alkene ligands. The π-accepting ligands of this study would tend to destabilise all Pd(II) reaction intermediates, and should therefore promote all steps involving Pd in this oxidation state. At this stage we cannot ascertain which of these steps is rate-limiting and shows a rate enhancement due to the presence of our ligands (it is possible that both steps benefit from the ligands). What is certain, though, is that the more electron-deficient the alkene, within this series of ligands, and the more sterically encumbered the ligand, the greater the rate of the reaction and the higher the stability of the catalyst. (Such steric effects have recently been observed elsewhere.[13]) This work provides an interesting contrast to earlier work,[14] which indicates that the transmetallation of Pt–phosphine complexes is somewhat inhibited by bulkier phosphines. Additionally, what is apparent is that the influence of the alkene is important in the rate-limiting step (which, we contend, is not the oxidative addition step). This again provides an interesting contrast to the prior work in which the electron-deficient alkene of the dba ligand determines the concentration of the active PdL_2 species, and therefrom the overall activity of the system.[9,10]

3. Conclusions

We have demonstrated, for the first time according to our knowledge, that electron-deficient alkene–phosphine bidentate ligands enhance the rate of the Suzuki reaction and also improve the stability of the catalyst. Initial indications are that this rate enhancement rests in one of the Pd(II) reaction intermediates and not in the oxidative addition step, which involves a Pd(0) species. The ligands have been found not to participate in Heck reactions, and are isolated intact from the reaction mixtures.

4. Experimental

4.1. General

Melting points were determined on a Gallenkamp digital melting point apparatus and are uncorrected. ^{1}H NMR (300 MHz), ^{13}C NMR (75 MHz) and ^{31}P NMR (121 MHz) spectra were recorded on a Varian Gemini 300 MHz spectrometer in $CDCl_3$ (internal references being TMS for ^{1}H, chloroform-*d* for ^{13}C and 85% aqueous H_3PO_4 for ^{31}P spectra). ^{13}C NMR data include P–C coupling information. IR spectra were recorded on a Tensor 27 Bruker IR spectrometer. Mass spectra were recorded on a Shimadzu GCMS-QP2010 instrument fitted with quadrupole mass detector. High resolution mass spectra were recorded on a VG 70-SEQ. DMF was pre-dried over phosphorus pentoxide and distilled over calcium hydride; THF was distilled from sodium/benzophenone and DCM was dried by passing it through alumina followed by distillation over calcium hydride prior to use. All other materials were commercially available. All reactions were carried out under an inert atmosphere. Column chromatography was performed on silica gel (230–400 mesh) using eluants as indicated.

4.2. (2-Vinylphenyl)diphenylphosphine 2

Methyltriphenylphosphonium bromide/sodium amide (398 mg, 1.85 equiv) was stirred in 4 mL THF for 30 min at room temperature. 2-(Diphenylphosphino)benzaldehyde (150 mg, 1 equiv) was dissolved in 2 mL of THF and added dropwise to the phosphonium solution over 10 min. The reaction mixture was allowed to stir for 4 h or until it was judged to be complete via TLC monitoring, whereafter it was quenched with a saturated aqueous $NaHCO_3$ solution. The reaction mixture was then extracted with diethyl ether and washed with brine. The organic layer was dried over $MgSO_4$ and the excess solvent removed in vacuo. Flash chromatography in 10:1 hexane/EtOAc afforded product **2** as a white solid (81%). Mp 102–103 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.58 (dd, 1H, J=7.7 and 4.4 Hz), 7.32–7.23 (m, 12H), 7.14 (t, 1H, J=7.2 Hz), 6.81 (dd with unresolved fine coupling, 1H), 5.40 (dd with unresolved fine coupling, 2H, J=17.4 and 10.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 142.3 (d, 1C, J=22.3 Hz), 136.2 (d, 2C, J=10.0 Hz), 135.3 (d, 1C, J=24.0 Hz), 135.0 (d, 1C, J=14.0 Hz), 133.9 (d, 4C, J=19.4 Hz), 133.1 (1C), 128.9 (1C), 128.6 (2C), 128.4 (d, 4C, J=6.9 Hz), 127.8 (1C), 125.4 (d, 1C, J=4.3 Hz), 115.9 (d, 1C, J=2.3 Hz); ^{31}P NMR (121 MHz, $CDCl_3$) δ_P −13.4; IR ($CHCl_3$)/cm^{-1} 3012, 1434, 1200, 703; EIMS *m*/*z* (%) 289 (M^+, 100%) no discernable fragmentation pattern; HRMS found 288.1068, calcd 288.1070 for $C_{20}H_{17}P$.

4.3. General procedure for the synthesis of α,β-unsaturated esters

In a typical experiment, 2-(diphenylphosphino)benzaldehyde (0.52 mmol) and the triphenylphosphorane (1.21 equiv) were added together in 5 mL of dry DCM and stirred at room temperature for 12 h. Excess solvent was removed in vacuo and the pure product was obtained via flash chromatography.

4.3.1. Methyl acrylate 3. Flash chromatography in 10:1 hexane/EtOAc afforded product **3** as a yellow solid (92%). Mp 82–84 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.44 (dd, 1H, J=15.8 and 4.4 Hz), 7.61 (dd, 1H, J=7.5 and 4.2 Hz), 7.34–7.23 (m, 12H), 6.94 (dd, 1H, J=6.7 and 4.3 Hz), 6.27 (d, 1H, J=15.9 Hz), 3.71 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.9 (1C), 143.0 (d, 1C, J=25.7 Hz), 139.1 (d, 1C, J=22.6 Hz), 137.9 (d, 1C, J=16.1 Hz), 135.8 (d, 2C, J=9.8 Hz), 133.9 (d, 4C, J=19.8 Hz), 133.7 (1C), 129.8 (1C), 129.1 (1C), 128.8 (2C), 128.5 (d, 4C, J=7.1 Hz), 126.6 (d, 1C, J=4.0 Hz), 119.7 (d, 1C, J=2.6 Hz), 51.6 (1C); ^{31}P NMR (121 MHz, $CDCl_3$) δ_P −14.5; IR ($CHCl_3$)/cm^{-1} 3016, 1709, 1229, 795; EIMS *m*/*z* (%) 347 (M^+,

100), 287 (M−$C_2H_3O_2$, 5%); HRMS found 346.1131, calcd 346.1123 for $C_{22}H_{19}O_2P$.

4.3.2. *tert*-Butyl acrylate 4. Flash chromatography in 10:1 hexane/EtOAc afforded product **4** as a light yellow solid (80%). Mp 91–101 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ_H 8.29 (dd, 1H, *J*=15.9 and 4.5 Hz), 7.59 (dd, 1H, *J*=7.4 and 4.1 Hz), 7.30–7.19 (m, 12H), 6.91 (dd, 1H, *J*=7.1 and 4.4 Hz), 6.17 (d, 1H, *J*=15.9 Hz), 1.45 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.6 (1C), 141.8 (d, 1C, *J*=25.3 Hz), 139.1 (d, 1C, *J*=22.0 Hz), 137.8 (d, 1C, *J*=16.0 Hz), 135.8 (d, 2C, *J*=10.0 Hz), 134.0 (d, 4C, *J*=20.0 Hz), 133.4 (1C), 129.5 (1C), 129.0 (1C), 128.8 (2C), 128.5 (d, 4C, *J*=7.1 Hz), 126.4 (d, 1C, *J*=4.0 Hz), 121.9 (d, 1C, *J*=2.3 Hz), 80.2 (1C), 28.1 (3C); ^{31}P NMR (121 MHz, $CDCl_3$) δ −13.6; IR ($CHCl_3$)/cm^{-1} 2981, 1710, 1321, 1151; EIMS *m*/*z* (%) 389 (M^+, 30%), 333 (M−C_4H_9, 10%), 289 (M−$C_5H_9O_2$, 100%); HRMS found 388.1590, calcd 388.1592 for $C_{25}H_{25}O_2P$.

4.4. General procedure for the synthesis of Knoevenagel phosphine ligands

In a typical experiment dialkyl malonate (1 equiv), 2-(diphenylphosphino)benzaldehyde (1.1 equiv) and 0.01 mL of piperidine (0.1 equiv) were added to a flamed out Dean Stark apparatus with 2 mL of toluene and heated in an oil bath (130–150 °C) for 6–8 h until all of the water had been azeotropically removed. After cooling, 5 mL of toluene was added and the reaction mixture was washed with water (2×5 mL), 1 N HCl (2×5 mL) and saturated aqueous $NaHCO_3$ (2×5 mL). The combined aqueous layers were back-extracted once with 10 mL of toluene. The organic layers were combined, dried with Na_2SO_4, filtered, evaporated and purified via flash chromatography.

4.4.1. Benzylidene diester 5. Flash chromatography in 10:1 hexane/EtOAc afforded product **5** as a light yellow solid (66%). Mp 89–91 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.34 (d, 1H, *J*=2.7 Hz), 7.39 (dd with unresolved fine coupling, 1H), 7.32–7.23 (m, 12H), 6.94 (dt, 1H, *J*=5.4 and 1.5 Hz), 4.21 (q, 2H, *J*=7.2 Hz), 4.12 (q, 2H, *J*=7.1 Hz), 1.26 (t, 3H, *J*=6.9 Hz), 1.09 (t, 3H, *J*=7.1 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.6 (1C), 163.4 (1C), 141.9 (d, 1C, *J*=22.6 Hz), 138.2 (d, 1C, *J*=23.1 Hz), 137.8 (d, 1C, *J*=14.9 Hz), 135.2 (d, 2C, *J*=9.4 Hz), 133.8 (d, 4C, *J*=19.8 Hz), 132.8 (1C), 129.5 (1C), 128.8 (2C), 128.5 (1C), 128.3 (d, 4C, *J*=7.1 Hz), 128.0 (d, 1C, *J*=4.3 Hz), 127.8 (d, 1C, *J*=2.6 Hz), 61.2 (1C), 61.0 (1C), 13.9 (1C), 13.6 (1C); ^{31}P NMR (121 MHz, $CDCl_3$) δ_P −13.0; IR ($CHCl_3$)/cm^{-1} 2985, 1727, 1255, 1070; EIMS *m*/*z* (%) 433 (M^+, 100%), 387 (M−C_2H_5O, 40%), 359 (M−$C_3H_5O_2$, 45%); HRMS found 432.1485, calcd 432.1491 for $C_{26}H_{25}O_4P$.

4.4.2. Benzylidene diester 9. Flash chromatography in 10:1 hexane/EtOAc afforded product **9** as a yellow crystalline solid (56%). Mp 109–111 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.39 (d, 1H, *J*=3.3 Hz), 7.39–7.25 (m, 13H), 6.95 (t, 1H, *J*=5.7 Hz), 3.76 (s, 3H), 3.63 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.3 (1C), 164.0 (1C), 142.9 (d, 1C, *J*=22.6 Hz), 138.4 (d, 1C, *J*=23.5 Hz), 138.1 (d, 1C, *J*=14.6 Hz), 135.3 (d, 2C, *J*=9.1 Hz), 133.9 (d, 4C, *J*=19.8 Hz), 133.1 (1C), 129.8 (1C), 128.9 (2C), 128.8 (1C), 128.5 (d, 4C, *J*=7.1 Hz), 128.0 (d, 1C, *J*=4.3 Hz), 127.2 (d, 1C, *J*=2.6 Hz), 52.5 (1C), 52.2 (1C); ^{31}P NMR (121 MHz, $CDCl_3$) δ_P −13.2; IR ($CHCl_3$)/cm^{-1} 3620, 2976, 2401, 1691, 1477; EIMS *m*/*z* (%) 404 (M^+, 1%), 345 (M−$C_2H_3O_2$, 100%); HRMS found 404.1155, calcd 404.1178 for $C_{24}H_{21}O_4P$.

4.4.3. Benzylidene diester 10. Flash chromatography in 10:1 hexane/EtOAc afforded product **10** as a yellow solid (72%). Mp 86–87 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.25 (d, 1H, *J*=2.7 Hz), 7.44 (dd with unresolved fine coupling, 1H), 7.31–7.21 (m, 12H), 6.92 (t, 1H, *J*=4.9 Hz), 5.06 (m, 2H), 1.24 (d, 6H, *J*=6.3 Hz), 1.13 (d, 6H, *J*=6.2 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.4 (1C), 163.1 (1C), 141.1 (d, 1C, *J*=22.3 Hz), 138.3 (d, 1C, *J*=22.6 Hz), 138.0 (d, 1C, *J*=14.6 Hz), 135.4 (d, 2C, *J*=9.2 Hz), 134.0 (d, 4C, *J*=19.7 Hz), 132.8 (1C), 129.5 (1C), 128.9 (2C), 128.5 (d, 6C), 128.3 (d, 1C, *J*=3.97 Hz), 68.9 (1C), 68.7 (1C), 21.6 (2C), 21.4 (2C); ^{31}P NMR (121 MHz, $CDCl_3$) δ_P −12.5; IR ($CHCl_3$)/cm^{-1} 3622, 2980, 2402, 1724, 1523; EIMS *m*/*z* (%) 460 (M^+, 1%), 417 (M−C_3H_7, 40%), 373 (M−$C_4H_7O_2$, 100%), 331 (M−$C_7H_{13}O_2$, 98%); HRMS found 460.1802, calcd 460.1804 for $C_{28}H_{29}O_4P$.

4.4.4. Benzylidene diester 11. Flash chromatography in 10:1 hexane/EtOAc afforded product **11** as a light orange solid (47%). Mp 91–93 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.05 (d, 1H, *J*=3.0 Hz), 7.51 (dd, 1H, *J*=6.1 and 4.3 Hz), 7.32–7.21 (m, 12H), 6.91 (t, 1H, *J*=6.0 Hz), 1.44 (s, 9H), 1.39 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.3 (1C), 163.0 (1C), 139.3 (d, 1C, *J*=22.3 Hz), 138.3 (d, 1C, *J*=22.3 Hz), 137.8 (d, 1C, *J*=14.9 Hz), 135.6 (d, 2C, *J*=9.7 Hz), 134.0 (d, 4C, *J*=19.8 Hz), 132.9 (1C), 130.4 (d, 1C, *J*=2.3 Hz), 129.4 (1C), 128.9 (2C), 128.6 (1C), 128.5 (d, 2C, *J*=7.1 Hz), 128.4 (1C), 81.8 (1C), 81.6 (1C), 28.0 (3C), 27.8 (3C); ^{31}P NMR (121 MHz, $CDCl_3$) δ −12.1; IR ($CHCl_3$)/cm^{-1} 3623, 2979, 2402, 1723, 1479; EIMS *m*/*z* (%) 488 (M^+, 1%), 431 (M−C_4H_9, 15%), 387 (M−$C_5H_9O_2$, 30%), 331 (M−$C_9H_{17}O_2$, 100%); HRMS found 488.2113, calcd 488.2117 for $C_{30}H_{33}O_4P$.

4.5. General procedure for the Suzuki reaction

In a typical experiment, the phosphine ligand, e.g. TPP (0.114 mmol) was dissolved in 5 mL of solvent and $Pd(OAc)_2$ (0.057 mmol) was added. The reaction mixture was allowed to stir for 20 min. Potassium phosphate (1.71 mmol), bromobenzonitrile (1.14 mmol) and phenylboronic acid (1.14 mmol) were added and the reaction mixture was stirred at the relevant temperature for the relevant time.

4.5.1. 4-Cyanobiphenyl 8.[15] Flash chromatography in 10:1 hexane/EtOAc afforded product **8**. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.72–7.64 (m, 4H), 7.59–7.39 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 145.5 (1C), 139.0 (1C), 132.5 (2C), 129.0 (2C), 128.5 (1C), 127.6 (2C), 127.1 (2C), 118.8 (1C), 110.8 (1C).

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2006.12.012.

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