Supporting Information

Dual Photoredox and Nickel Catalysed Reductive Coupling of Alkynes and Aldehydes

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Experimental Procedures

General methods and materials

^{1}H-NMR spectra were recorded on Varian Mercury 400 spectrometer. Chemical shifts are reported in ppm from TMS with the solvent resonance as the internal standard ($CHCl_3$: δ = 7.27 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = duplet, t = triplet, q = quartet, dd = double duplet, m = multiplet), coupling constants (Hz). ^{13}C-NMR spectra were recorded on Varian Mercury 400 spectrometer. Chemical shifts are reported in ppm from TMS with the solvent as the internal standard ($CDCl_3$: δ = 77.0 ppm). Chromatographic purifications were done with 240-400 mesh silica gel. All reactions were set up under an argon atmosphere in oven-dried glassware using standard Schlenk techniques.
Anhydrous solvents were supplied by Aldrich in Sureseal® bottles. Anhydrous THF and DME were freshly distilled over sodium and benzophenone under argon atmosphere, before the use in order to remove the radical inhibitor BHT present as stabilizer. Unless specified, other anhydrous solvents were used without further purifications. All the reagents were purchased from commercial sources (Sigma-Aldrich, Alfa Aesar, Fluorochem, Strem Chemicals, TCI) and used without further purification unless specified. Reaction mixture was irradiated with Kessil® PR160L@456 nm.[1]

Figure S1. Emission profile of the Kessil® PR160L@456 nm used to irradiate the solutions (form Kessil® website: https://www.kessil.com/science/PR160L.php).

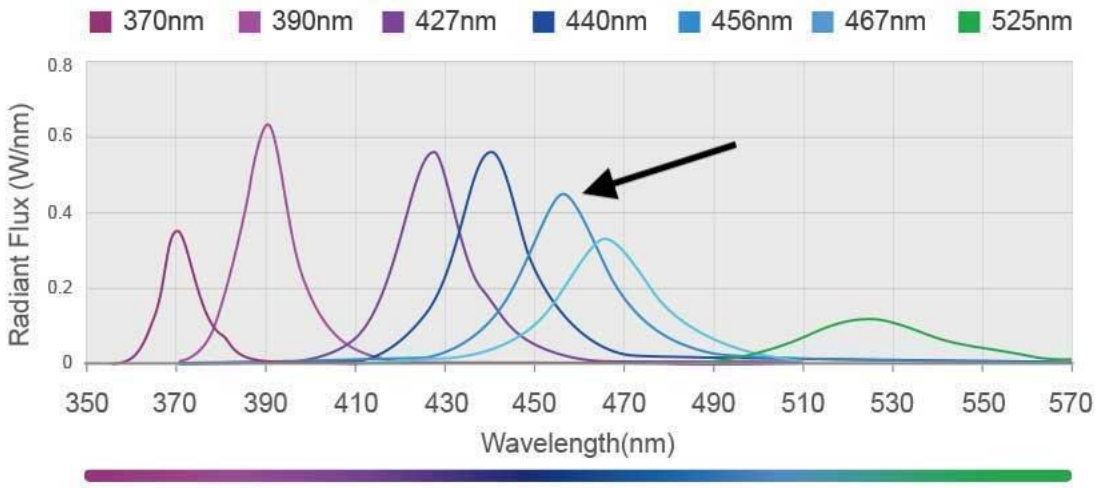
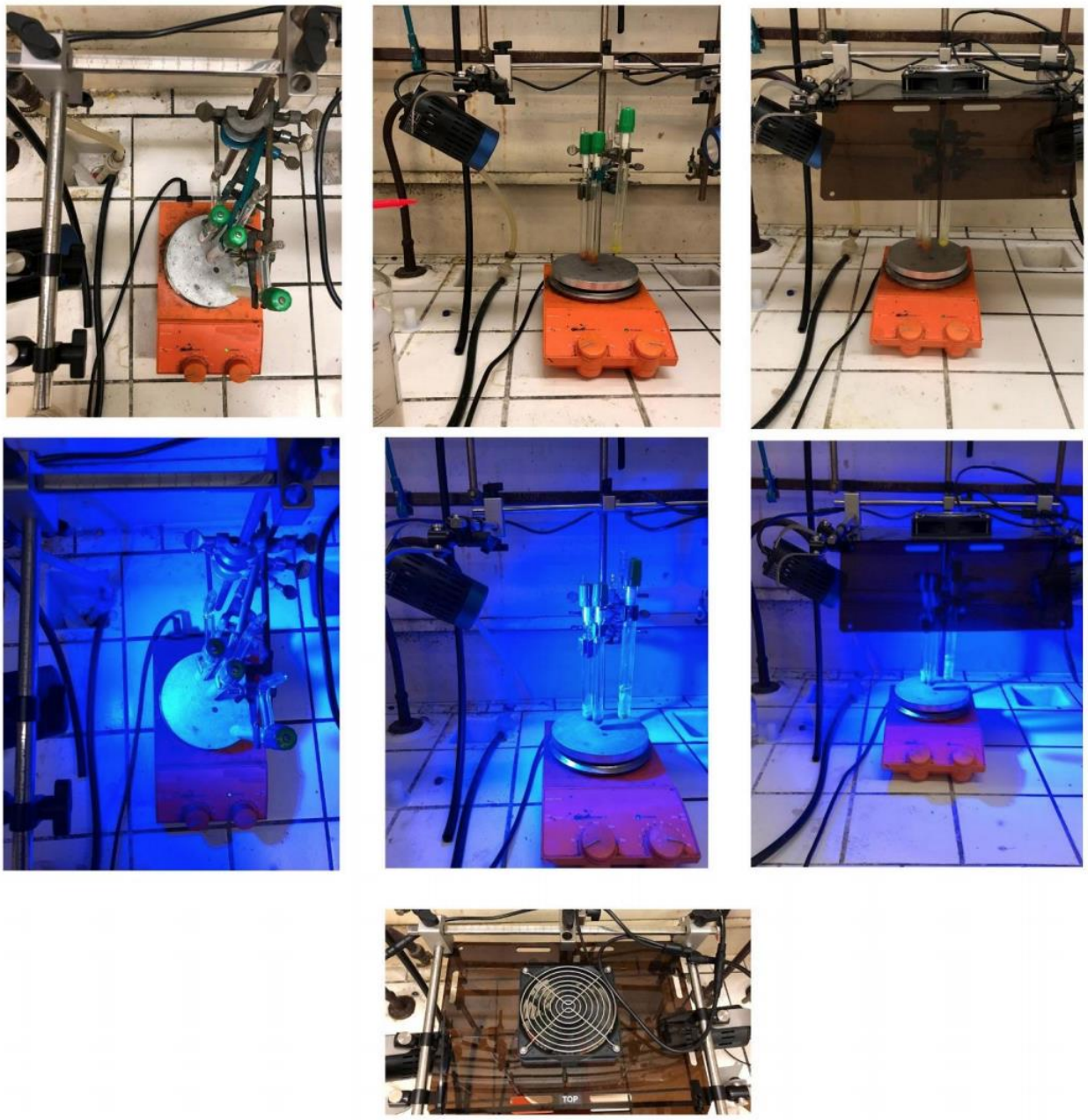
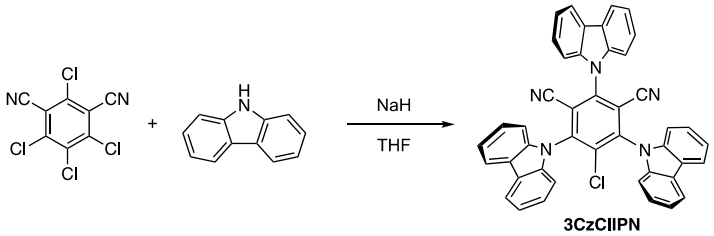


Figure S2. Reaction set-up.



Synthesis and characterization of the photocatalysts

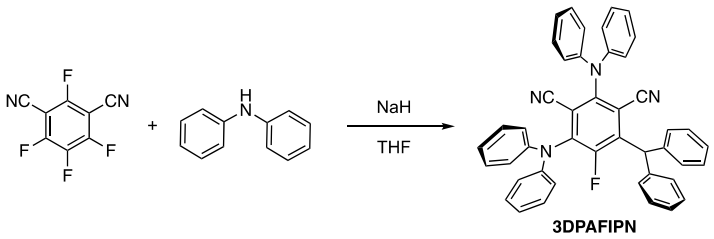
*Synthesis of 2,4,6-Tri(9H-carbazol-9-yl)-5-chloroisophthalonitrile (**3CzClIPN**)*



3CzClIPN

A 50 mL round-bottom-flask was charged with diphenylamine (5.0 equiv., 10 mmol, 1.69 g) and dry THF (20 mL). The solution was cooled to 0 °C and NaH (60% in mineral oil, 7.5 equiv., 15 mmol, 600 mg) was slowly added under vigorous stirring. After 2 hours tetrachloroisophtalonitrile (1.0 equiv., 2 mmol, 530 mg) was added and the mixture was stirred at room temperature. The solution slowly turned from yellow to dark brown. When the TLC showed a complete consumption of the starting material (usually 2 days are needed), water (1 mL) was added to neutralize the excess of NaH and the mixture was evaporated to give a yellow solid. The residue was purified by flash chromatography (Hex/Et_2O 2/1) to obtain 3DPAClIPN as bright yellow solid 35% yield (0.7 mmol, 460 mg). Spectroscopic data were according to the literature.[2]

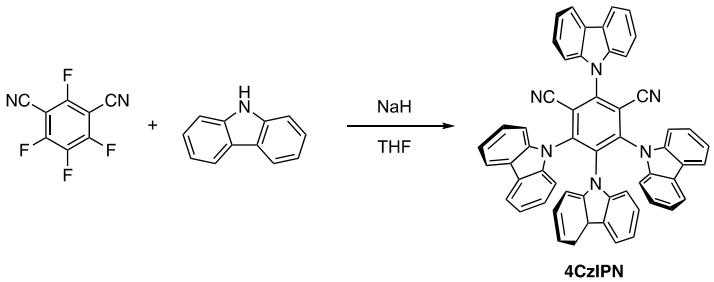
*Synthesis of 2,4,6-Tris(diphenylamino)-5-fluoroisophthalonitrile (**3DPAFIPN**)*



3DPAFIPN

A 50 mL round-bottom-flask, equipped with a magnetic stirring bar, was charged with diphenylamine (5.0 equiv., 10 mmol, 1.69 g) and dry THF (20 mL). The solution was cooled down to 0 °C and NaH (60% in mineral oil, 7.5 equiv., 15 mmol, 600 mg) was slowly added under vigorous stirring. After 2 hours, tetrafluoroisophthalonitrile (1.0 equiv., 2 mmol, 400 mg) was added, and the mixture was stirred at room temperature. The solution slowly turned from colorless to dark brown. When the TLC showed a complete consumption of the starting material (usually 2 days are needed), water (1 mL) was added dropwise under vigorous stirring to neutralize the excess of NaH, and the mixture was evaporated to give a yellow solid. The residue was purified by flash chromatography (cyHex/AcOEt 2/1) to obtain **3DPAFIPN** as bright yellow solid (1.04 g, 1.6 mmol, 80% yield). Spectroscopic data are in agreement with those reported in literature.[2]

*Synthesis of 2,4,5,6-tetrakis(carbazol-9-yl)-4,6-dicyanobenzene (**4CzIPN**)*



4CzIPN

A 50 mL round-bottom-flask, equipped with a magnetic stirring bar, was charged with carbazole (5.0 equiv., 10 mmol, 1.67 g) and dry THF (20 mL). The solution was cooled down to 0 °C and NaH (60% in mineral oil, 7.5 equiv., 15 mmol, 600 mg) was slowly added under vigorous stirring. After 2 hours, tetrafluoroisophthalonitrile (1.0 equiv., 2 mmol, 400 mg) was added and the mixture was stirred at room temperature overnight. A yellow precipitate progressively appeared.

When the TLC showed a complete consumption of the starting material, water (1 mL) was added dropwise under vigorous stirring to neutralize the excess of NaH, and the mixture was evaporated to give a yellow solid. The solid was successively washed with water and ethanol to afford 1.09 g (1.38 mmol, 69% yield) of spectroscopically pure **4CzIPN**. Spectroscopic data are in agreement with those reported in literature.[2]

General procedure for the synthesis of internal alkynes

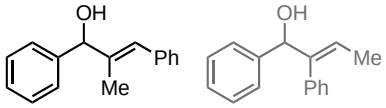
Internal alkynes **2b-g** were synthetized according to the classical Sonogashira procedure. A flame-dried two-necked round bottom flask connected to a Schlenk line through a gas inlet, under inert atmosphere, was charged with the corresponding aryl iodide (1 equiv., 2.0 mmol), $Pd(Ph_3P)_2Cl_2$ (0.05 equiv, 0.1 mmol, 70 mg), CuI (0.1 equiv., 0.2 mmol, 38 mg). Then, Et_3N (5 mL) and the alkyne substrate (1.2 equiv., 2.4 mmol) were added and N_2 was bubbled for thirty second in the reaction mixture. The mixture was stirred at room temperature until all the aryl iodide was consumed. The solvent was evaporated, and the residue was dissolved in diethyl ether (*ca.* 10 ml) and filtered over a small plug of Celite®. The filtrate was concentrated under vacuum and the desired product was purified through silica gel flash chromatography. Spectroscopic data matches with those reported in literature.[3]

General procedure: dual photoredox and nickel catalysed reductive coupling of alkynes and aromatic aldehydes

All the reactions were performed on 0.2 mmol scale of aldehyde. A dry 10 mL Schlenk tube, equipped with a Rotaflo® stopcock, magnetic stirring bar and an argon supply tube, was first charged under argon with $Ni(nBu_3P)_2Cl_2$ (10 mol%, 0.01 mmol, 5.4 mg). Then, the substrate **1** (0.2 mmol), the organic photocatalyst 3CzClIPN (5 mol%, 0.01 mmol, 6.6 mg), diethyl 1,4-dihydro-2,6-diethyl-3,5-pyridinedicarboxylate Hantzsch's ester (3 equivalents, 0.6 mmol, 152 mg) were added. Freshly distilled inhibitor-free DME (2 mL in order to obtain a [**1**] = 0.1 M substrate solution) was then added. The orange reaction mixture was allowed to stir for 5 min. and the alkyne **2a-g** was added dropwise to the solution. The reaction mixture was further subjected to a freeze-pump-thaw procedure (three cycles, two minutes each) and the vessel was refilled with argon. The reaction mixture was irradiated under vigorous stirring for 14 h and was quenched with water (approx. 4 mL) and extracted with AcOEt (4 x 3 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and the solvent was removed under reduced pressure. The ^1H NMR of the reaction crude to evaluate the regioisomeric ratio, was recorded previous filtration over a small plug of celite with DCM. The crude was purified by flash column chromatography (SiO_2) to afford products **3** in the stated yields.

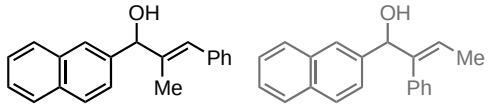
General procedure: dual photoredox and nickel catalysed reductive coupling of alkynes and aliphatic aldehydes

All the reactions were performed on 0.2 mmol scale of aldehyde. A dry 10 mL Schlenk tube, equipped with a Rotaflo® stopcock, magnetic stirring bar and an argon supply tube, was first charged under argon with $Ni(nBu_3P)_2Cl_2$ (10 mol%, 0.01 mmol, 5.4 mg). Then, the substrate **1** (0.2 mmol), the organic photocatalyst 3CzClIPN (5 mol%, 0.01 mmol, 6.6 mg), diethyl 1,4-dihydro-2,6-diethyl-3,5-pyridinedicarboxylate Hantzsch's ester (3 equivalents, 0.6 mmol, 152 mg) and $MgBr_2 \cdot Et_2O$ (2 equivalents, 0.4 mmol, 103 mg) were added. Freshly distilled inhibitor-free DME (2 mL in order to obtain a [**1**] = 0.1 M substrate solution) was then added. The orange reaction mixture was allowed to stir for 5 min. and the alkyne **2a-g** was added dropwise to the solution. The reaction mixture was further subjected to a freeze-pump-thaw procedure (three cycles, two minutes each) and the vessel was refilled with argon. The reaction mixture was irradiated under vigorous stirring for 14 h and was quenched with water (approx. 4 mL) and extracted with AcOEt (4 x 3 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and the solvent was removed under reduced pressure. The ^1H NMR of the reaction crude to evaluate the regioisomeric ratio, was recorded previous filtration over a small plug of celite with DCM. The crude was purified by flash column chromatography (SiO_2) to afford products **3** in the stated yields.



3a:**3a'**

(**3a**-**3a'**): pale yellow oil, 71% (0.14 mmol, 32 mg) as mixture regioisomers **3a**:**3a'** of 92:8. The general procedure was applied using freshly distilled **1a** (0.2 mmol, 20.4 µL) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.30 ppm related to the product **3a**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM). Spectroscopic data were according to the literature.[4]

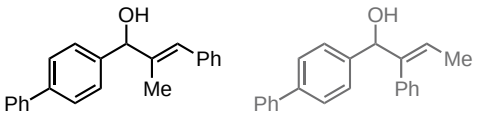


3b:**3b'**

(**3b-3b'**): pale yellow oil, 68% (0.14 mmol, 37 mg) as mixture regioisomers **3b**:**3b'** of 84:16. The general procedure was applied using **1b** (0.2 mmol, 31.2 mg) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}HNMR spectrum of the reaction crude considering the singlet (1H) at 5.64 ppm related to the product **3b**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM).

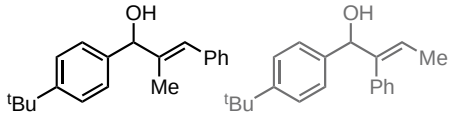
^{1}H NMR (401 MHz, $CDCl_3$) δ 7.94 (s, 1H), 7.90 – 7.81 (m, 3H), 7.55 – 7.46 (m, 3H), 7.39 – 7.32 (m, 4H), 7.28 – 7.21 (m, 1H), 6.87 (s, 1H), 5.46 (s, 1H), 1.78 (d, J = 1.0 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 139.6, 137.6, 133.4, 133.1, 129.5, 129.2 (2C), 128.34, 128.30 (2C), 128.2, 127.8, 126.8, 126.5, 126.3, 126.1, 125.3, 124.7, 79.8, 14.2.



3c:**3c'**

(**3c-3c'**): pale yellow oil, 96% (0.19 mmol, 57 mg) as mixture regioisomers **3c**:**3c'** of 90:10. The general procedure was applied using **1c** (0.2 mmol, 36 mg) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.35 ppm related to the product **3c**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM). Spectroscopic data were according to the literature.[4]

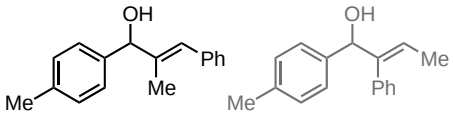


3d:**3d'**

(**3d-3d'**): pale yellow oil, 86% (0.17 mmol, 48 mg) as mixture regioisomers **3d**:**3d'** of 97:3. The general procedure was applied using freshly distilled **1d** (0.2 mmol, 32 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.26 ppm related to the product **3d**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM).

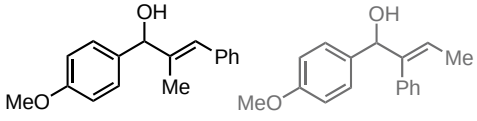
^{1}H NMR (401 MHz, $CDCl_3$) δ 7.42 – 7.19 (m, 9H), 6.80 (s, 1H), 5.26 (s, 1H), 1.76 (s, 3H), 1.33 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 150.7, 139.8, 139.2, 137.7, 129.2 (2C), 128.2 (2C), 126.6, 126.4 (2C), 125.7, 125.5 (2C), 79.4, 34.7, 31.5 (3C), 14.4.



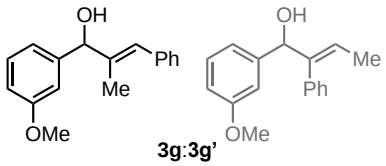
3e:**3e'**

(**3e-3e'**): pale yellow oil, 50% (0.1 mmol, 24 mg) as mixture regioisomers **3e**:**3e'** of 84:16. The general procedure was applied using freshly distilled **1e** (0.2 mmol, 24 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.25 ppm related to the product **3e**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM). Spectroscopic data were according to the literature. [4]



3f:**3f'**

(**3f-3f'**): pale yellow oil, 38% (0.07 mmol, 19 mg) as mixture regioisomers **3e**:**3e'** of 91:9. The general procedure was applied using freshly distilled **1f** (0.2 mmol, 24 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.23 ppm related to the product **3f**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM). Spectroscopic data were according to the literature. [4]

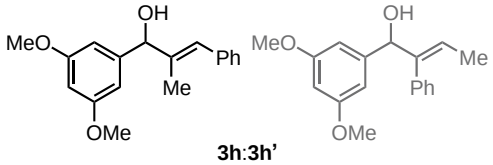


3g:**3g'**

(**3g-3g'**): pale yellow oil, 64% (0.13 mmol, 32 mg) as mixture regioisomers **3g**:**3g'** of 86:14. The general procedure was applied using freshly distilled **1g** (0.2 mmol, 24 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.26 ppm related to the product **3g**.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.37 – 7.24 (m, 6H), 7.04 – 6.99 (m, 2H), 6.86 – 6.82 (m, 1H), 6.78 (s, 1H), 5.26 (s, 1H), 3.82 (s, 3H), 1.75 (d, J = 1.1 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 159.9, 143.9, 139.6, 137.6, 129.6, 129.2 (2C), 128.3 (2C), 126.7, 126.3, 119.0, 113.2, 112.2, 79.6, 55.4, 14.1.

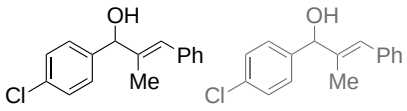


3h:**3h'**

(**3h-3h'**): pale yellow oil, 53% (0.11 mmol, 30 mg) as mixture regioisomers **3h**:**3h'** of 90:10. The general procedure was applied using **1h** (0.2 mmol, 33 mg) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.22 ppm related to the product **3h**.

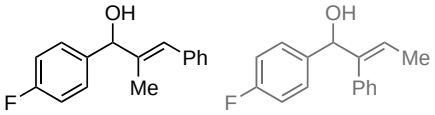
^{1}H NMR (401 MHz, $CDCl_3$)) δ 7.38 – 7.28 (m, 5H), 6.76 (s, 1H), 6.61 (d, J = 2.0 Hz, 2H), 6.40 (t, J = 2.1 Hz, 1H), 5.22 (s, 1H), 3.80 (s, 6H), 1.76 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 161.0 (2C), 144.8, 139.5, 137.6, 129.2 (2C), 128.3 (2C), 126.7, 126.4, 104.6 (2C), 99.6, 79.7, 55.5 (2C), 14.1.



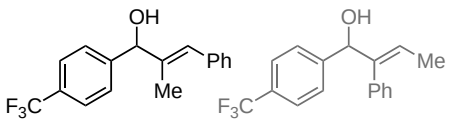
3i:**3i'**

(**3i-3i'**): pale yellow oil, 88% (0.18 mmol, 45 mg) as mixture regioisomers **3i**:**3i'** of 86:14. The general procedure was applied using **1i** (0.2 mmol, 28 mg) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.27 ppm related to the product **3i**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM). Spectroscopic data were according to the literature. [4]



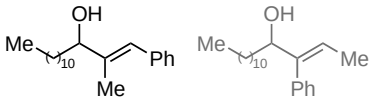
3j:**3j'**

(**3j-3j'**): pale yellow oil, 63% (0.13 mmol, 30.5 mg) as mixture regioisomers **3j**:**3j'** of 86:14. The general procedure was applied using freshly distilled **1j** (0.2 mmol, 22 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.28 ppm related to the product **3j**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM). Spectroscopic data were according to the literature. [4]



3k:**3k'**

(**3k-3k'**): pale yellow oil, 66% (0.13 mmol, 38 mg) as mixture regioisomers **3k**:**3k'** of 76:24. The general procedure was applied using freshly distilled **1k** (0.2 mmol, 28 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.37 ppm related to the product **3l**. The title compound was isolated by flash column chromatography (1:1 Hex:DCM). Spectroscopic data were according to the literature. [4]

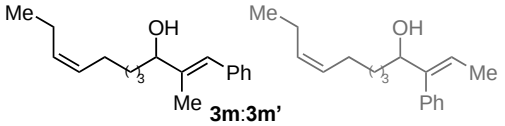


3l:**3l'**

(**3l-3l'**): pale yellow oil, 40% (0.08 mmol, 24 mg) as mixture regioisomers **3l**:**3l'** > 95:5. The general procedure for aliphatic aldehydes was applied using freshly distilled **1l** (0.2 mmol, 44 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the triplet (1H) at 4.17 ppm related to the product **3l**.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.36 – 7.27 (m, 5H), 6.49 (s, 1H), 4.17 (t, J = 6.6 Hz, 1H), 1.87 (d, J = 1.3 Hz, 3H), 1.27 (s, 20H), 0.88 (t, J = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 140.6, 137.8, 129.1 (2C), 128.2 (2C), 126.5, 125.9, 78.4, 35.3, 32.1, 29.8 (5C), 29.5, 26.0, 22.8, 14.3, 13.3.

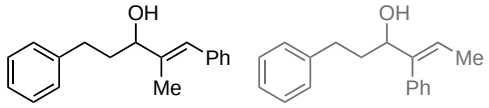


3m:**3m'**

(**3m-3m'**): pale yellow oil, 45% (0.09 mmol, 23 mg) as mixture regioisomers **3m**:**3m'** > 95:5. The general procedure for aliphatic aldehydes was applied using freshly distilled **1m** (0.2 mmol, 33 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the triplet (1H) at 4.17 ppm related to the product **3m**.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.36 – 7.27 (m, 5H), 6.49 (s, 1H), 5.41 – 5.29 (m, 2H), 4.17 (t, J = 6.6 Hz, 1H), 2.08 – 2.01 (m, 6H), 1.87 (d, J = 1.2 Hz, 3H), 1.68 – 1.62 (m, 2H), 1.45 – 1.36 (m, 2H), 0.95 (t, J = 7.5 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 131.9, 129.1 (2C), 128.3 (2C), 126.6, 125.9, 78.3, 35.1, 29.8, 27.2, 25.6, 22.0 (3C), 20.7, 14.5, 13.3.

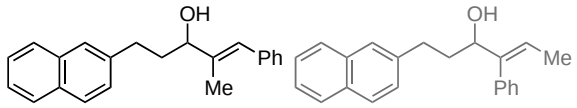


3n:**3n'**

(**3n-3n'**): pale yellow oil, 60% (0.12 mmol, 30 mg) as mixture regioisomers **3n**:**3n'** > 95:5. The general procedure for aliphatic aldehydes was applied using freshly distilled **1n** (0.2 mmol, 26 µl) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the triplet (1H) at 4.21 ppm related to the product **3n.**

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.34 – 7.21 (m, 10H), 6.51 (s, 1H), 4.21 (t, J = 6.5 Hz, 1H), 2.79 – 2.66 (m, 2H), 2.03 – 1.95 (m, 2H), 1.89 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 142.0, 140.2, 137.6, 129.1 (2C), 128.6 (2C), 128.5 (2C), 128.3 (2C), 126.7, 126.2, 126.0, 77.6, 36.8, 32.2, 13.4.

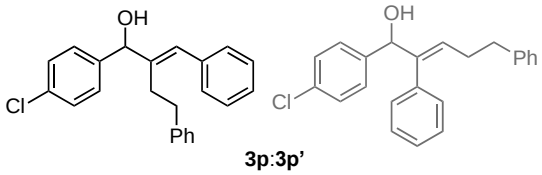


3o:**3o'**

(**3o-3o'**): pale yellow oil, 30% (0.06 mmol, 18 mg) as mixture regioisomers **3o**:**3o'** > 95:5. The general procedure for aliphatic aldehydes was applied using freshly distilled **1o** (0.2 mmol, 37 mg) and **2a** (0.6 mmol, 70 mg, 76 µl). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the triplet (1H) at 4.24 ppm related to the product **3o**.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.83 – 7.76 (m, 3H), 7.67 (s, 1H), 7.50 – 7.19 (m, 8H), 6.52 (s, 1H), 4.24 (td, J = 6.5, 2.6 Hz, 1H), 2.97 – 2.84 (m, 2H), 2.12 – 2.03 (m, 2H), 1.90 (d, J = 1.3 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 140.2, 139.5, 137.6, 133.8, 132.2, 129.1 (2C), 128.3 (2C), 128.1, 127.8, 127.6, 127.5, 126.7, 126.6, 126.3, 126.1, 125.3, 77.6, 36.6, 32.4, 13.4.

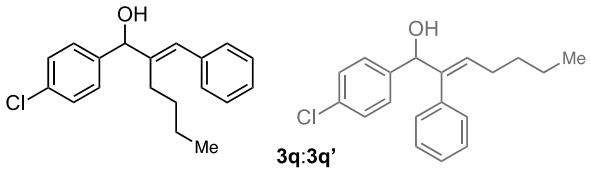


3p:**3p'**

(**3p-3p'**): pale yellow oil, 54% (0.11 mmol, 37 mg) as mixture regioisomers **3p**:**3p'** of 90:10. The general procedure was applied using **1i** (0.2 mmol, 28 mg) and **2b** (0.6 mmol, 144 mg). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.29 ppm related to the product **3p**. The title compound was isolated by flash column chromatography. Two consecutive purification were required for the isolation of the product. The first one, 1:1 Hex:DCM to remove the excess of pyridine deriving from the oxidation of the Hantzsch'ester; the second, 9:1 Hex:AcOEt to remove the traces of photocatalyst.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.42 – 7.32 (m, 8H), 7.30 – 7.20 (m, 4H), 7.03 (d, J = 7.1 Hz, 2H), 6.81 (s, 1H), 5.29 (s, 1H), 2.69 – 2.61 (m, 1H), 2.60 – 2.53 (m, 2H), 2.38 (t, J = 9.5 Hz, 1H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 143.1, 141.8, 140.7, 137.3, 133.6, 128.7 (4C), 128.5 (4C), 128.30 (2C), 128.26 (2C), 127.7, 127.1, 126.1, 77.9, 35.0, 30.4.

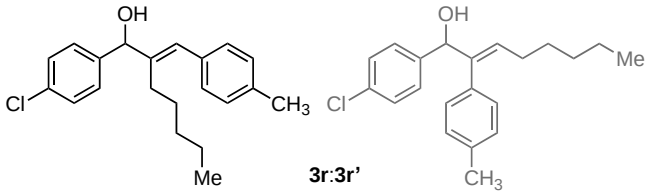


3q:**3q'**

(**3q-3q'**): pale yellow oil, 80% (0.16 mmol, 50 mg) as mixture regioisomers **3q**:**3q'** of 90:10. The general procedure was applied using **1i** (0.2 mmol, 28 mg) and **2c** (0.6 mmol, 103 mg). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.31 ppm related to the product **3q**. The title compound was isolated by flash column chromatography. Two consecutive purification were required for the isolation of the product. The first one, 1:1 Hex:DCM to remove the excess of pyridine deriving from the oxidation of the Hantzsch'ester; the second, 9:1 Hex:DCM to remove the traces of photocatalyst.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.41 – 7.24 (m, 9H), 6.74 (s, 1H), 5.31 (s, 1H), 2.27 (ddd, J = 13.8, 10.6, 5.7 Hz, 1H), 2.00 (ddd, J = 13.9, 10.7, 5.2 Hz, 1H), 1.42 – 1.29 (m, 2H), 1.28 – 1.20 (m, 2H), 0.82 (t, J = 7.2 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$)) δ 144.2, 141.0, 137.5, 133.6, 128.8 (2C), 128.7 (2C), 128.4 (2C), 128.3 (2C), 126.8, 126.5, 77.5, 31.2, 28.4, 23.1, 13.9.

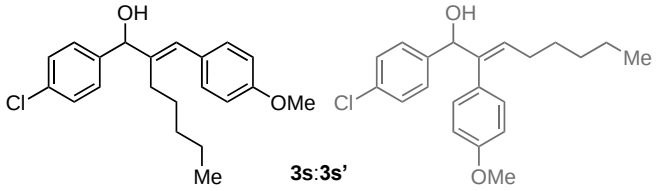


3r:**3r'**

(**3r-3r'**): pale yellow oil, 41% (0.08 mmol, 27 mg) as mixture regioisomers **3r**:**3r'** > 95:5. The general procedure was applied using **1i** (0.2 mmol, 28 mg) and **2d** (0.6 mmol, 111 mg). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.30 ppm related to the product **3r**. The title compound was isolated by flash column chromatography. Two consecutive purification were required for the isolation of the product. The first one, 1:1 Hex:DCM to remove the excess of pyridine deriving from the oxidation of the Hantzsch'ester; the second, 9:1 Hex:DCM to remove the traces of photocatalyst.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.41 – 7.29 (m, 4H), 7.22 – 7.11 (m, 4H), 6.68 (s, 1H), 5.30 (s, 1H), 2.35 (s, 3H), 2.23 (ddd, J = 13.6, 10.9, 5.5 Hz, 1H), 1.99 (ddd, J = 13.8, 11.0, 5.3 Hz, 1H), 1.38 – 1.30 (m, 2H), 1.24 – 1.17 (m, 4H), 0.82 (t, J = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 143.5, 141.0, 136.6, 134.5, 133.5, 129.1 (2C), 128.74 (2C), 128.66 (2C), 128.3 (2C), 126.5, 77.8, 32.3, 28.71, 28.66, 22.4, 21.3, 14.1.

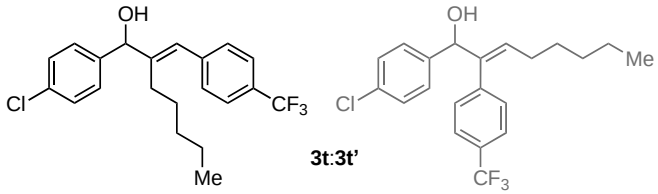


3s:**3s'**

(**3s-3s'**): pale yellow oil, 75% (0.15 mmol, 52 mg) as mixture regioisomers **3s**:**3s'** of 87:13. The general procedure was applied using **1i** (0.2 mmol, 28 mg) and **2e** (0.6 mmol, 121 mg). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.29 ppm related to the product **3s**. The title compound was isolated by flash column chromatography. Two consecutive purification were required for the isolation of the product. The first one, 1:1 Hex:DCM to remove the excess of pyridine deriving from the oxidation of the Hantzsch'ester; the second, 9:1 Hex:DCM to remove the traces of photocatalyst.

^{1}H NMR (401 MHz, $CDCl_3$) δ 7.40 – 7.29 (m, 4H), 7.25 – 7.21 (m, 2H), 6.92 – 6.84 (m, 2H), 6.65 (s, 1H), 5.29 (s, 1H), 3.82 (s, 3H), 2.23 (ddd, J = 13.8, 10.9, 5.5 Hz, 1H), 2.01 (ddd, J = 13.6, 10.9, 5.2 Hz, 1H), 1.42 – 1.31 (m, 2H), 1.24 – 1.17 (m, 4H), 0.83 (t, J = 6.5 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 158.5, 142.7, 141.1, 133.4, 130.03 (2C), 129.97, 128.6 (2C), 128.3 (2C), 126.2, 113.9 (2C), 77.9, 55.4, 32.3, 28.7, 28.6, 22.4, 14.1.

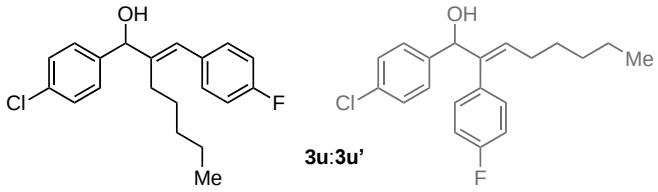


3t:**3t'**

(**3t-3t'**): pale yellow oil, 38% (0.08 mmol, 29 mg) as mixture regioisomers **3t**:**3t'** > 95:5. The general procedure was applied using **1i** (0.2 mmol, 28 mg) and **2e** (0.6 mmol, 144 mg). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.31 ppm related to the product **3t**. The title compound was isolated by flash column chromatography. Two consecutive purification were required for the isolation of the product. The first one, 1:1 Hex:DCM to remove the excess of pyridine deriving from the oxidation of the Hantzsch'ester; the second, 9:1 Hex:DCM to remove the traces of photocatalyst.

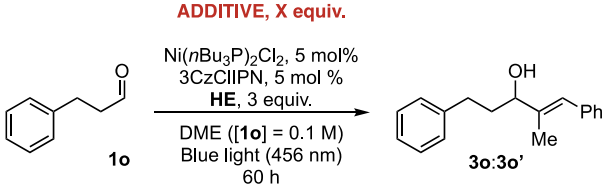
^{1}H NMR (401 MHz, $CDCl_3$) δ 7.59 (d, J = 8.2 Hz, 2H), 7.40 – 7.32 (m, 6H), 6.78 (s, 1H), 5.31 (s, 1H), 2.24 (ddd, J = 13.8, 9.7, 6.9 Hz, 1H), 1.95 (ddd, J = 13.8, 9.3, 6.9 Hz, 2H), 1.40 – 1.31 (m, 2H), 1.24 – 1.15 (m, 4H), 0.81 (t, J = 6.7 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 146.3, 141.3, 140.6, 133.9, 129.8 (q, J = 32.3 Hz), 129.0 (2C), 128.9 (2C), 128.4 (2C), 125.3 (q, J = 3.7 Hz, 2C), 124.8 124.4 (q, J = 271.8 Hz), 77.1, 32.1, 28.7, 28.6, 22.4, 14.0.
^{19}F NMR (377 MHz, $CDCl_3$) δ -62.49.



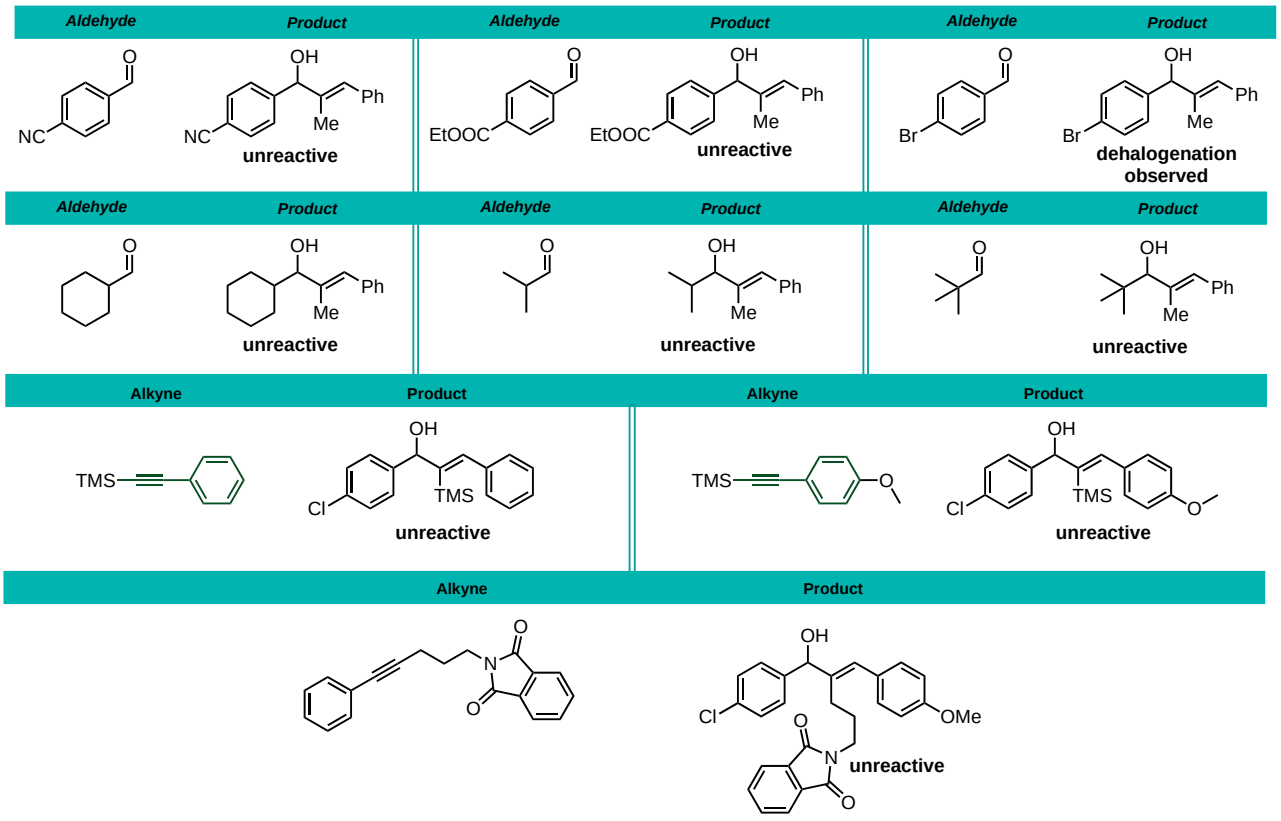
(**3u**-**3u'**): pale yellow oil, 36% (0.07 mmol, 24 mg) as mixture regioisomers **3u**:**3u'**:80:20. The general procedure was applied using **1i** (0.2 mmol, 28 mg) and **2g** (0.6 mmol, 114 mg). The regioisomeric ratio was calculated considering the ^{1}H NMR spectrum of the reaction crude considering the singlet (1H) at 5.27 ppm related to the product **3u**. The title compound was isolated by flash column chromatography. Two consecutive purification were required for the isolation of the product. The first one, 1:1 Hex:DCM to remove the excess of pyridine deriving from the oxidation of the Hantzsch's ester; the second, 9:1 Hex:DCM to remove the traces of photocatalyst.
^{1}H NMR (401 MHz, $CDCl_3$) δ 7.36–7.29 (m, *J* = 5.9 Hz), 7.25 – 7.19 (m, 3H), 7.16–11 (m, 1H), 7.06–6.99 (m, 2H), 6.95 – 6.79 (m, 2H), 6.67 (s, 1H), 5.29–5.27 (m, 1H), 2.19 (ddd, *J* = 13.8, 10.6, 5.9 Hz, 1H), 2.04 – 1.82 (m, 3H), 1.28 – 1.11 (m, 8H), 0.85 – 0.79 (m, 4H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 160.4 (d, *J* = 246 Hz, 1C), 144.04 (d, *J* = 1.4 Hz, 1C), 140.73, 133.48, 130.49, 130.15 (d, *J* = 8 Hz, 1C), 128.57, 128.15, 125.17, 115.01 (d, *J* = 21 Hz, 1C), 77.26, 31.99, 28.41, 28.35, 22.18, 13.88.
^{19}F NMR (377 MHz, $CDCl_3$) δ -115.54 (ddd, *J* = 14.2, 8.7, 5.3 Hz).

Table S1. Optimization for coupling of aliphatic aldehydes.



Entry	Additive	Yield %
1	none	Traces
2	$MgBr_2•Et_2O$, 2 equiv.	66
3	$Sc(OTf)_3$, 20 mol%	39
4	TesCl, 1.5 equiv.	49
5	LiBr, 2 equiv.	52
6	NaI, 2 equiv.	Traces
7	$Mg(OAc)_2$, 2 equiv.	Traces
8	$Mg(OAc)_2$, 2 equiv.	Traces

Unreactive substrates



Photophysical analyses

All the photophysical analyses were carried out in freshly distilled 1,2-dimethoxyethane or CH_3CN at 298 K, unless otherwise specified. UV–vis absorption spectra were recorded with a PerkinElmer λ40 spectrophotometer using quartz cells with path length of 1.0 cm. Luminescence spectra were performed with a PerkinElmer LS-50 or an Edinburgh FS5 spectrofluorometer equipped with a Hamamatsu Photomultiplier R928P and are not corrected by the instrument response unless otherwise indicated. Lifetimes shorter than 10 μs were measured by an Edinburgh FLS920 spectrofluorometer by time-correlated single-photon counting (TCSPC) technique. Quantum yields are determined with the method of Demas and Crosby[5] using quinine sulfate in air-equilibrated aqueous H_2SO_4 (0.5 M) as a standard (Φ= 0.55). Experiments in absence of oxygen were carried out in custom-made sealed quartz cuvettes, upon degassing with repeated pump-freeze-thaw cycles in high vacuum. The estimated experimental errors are 2 nm on the band maximum, 5% on the molar absorption coefficient and luminescence lifetime, 10% on emission quantum yields.

Figure S3. Comparison between absorption and corrected emission spectra of solutions of 3CzClIPN in DME at r.t. λ_{ex} = 360 nm.

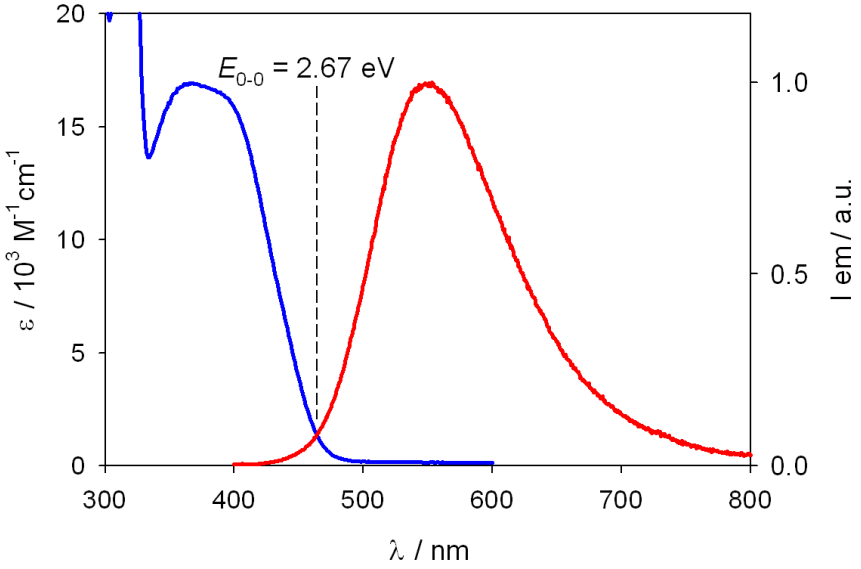


Figure S4. Emission decays recorded on air-equilibrated (blue dots) and deoxygenated (green dots) solutions of 3CzClIPN in DME at r.t. The corresponding double exponential fitting are displayed as the red and orange lines, respectively (only the short decay component is reported). The instrument response function (IRF) is also shown (black dots). λ_{ex} = 405 nm.

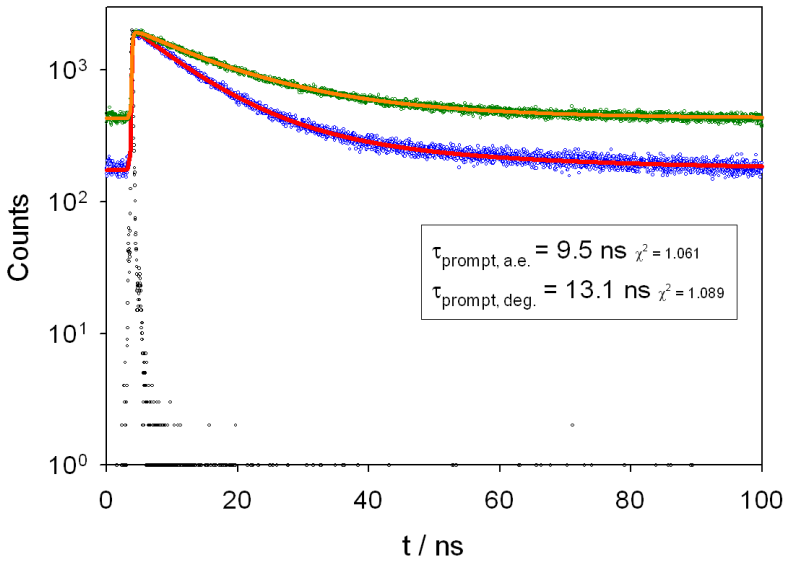


Figure S5. Comparison between emission spectra of solutions of 3CzClIPN in CH_2Cl_2:CH_3OH (1:1 v/v) rigid matrix at 77 K: fluorescence (blue line); phosphorescence (green line: gate = 1 ms, delay = 50 μs; red line: gate 1 ms, delay 0 μs). The absorption spectrum in DME is also shown for comparison as the black dashed line. λ_{ex} = 350-390 nm.

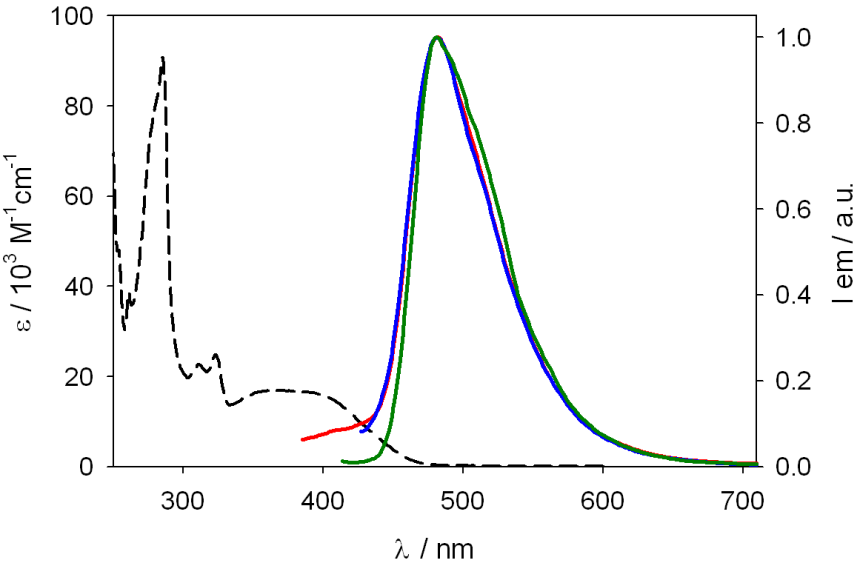


Figure S6. A: delayed fluorescence decays of 3CzClIPN in degassed DME at r.t., obtained upon addition of **HE** (up to 0.52 mM). λ_{em}= 545 nm; λ_{ex}= 405 nm; **B**: Stern-Volmer diagram relative to the fluorescence lifetimes shown in A.

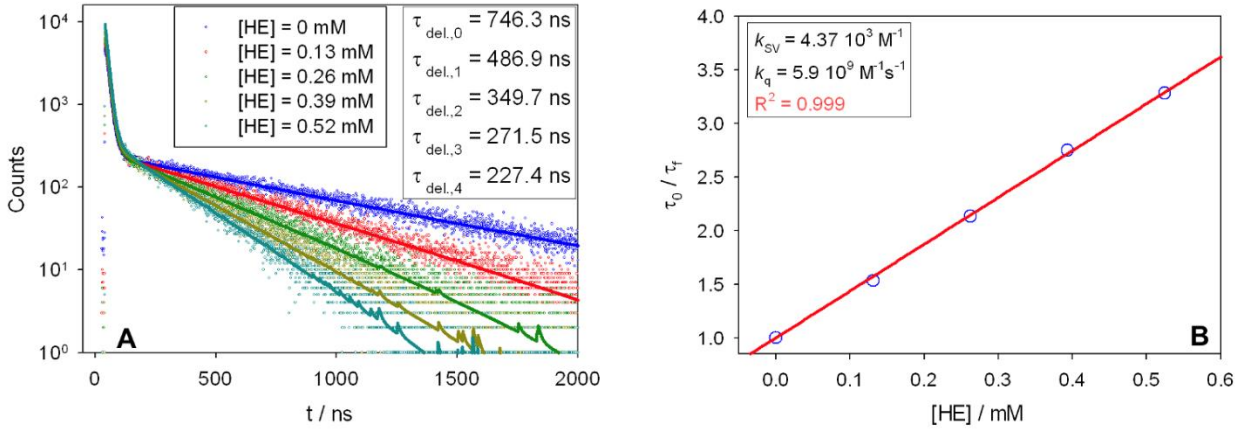


Figure S7. A: absorption spectra of solutions of 3CzClIPN in degassed DME at r.t. (ca. 41 μM, blue line) obtained upon addition of **HE** (0.52 mM, red line); **B**: fluorescence intensities of 3CzClIPN obtained from the same solutions at λ_{ex}= 440 nm; **C**: Stern-Volmer diagram relative to the fluorescence intensities shown in **B**. Note: k_q has been estimated calculated from emission intensities changes, without taking into account the contribution of the prompt fluorescence to the total emission intensity detected.

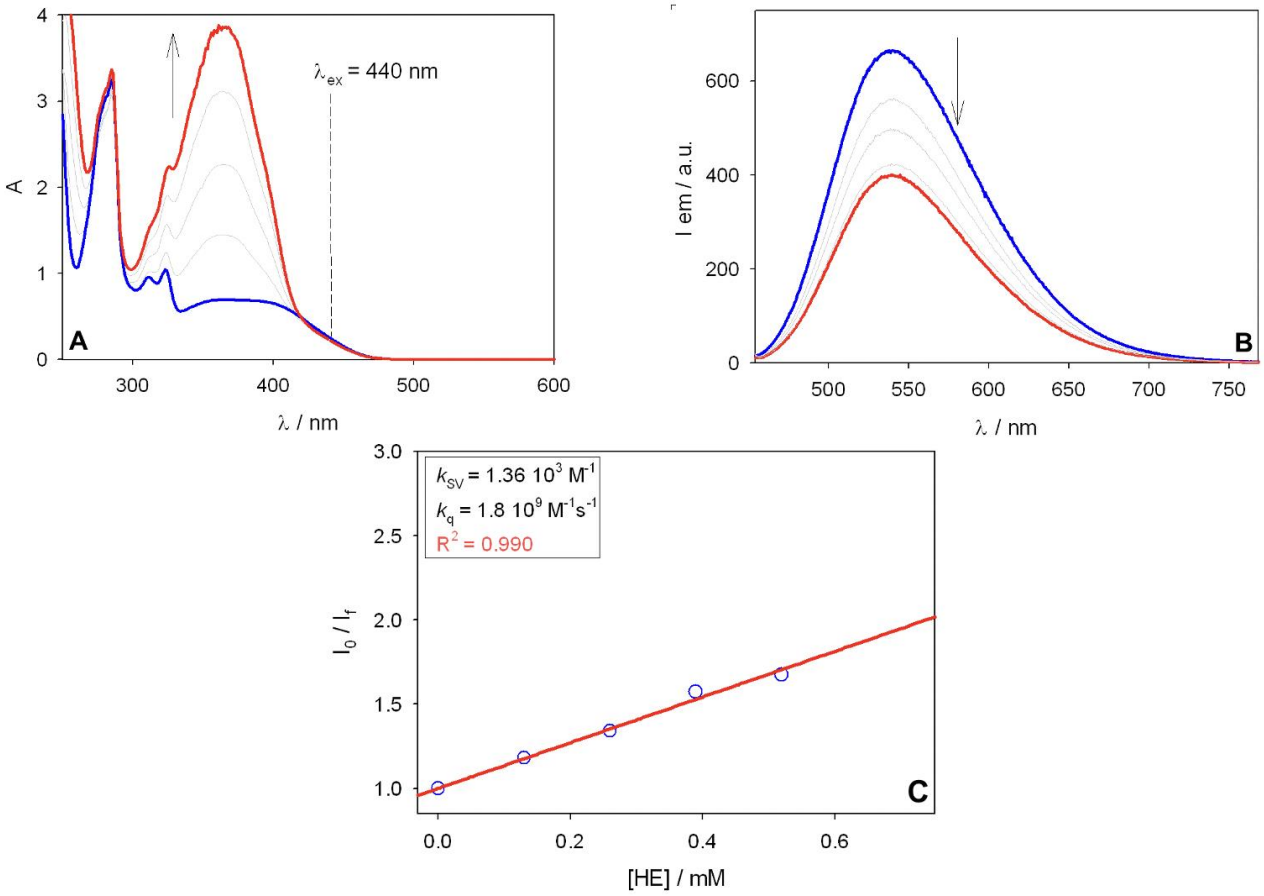


Figure S8. Comparison between prompt fluorescence decays of pure 3CzClIPN in degassed DME at r.t. (blue dots) and that obtained upon addition of **HE** (0.52 mM, red dots). λ_{em}= 545 nm; λ_{ex}= 405 nm. Lifetimes for [HE] = 0.52 mM are obtained with a triexponential function (χ^2 = 1.171; τ_2 = 0.15 ns, τ_3 = 24.7 ns).

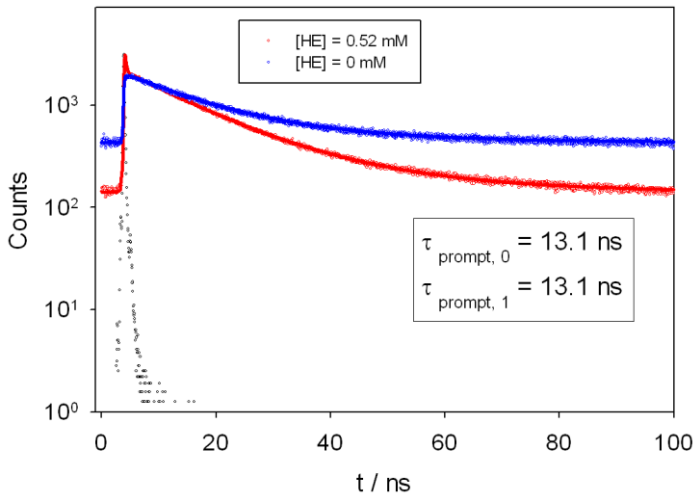


Figure S9 A: delayed fluorescence decays of 3CzClIPN in degassed CH_3CN at r.t., obtained upon addition of $[NiCl_2(nBu_3P)_2]$ (up to 0.52 mM). λ_{em}= 545 nm; λ_{ex}= 405 nm; **B**: Stern-Volmer diagram relative to the fluorescence lifetimes shown in **A**.

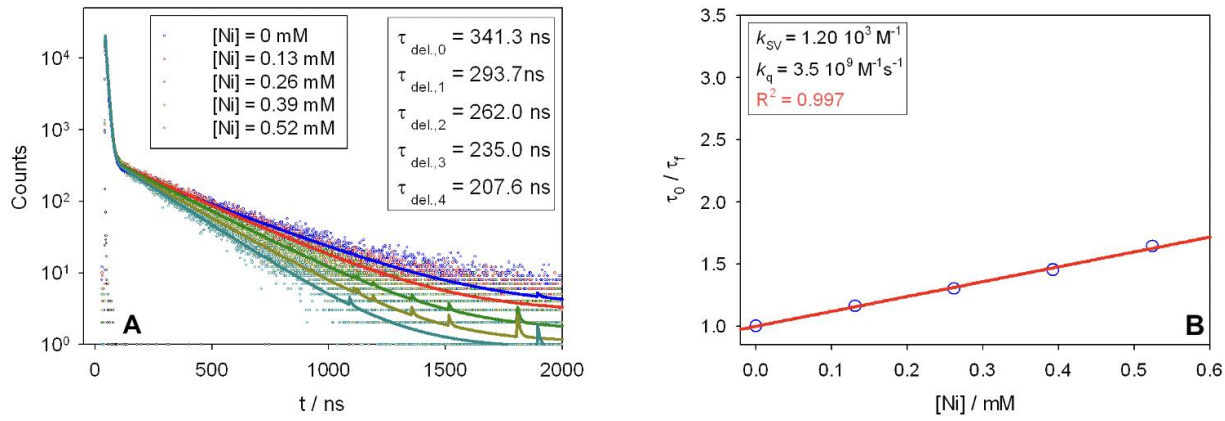


Figure S10 A: absorption spectra of solutions of 3CzClIPN in air-equilibrated CH_3CN at r.t. (ca. 37 µM, blue line) obtained upon addition of $[NiCl_2(nBu_3P)_2]$ (up to 0.52 mM, red line); **B**: delayed fluorescence decays of 3CzClIPN obtained from the same solutions at λ_{ex}= 440 nm. **C**: Stern-Volmer diagram relative to the fluorescence lifetimes shown in **B**.

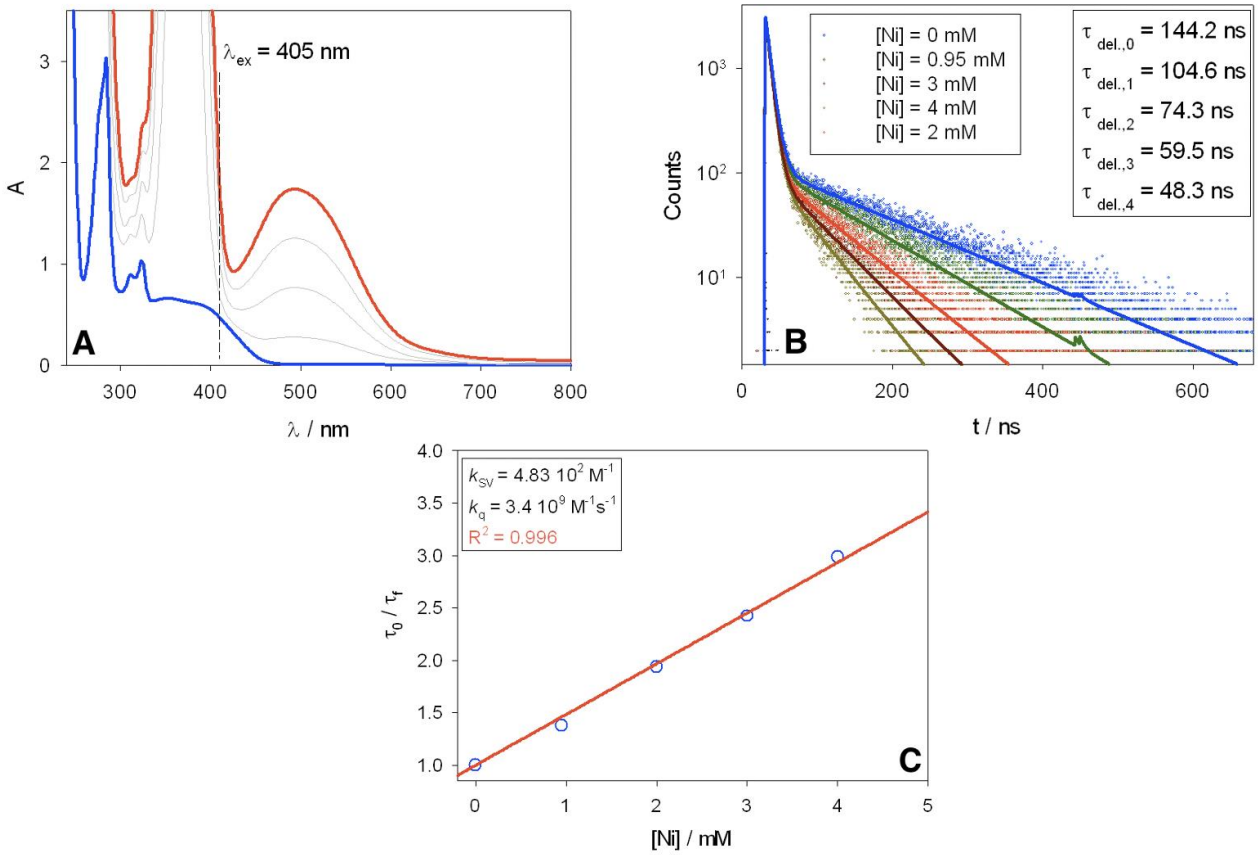


Figure S11. Comparison between prompt fluorescence decays of pure 3CzClIPN in degassed CH_3CN at r.t. (blue dots) and that obtained upon addition of $[NiCl_2(nBu_3P)_2]$ (0.52 mM, red dots). λ_{em} = 545 nm; λ_{ex}= 405 nm. Lifetimes are obtained with biexponential functions (χ^2_0 = 1.194; χ^2_1 = 1.663).

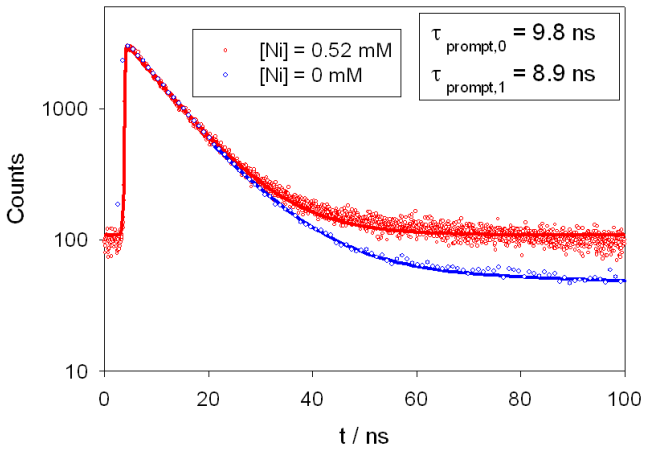


Figure S12. A: absorption spectra of solutions of 3CzClIPN in degassed DME at r.t. (ca. 41 µM, blue line) obtained upon addition of benzaldehyde (1a) (10 mM, red line); **B**: fluorescence intensities of 3CzClIPN obtained from the same solutions at λ_{ex}= 440 nm; **C**: Stern-Volmer diagram relative to the fluorescence intensities shown in **B**; estimated $k_q \approx 10^6$ $M^{-1}s^{-1}$.

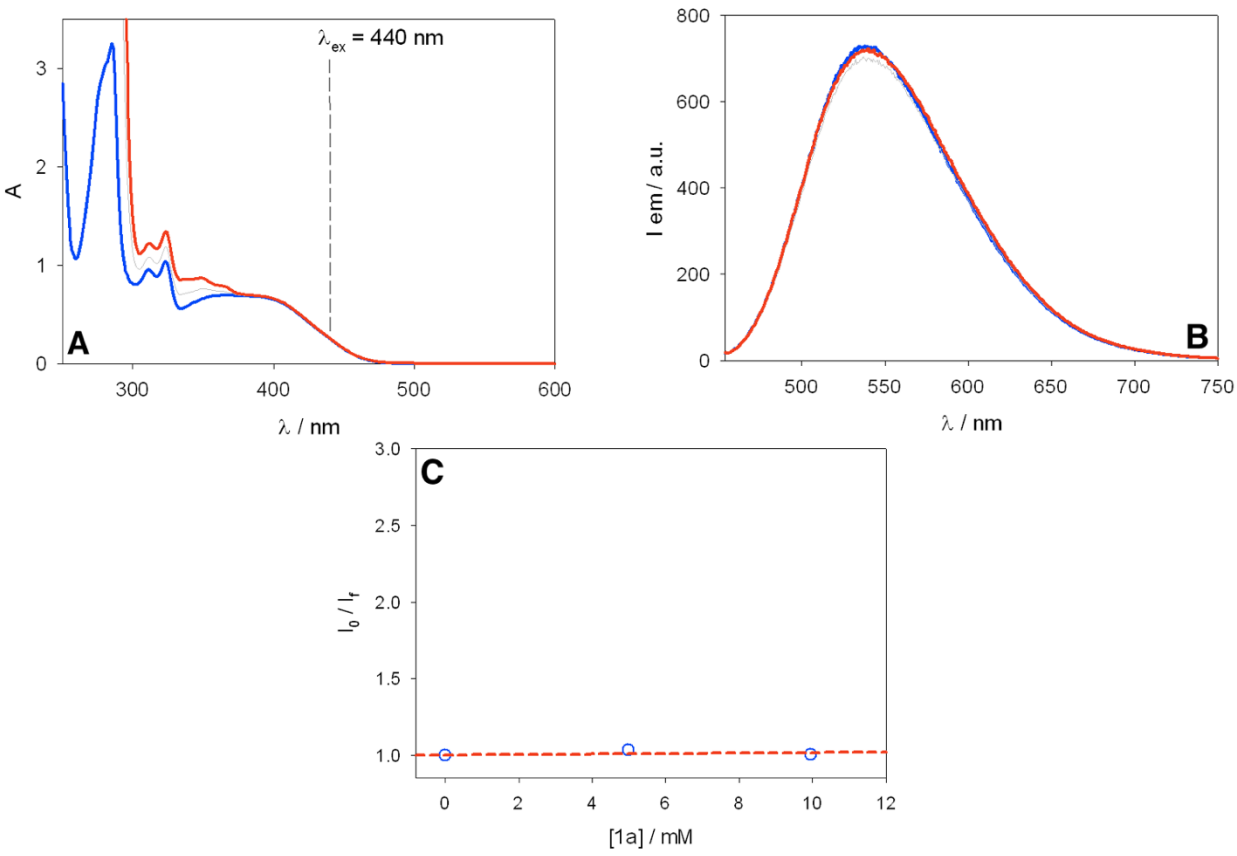


Figure S13. A: absorption spectra of solutions of 3CzClIPN in degassed DME at r.t. (ca. 44 μM, blue line) obtained upon addition of alkyne **2a** (48 mM, red line); **B**: fluorescence intensities of 3CzClIPN obtained from the same solutions at λ_{ex}= 456 nm. C: Stern-Volmer diagram relative to the fluorescence intensities shown in **B**; estimated $k_q \approx 10^6$ $M^{-1}s^{-1}$.

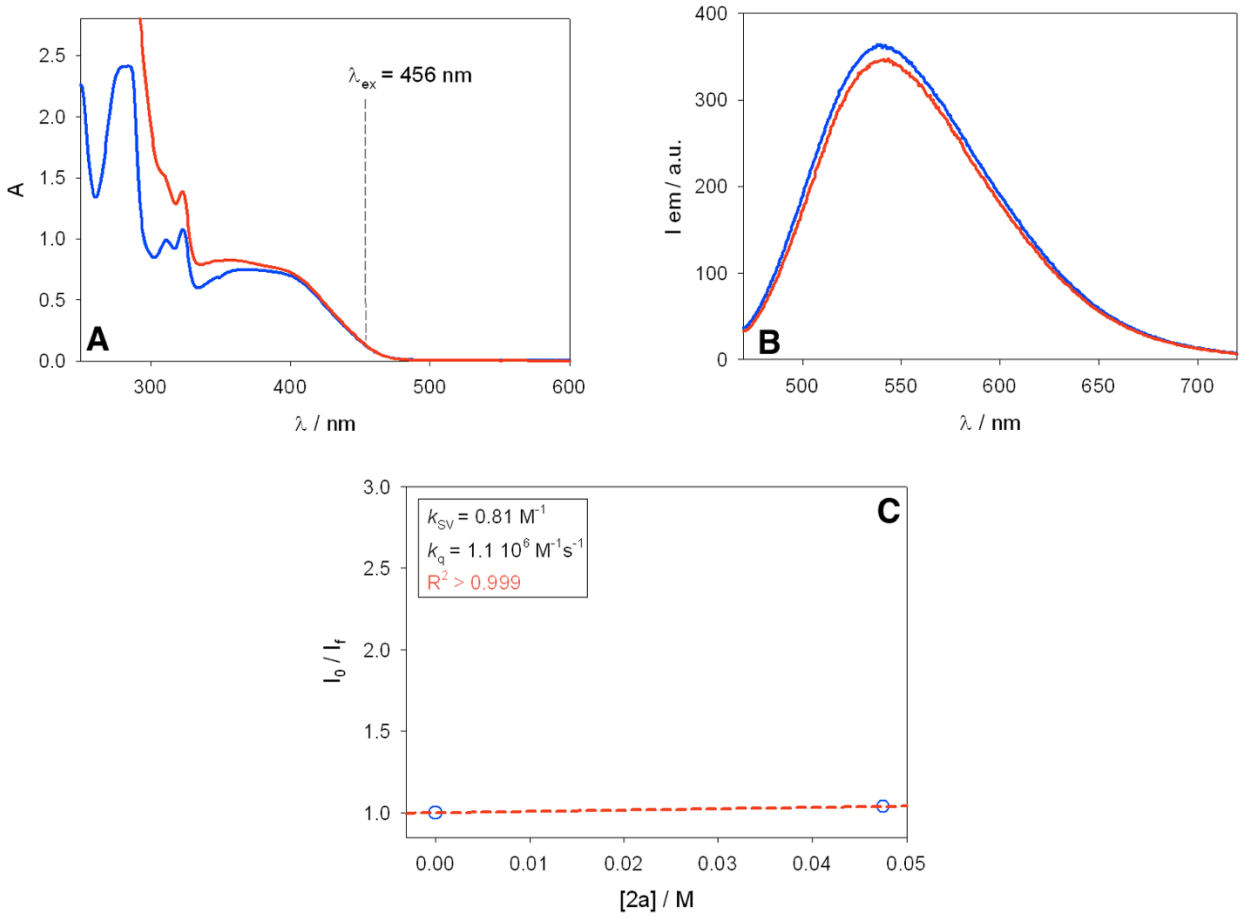


Figure S14. Absorption spectrum of $[NiCl_2(n Bu_3P)_2]$ in CH_3CN at r.t..

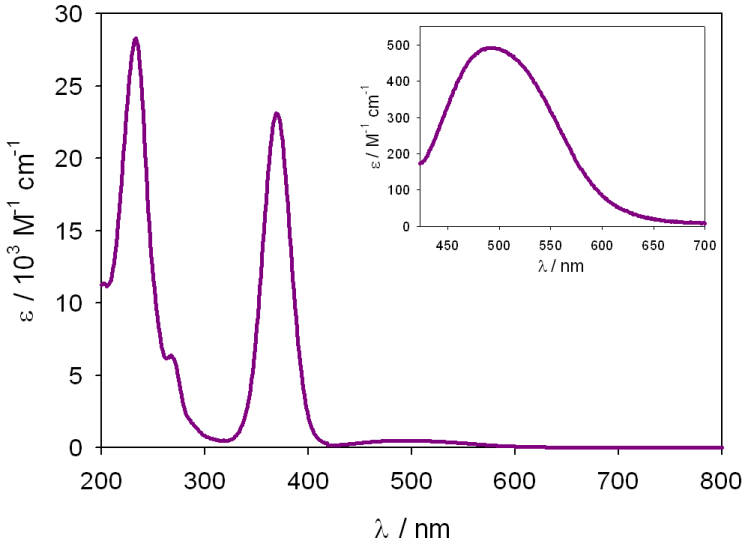
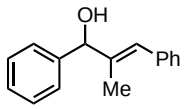


Table S2. Quenching efficiencies of the reactants in the reaction mixture.

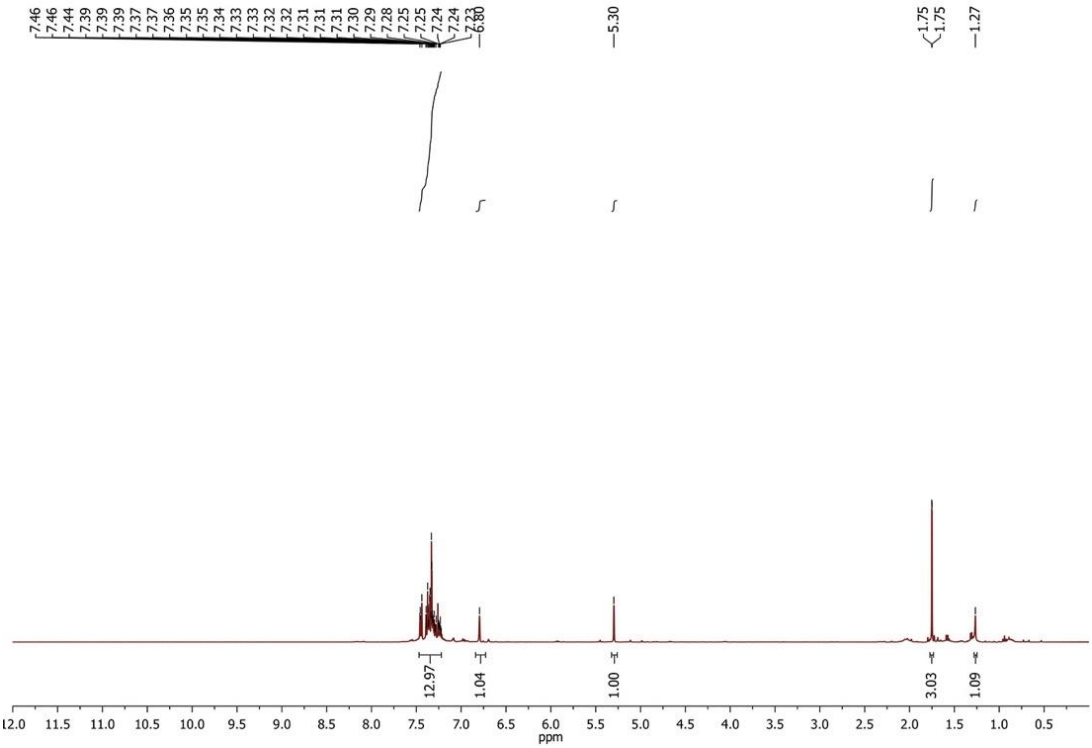
Quencher	k_q / $M^{-1}cm^{-1}$	**[quencher] / mM**	η_q / %
HE	5.9×10^9	300	ca. 99
$[NiCl_2(n Bu_3P)_2]$	3.5×10^9	5	< 1
1a	$\approx 10^6$	100	*negligible*
2a	$\approx 10^6$	300	*negligible*

Copies of NMR spectra

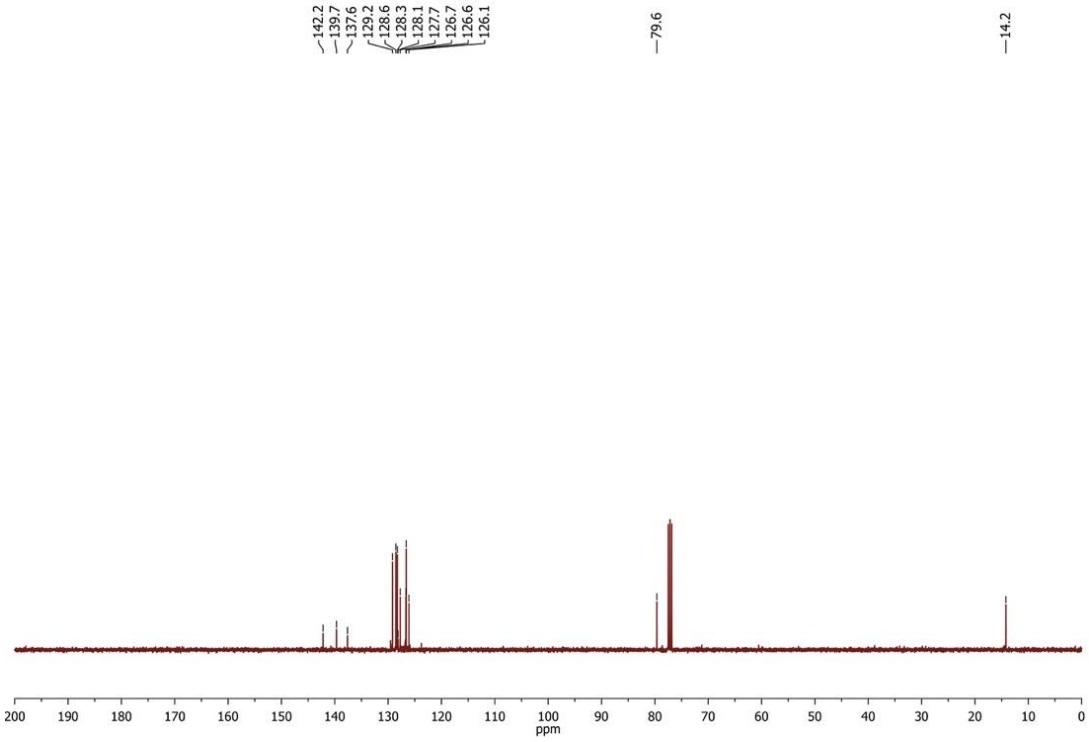


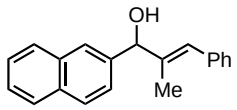
3a:**3a'**

^{1}H NMR (401 MHz, $CDCl_3$)



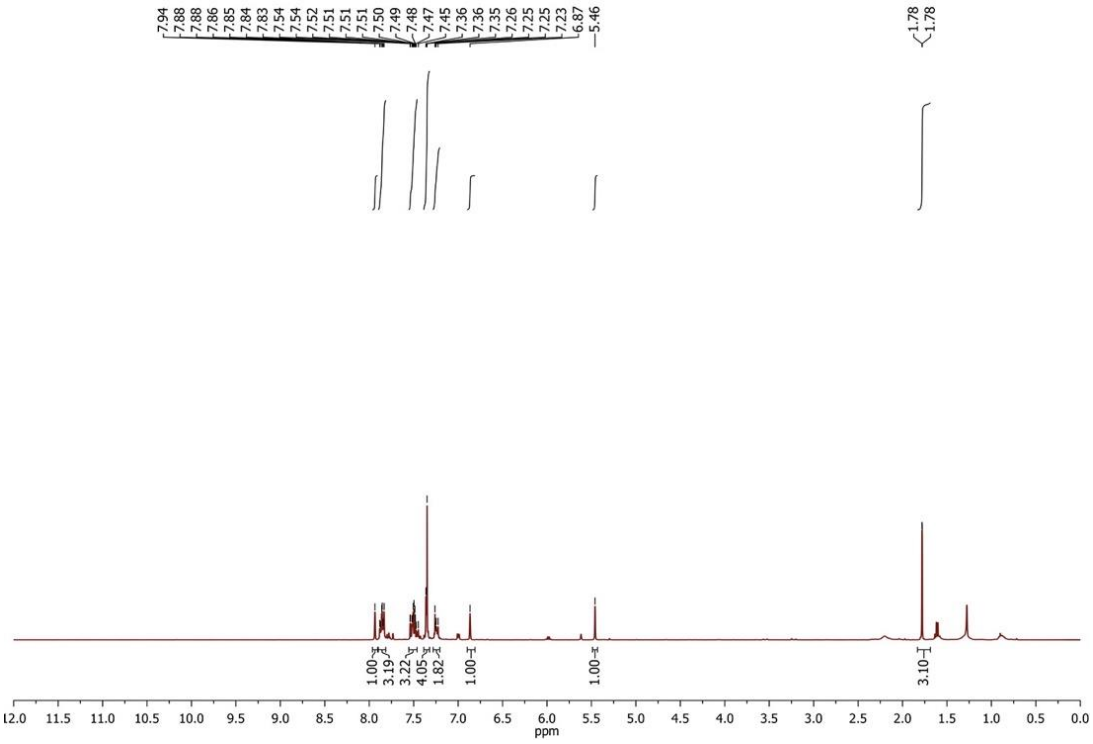
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)


142.2
139.7
137.6
129.2
128.6
128.3
128.1
127.7
126.7
126.6
126.1
79.6
14.2
200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0
ppm

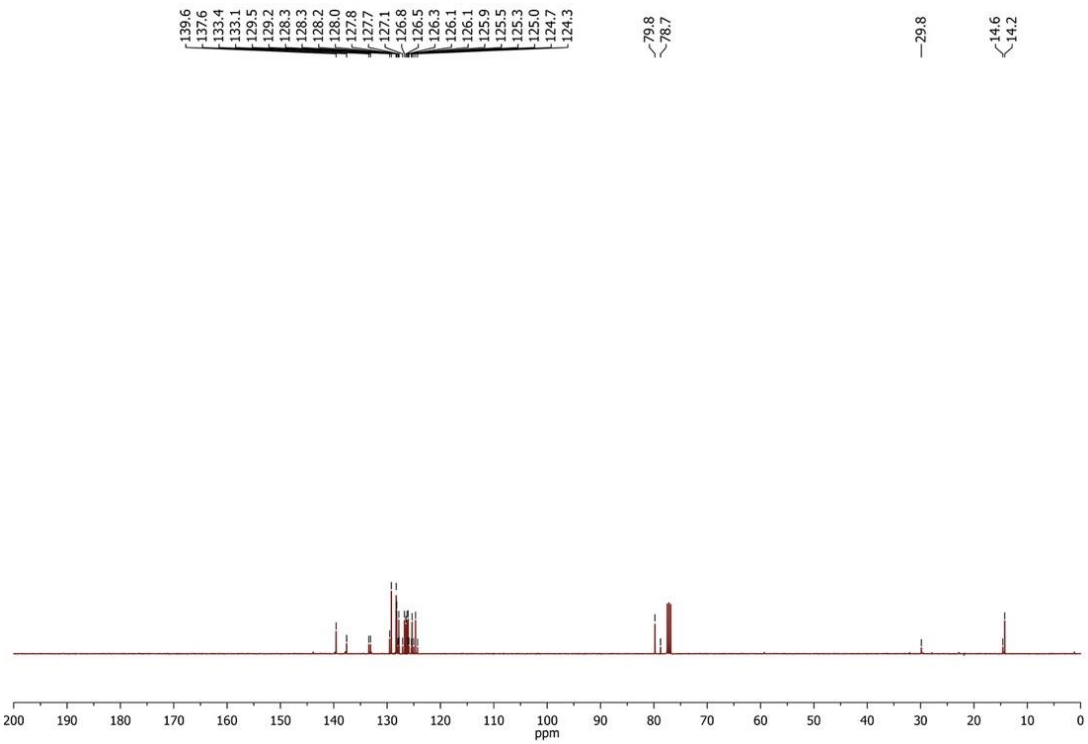


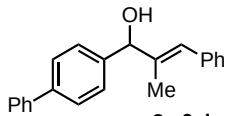
3b:**3b'**

^{1}H NMR (401 MHz, $CDCl_3$)



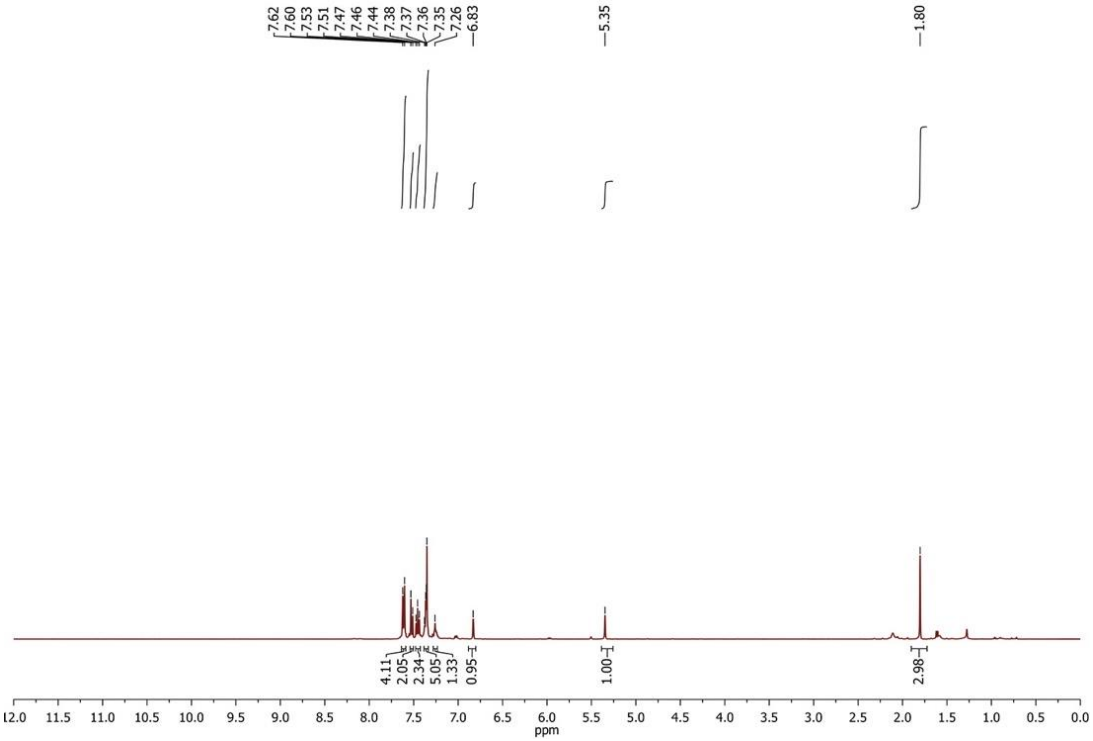
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



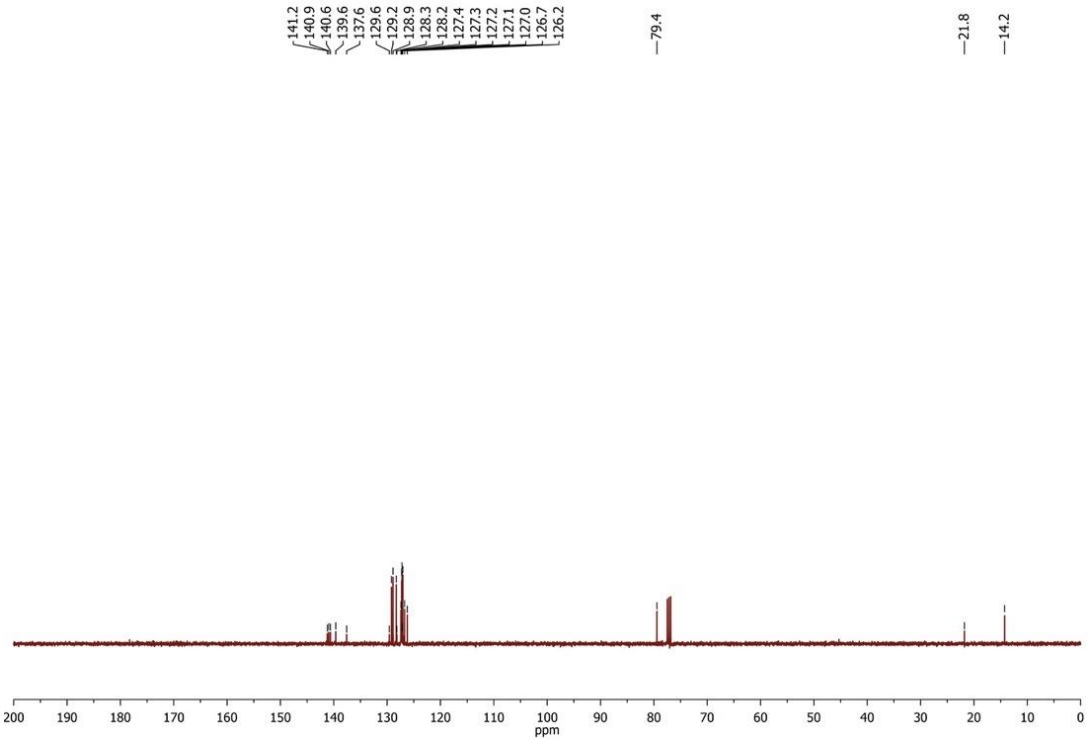


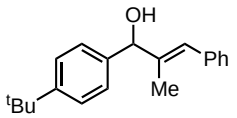
3c:**3c'**

^{1}H NMR (401 MHz, $CDCl_3$)



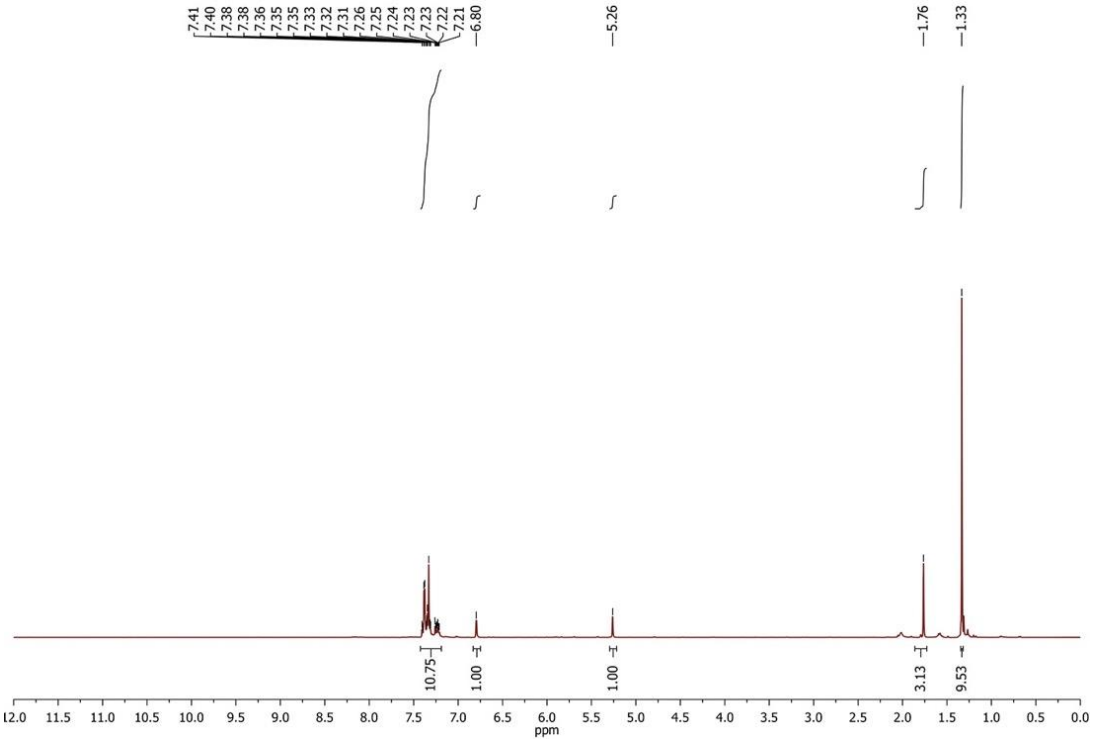
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



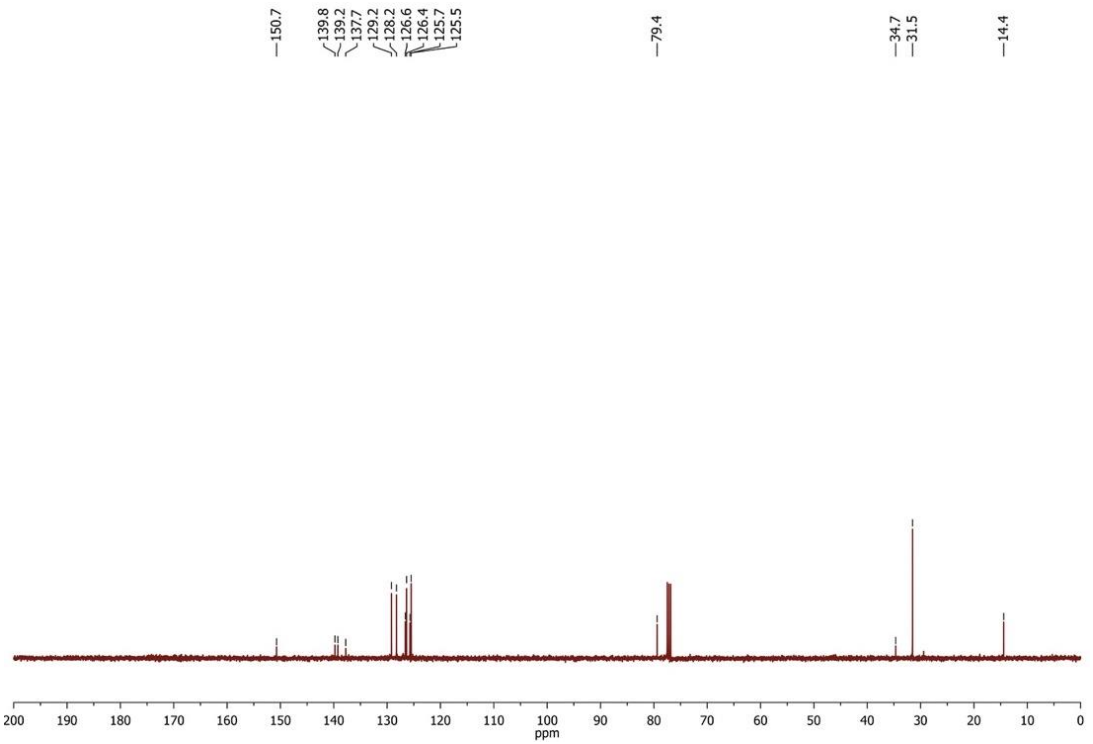


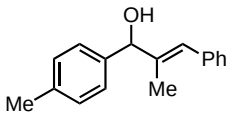
3d:**3d'**

^{1}H NMR (401 MHz, $CDCl_3$)



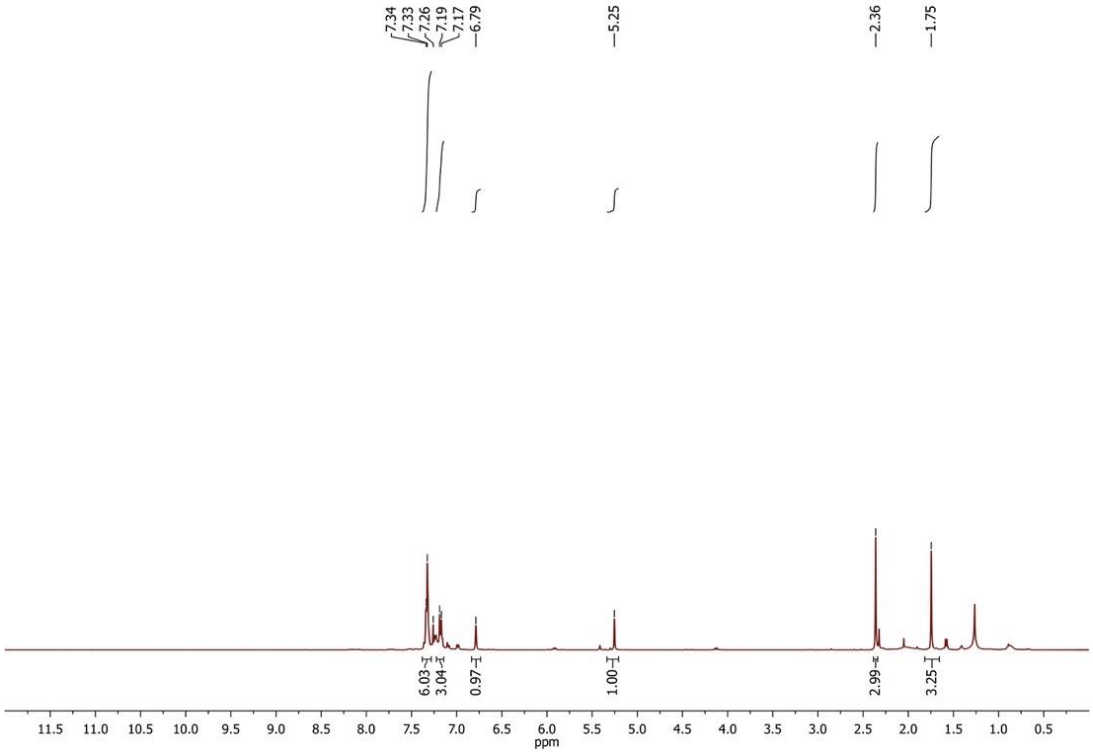
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



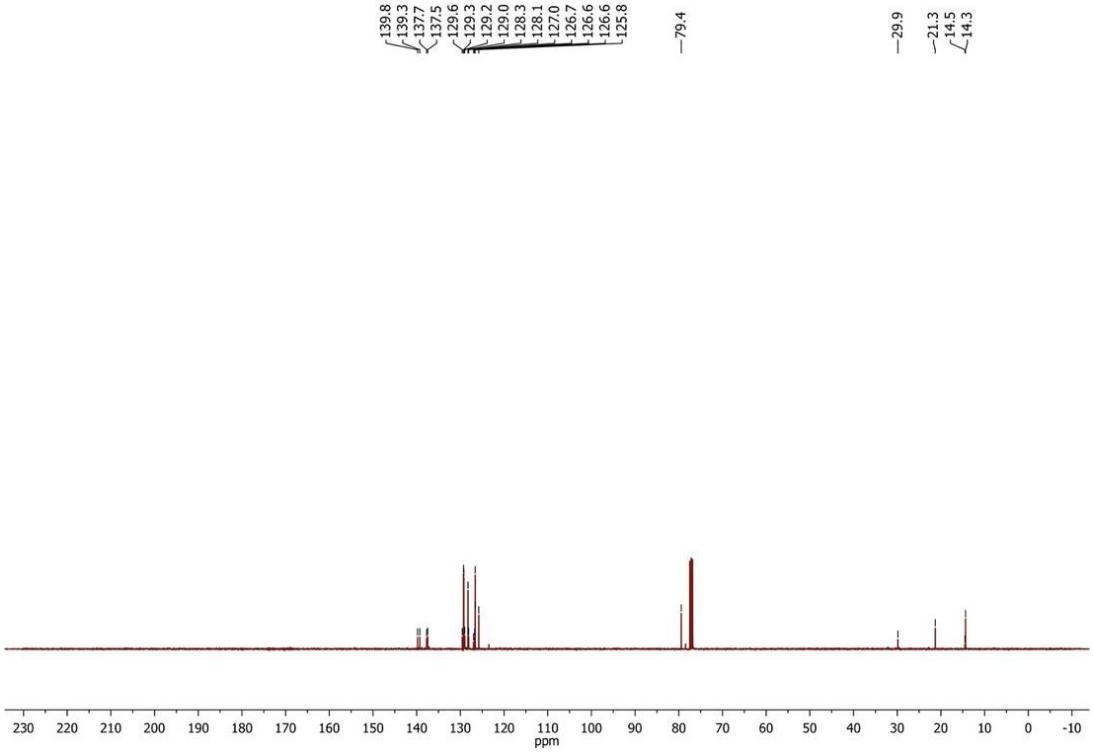


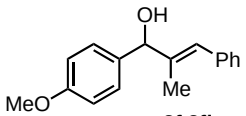
3e:**3e'**

^{1}H NMR (401 MHz, $CDCl_3$)



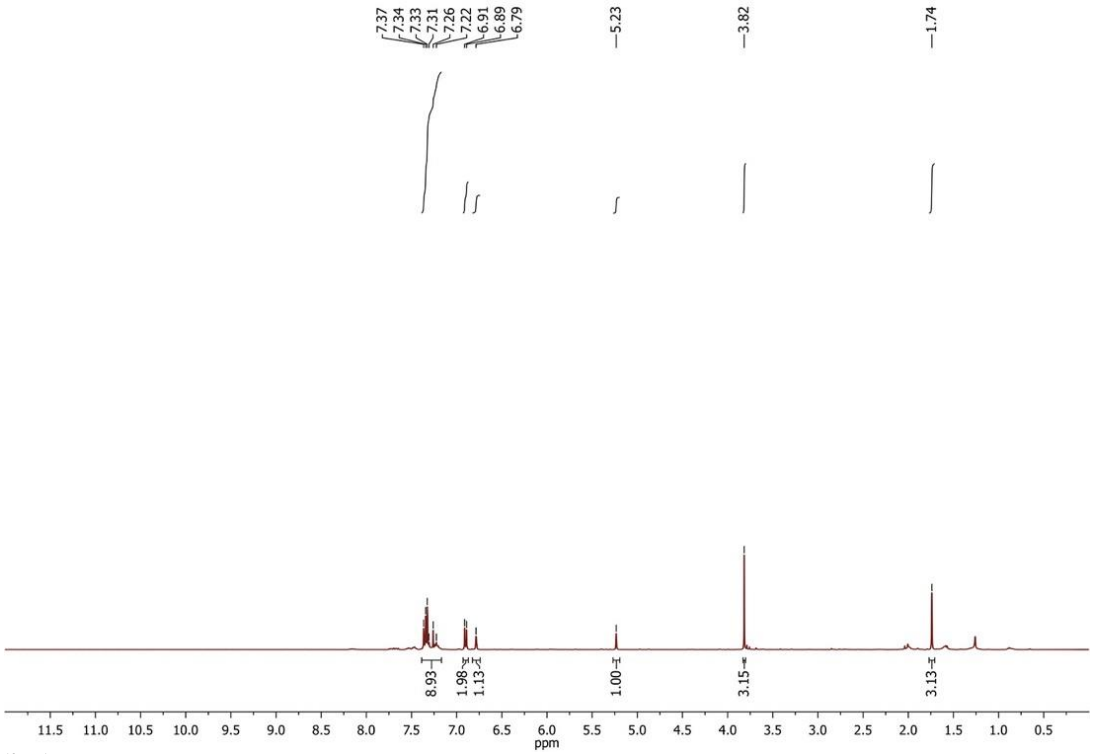
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



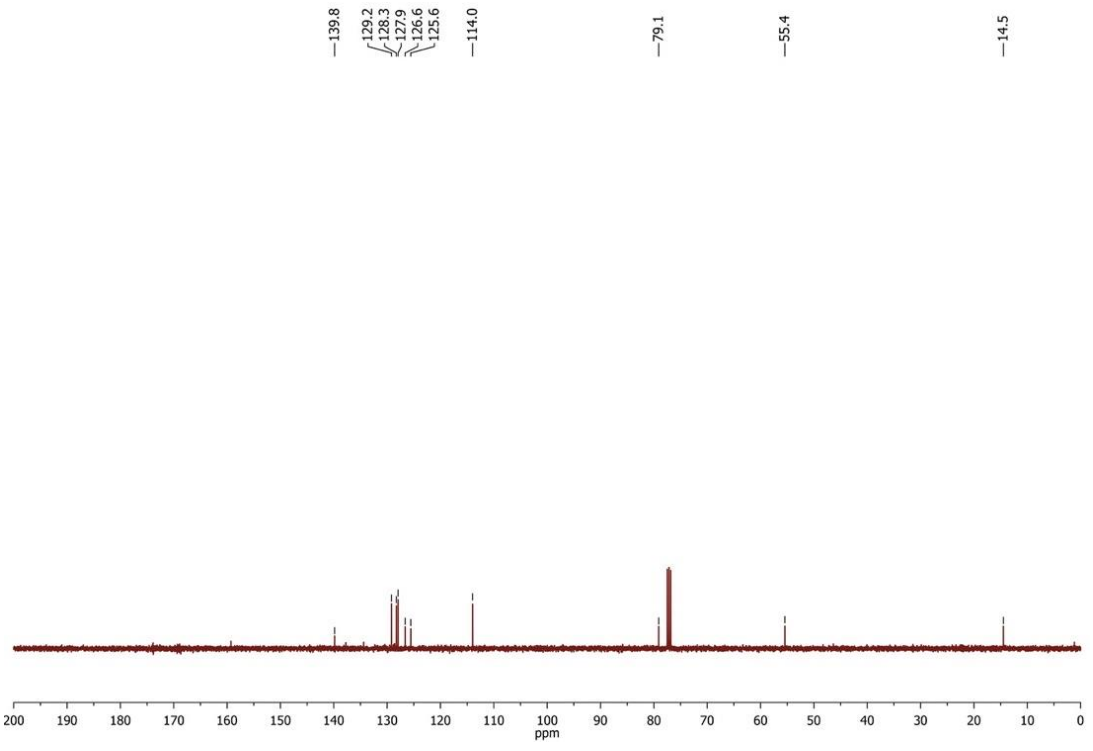


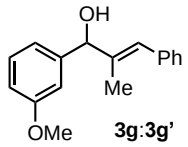
3f:**3f'**

^{1}H NMR (401 MHz, $CDCl_3$)



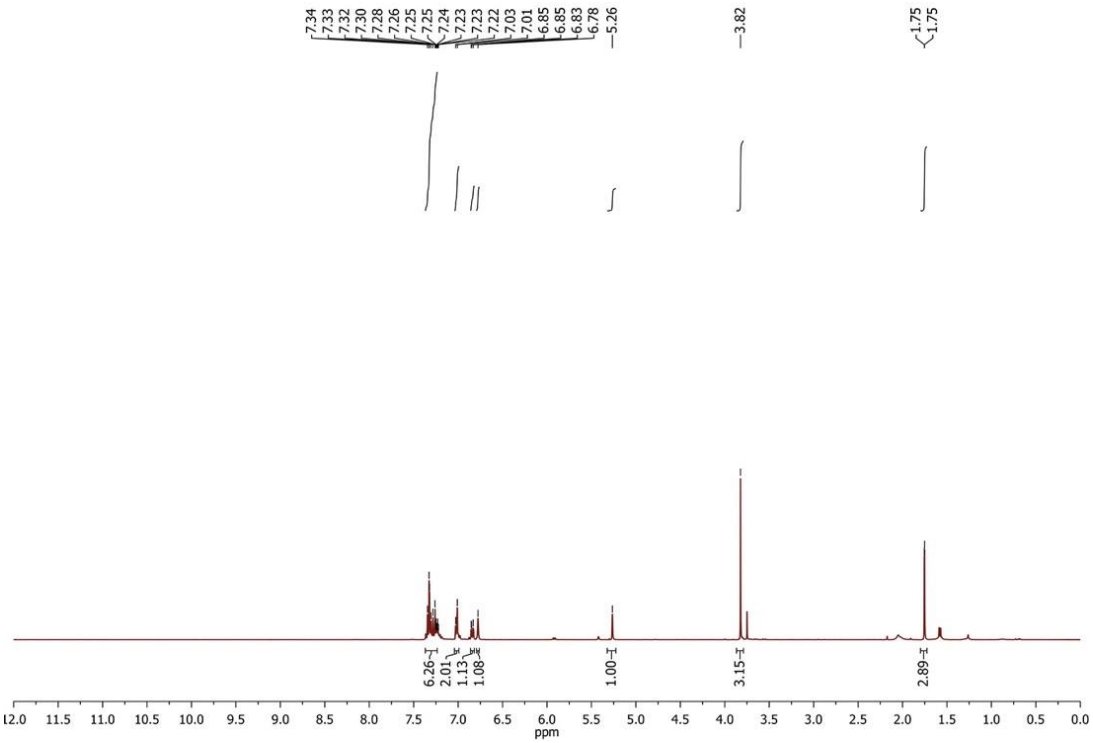
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



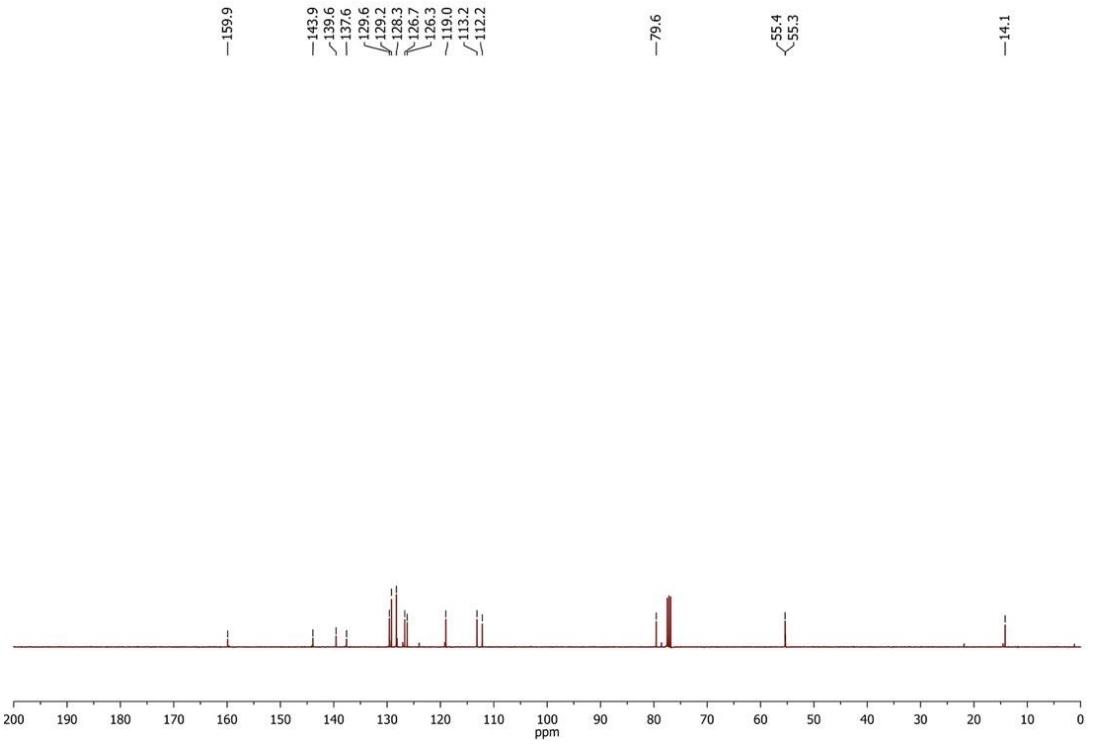


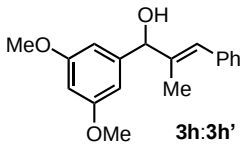
3g:**3g'**

^{1}H NMR (401 MHz, $CDCl_3$)



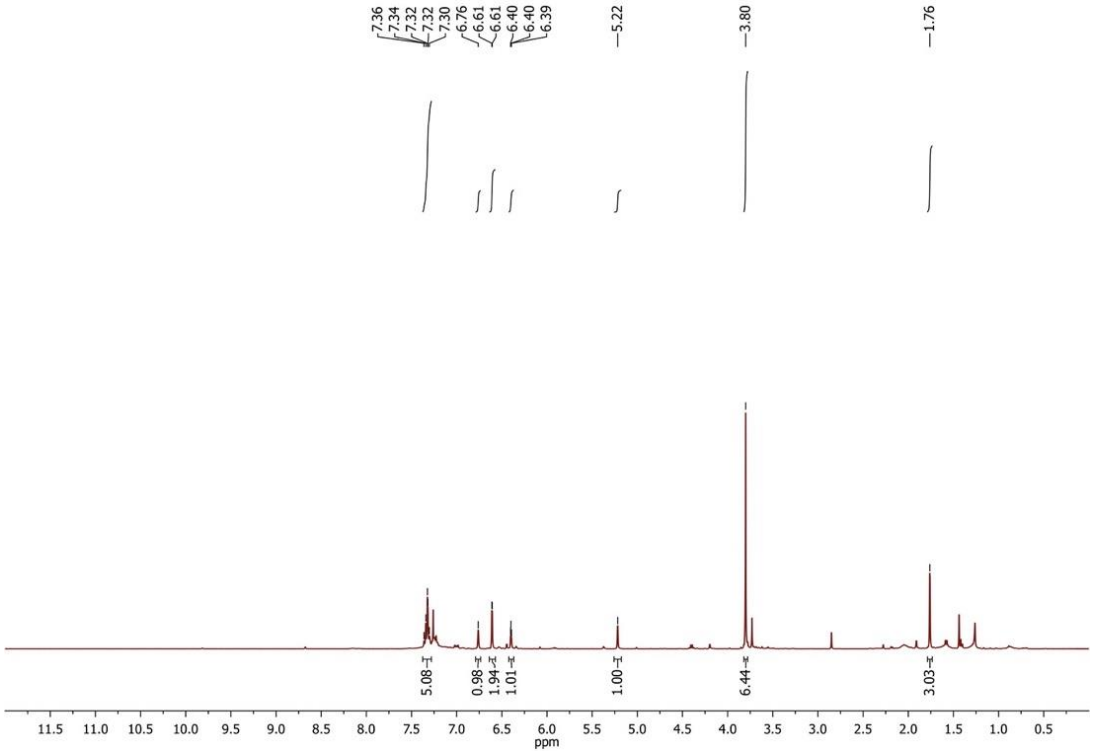
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



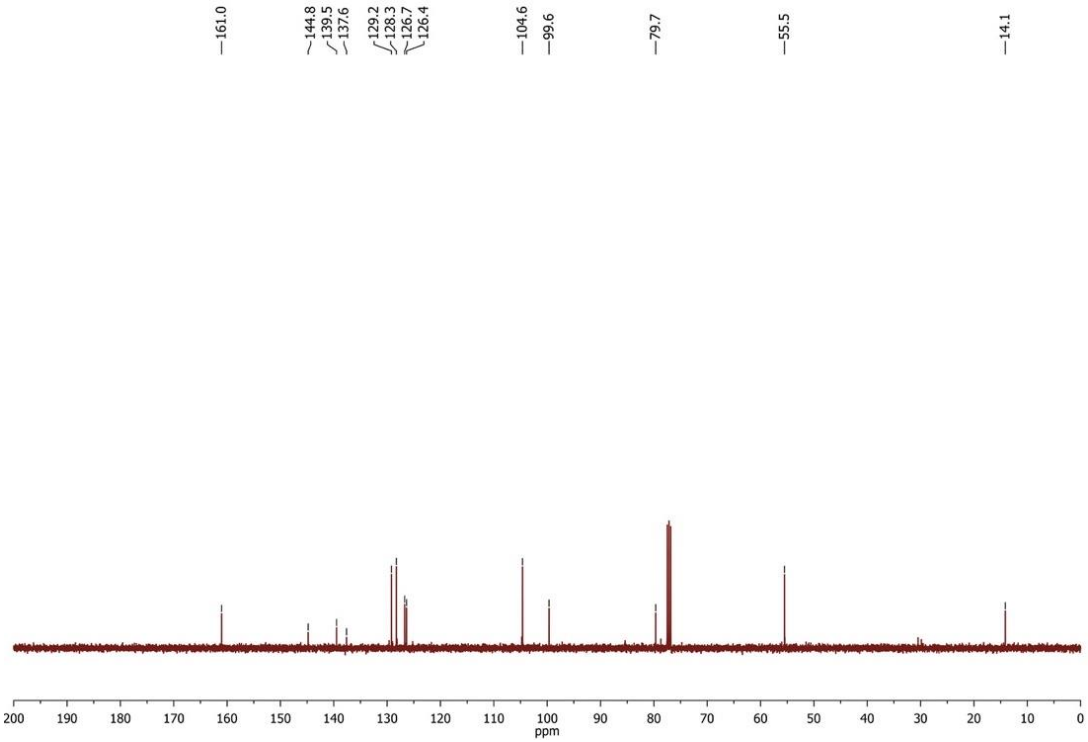


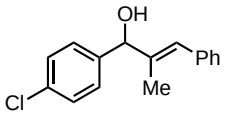
3h:**3h'**

^{1}H NMR (401 MHz, $CDCl_3$)



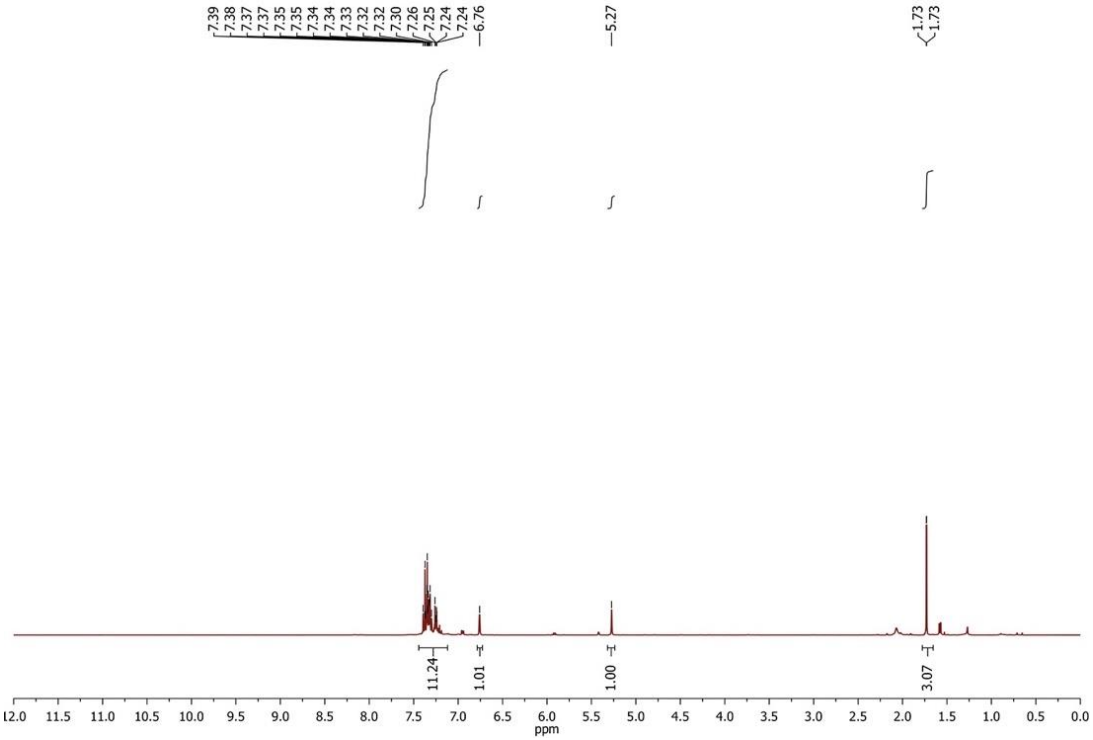
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



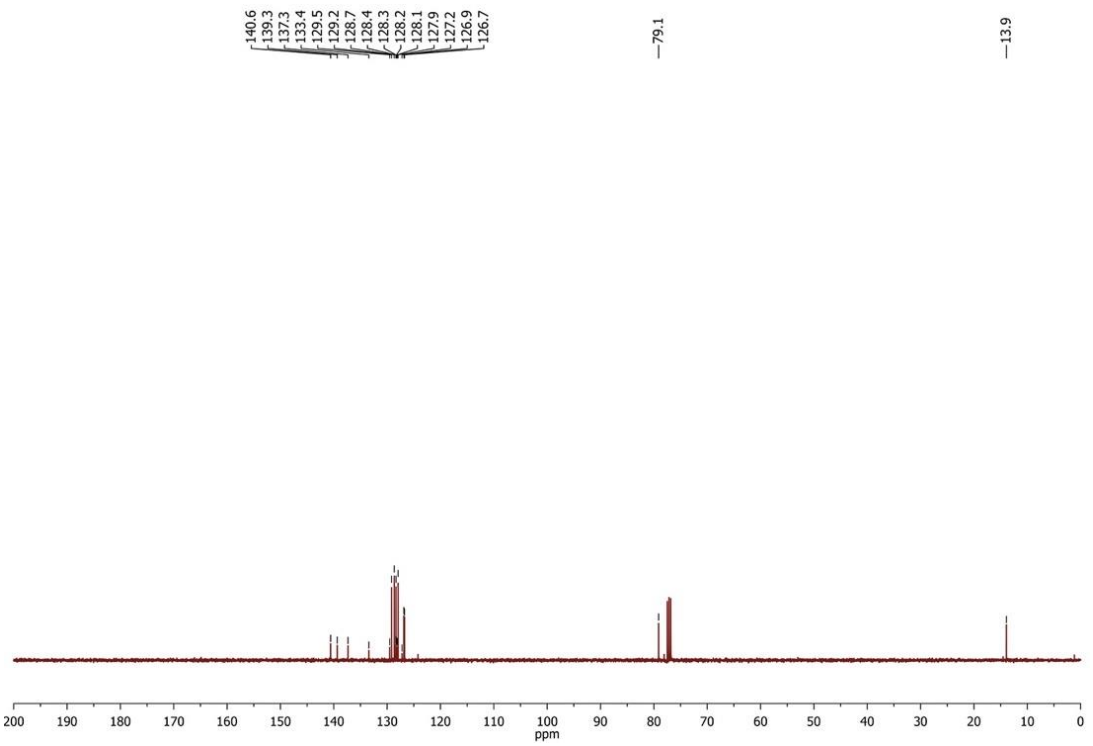


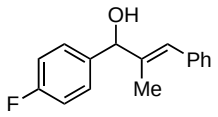
3i:**3i'**

^{1}H NMR (401 MHz, $CDCl_3$)



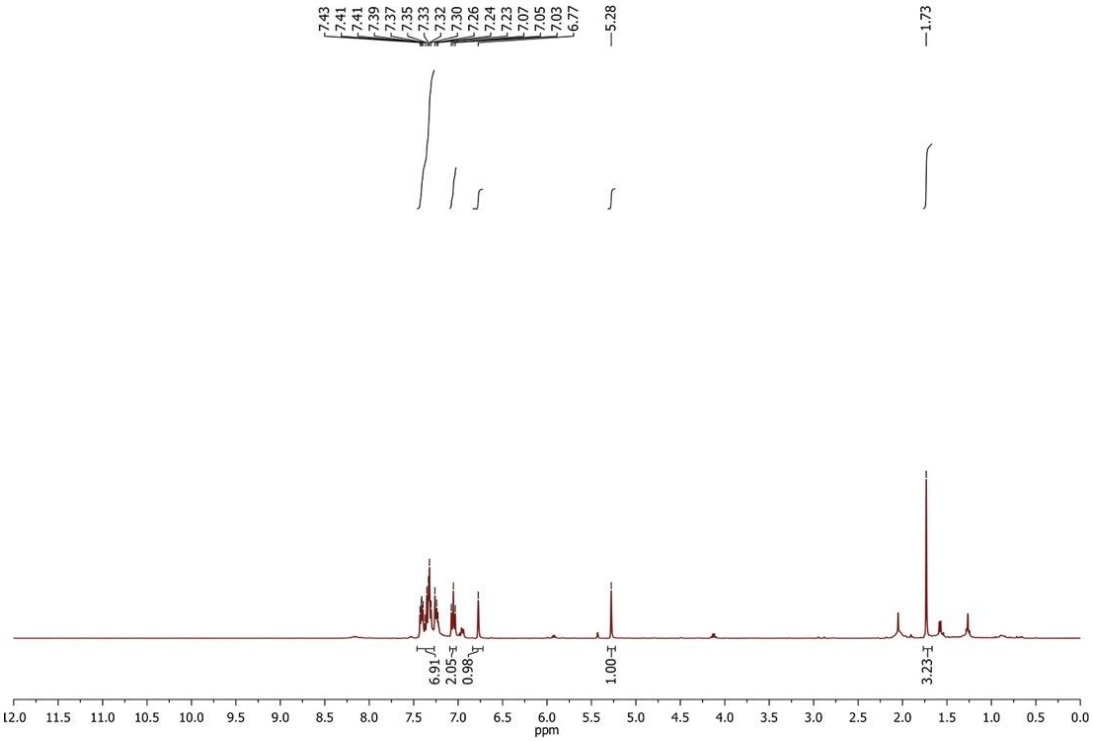
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



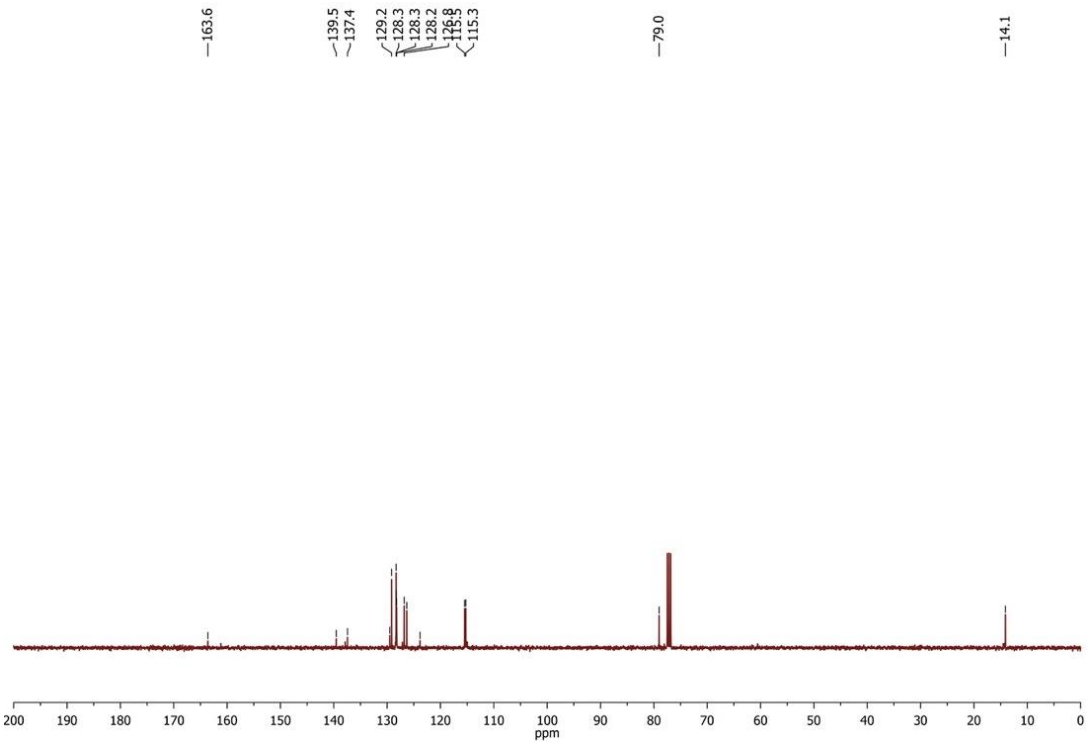


3j:**3j'**

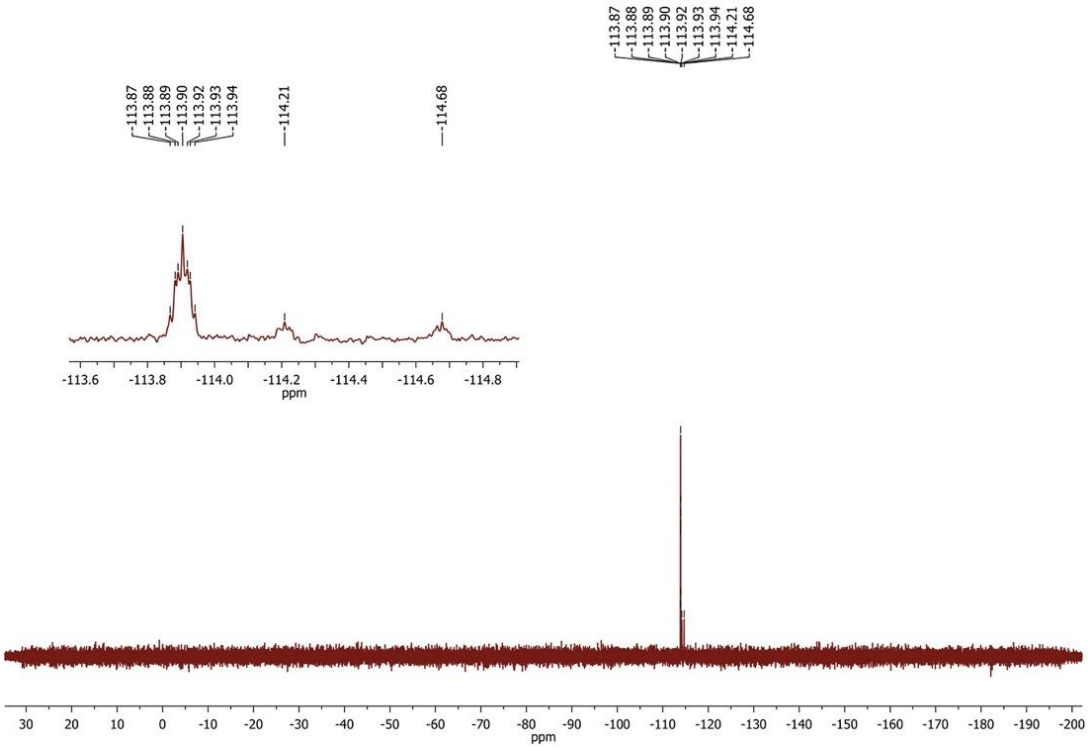
^{1}H NMR (401 MHz, $CDCl_3$)

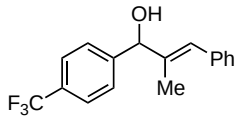


^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



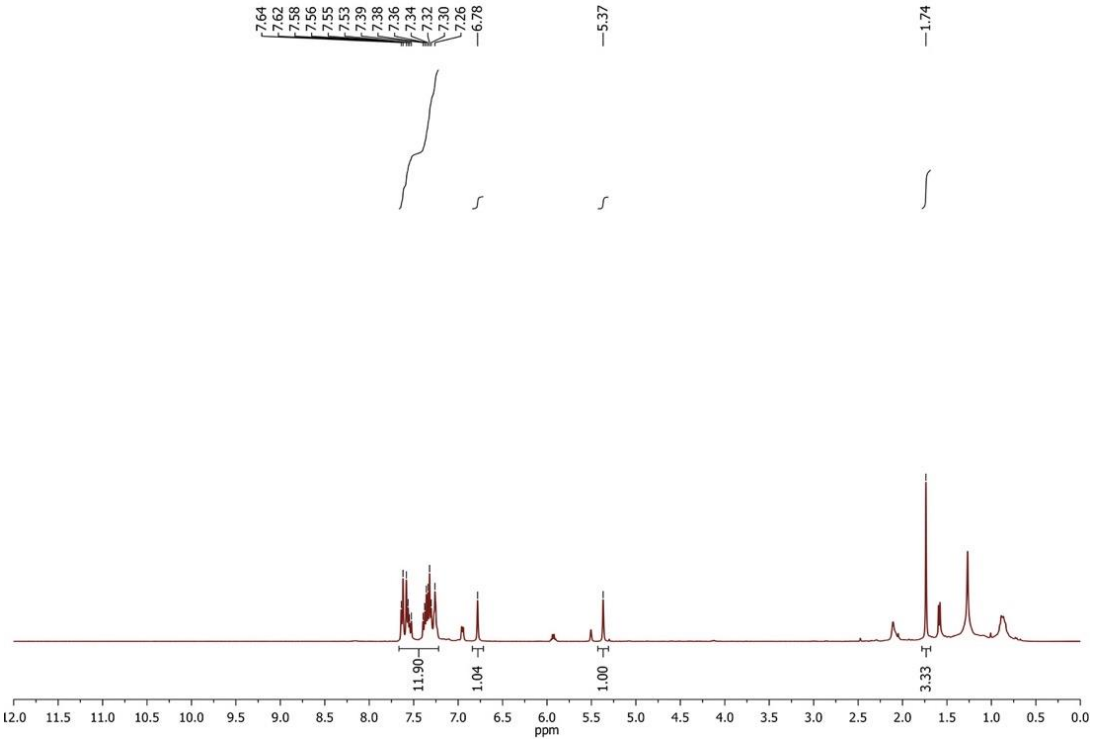
^{19}F NMR (376.5 Hz, $CDCl_3$)



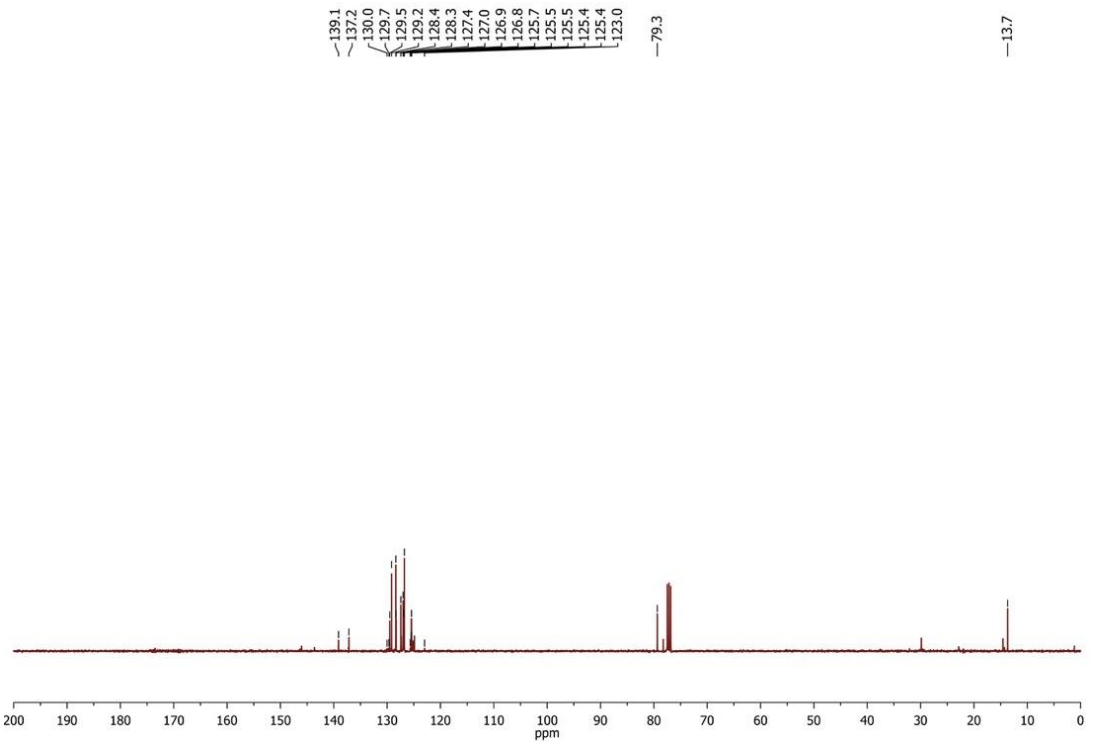


3k:**3k'**

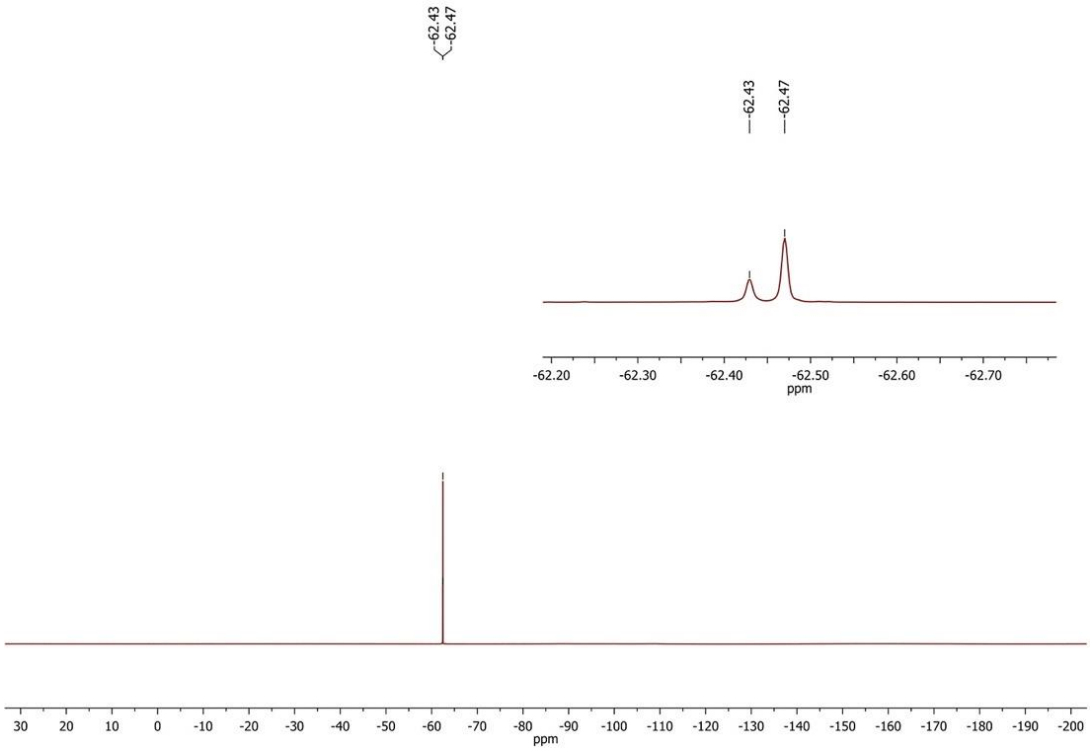
^{1}H NMR (401 MHz, $CDCl_3$)

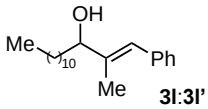


^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



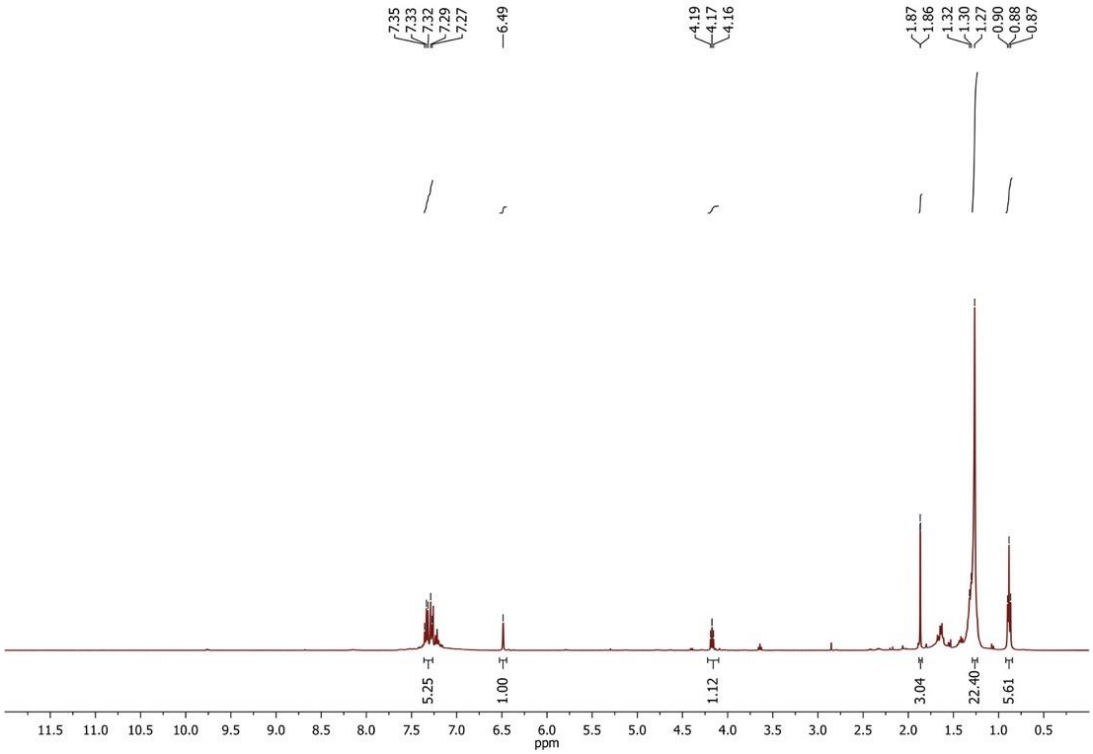
^{19}F NMR (376.5 Hz, $CDCl_3$)



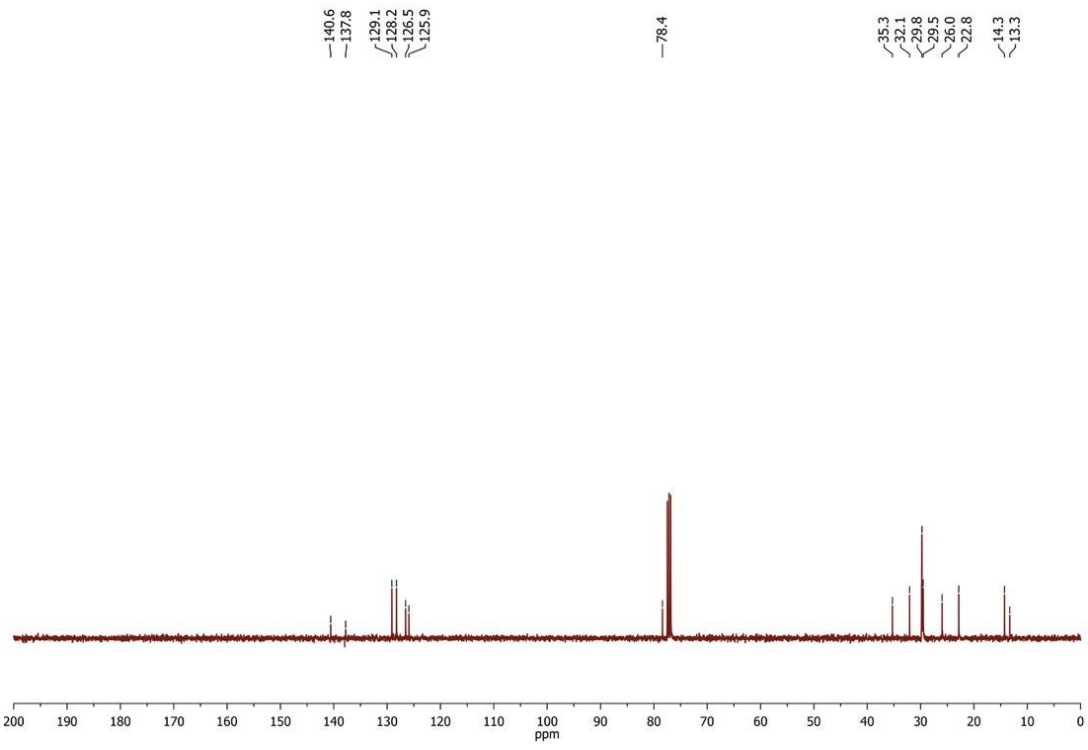


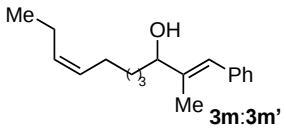
3l:**3l'**

^{1}H NMR (401 MHz, $CDCl_3$)

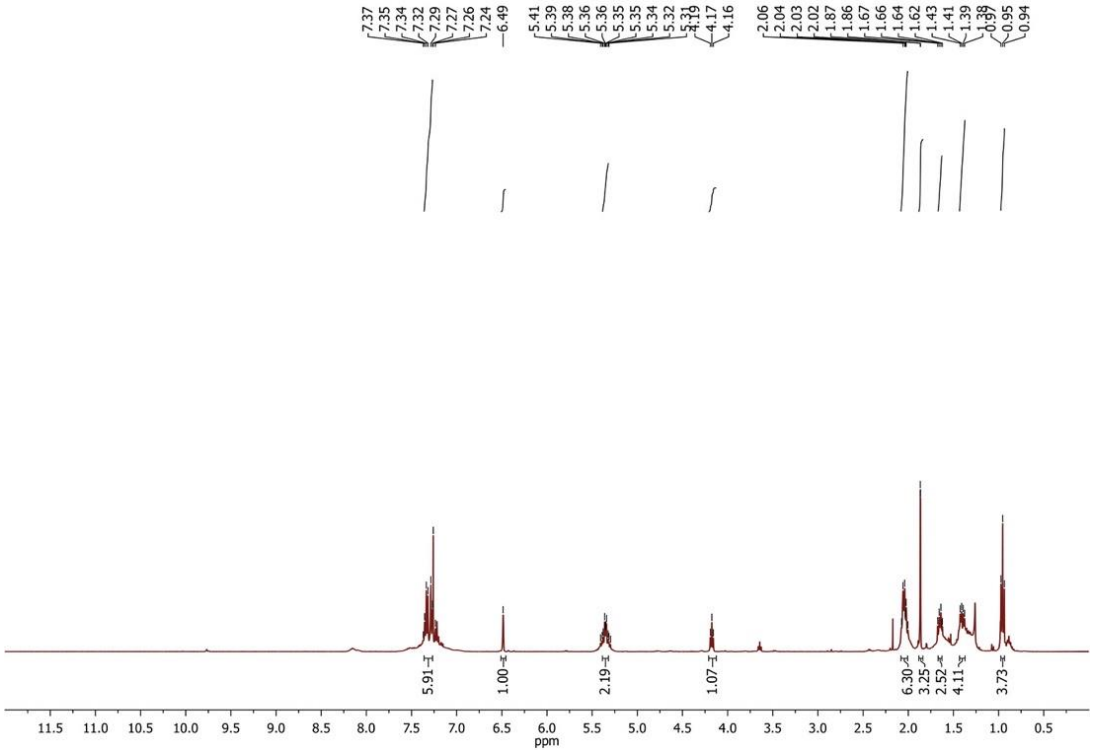


^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)

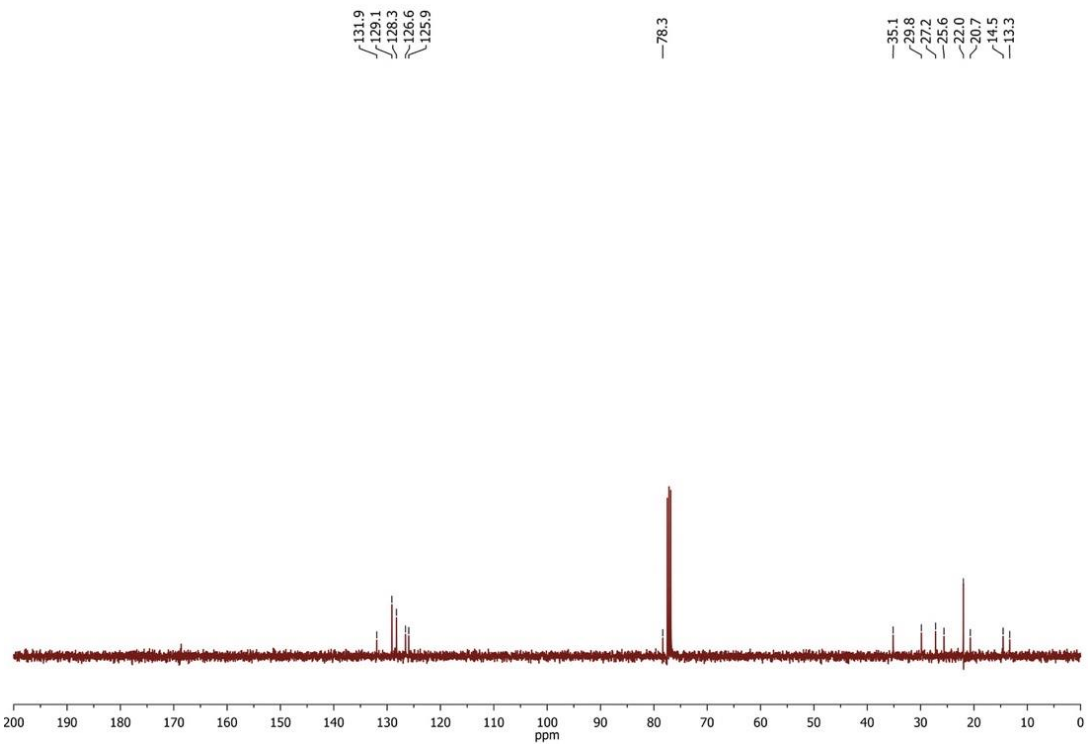


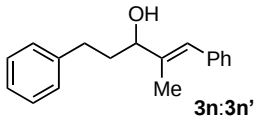


^{1}H NMR (401 MHz, $CDCl_3$)



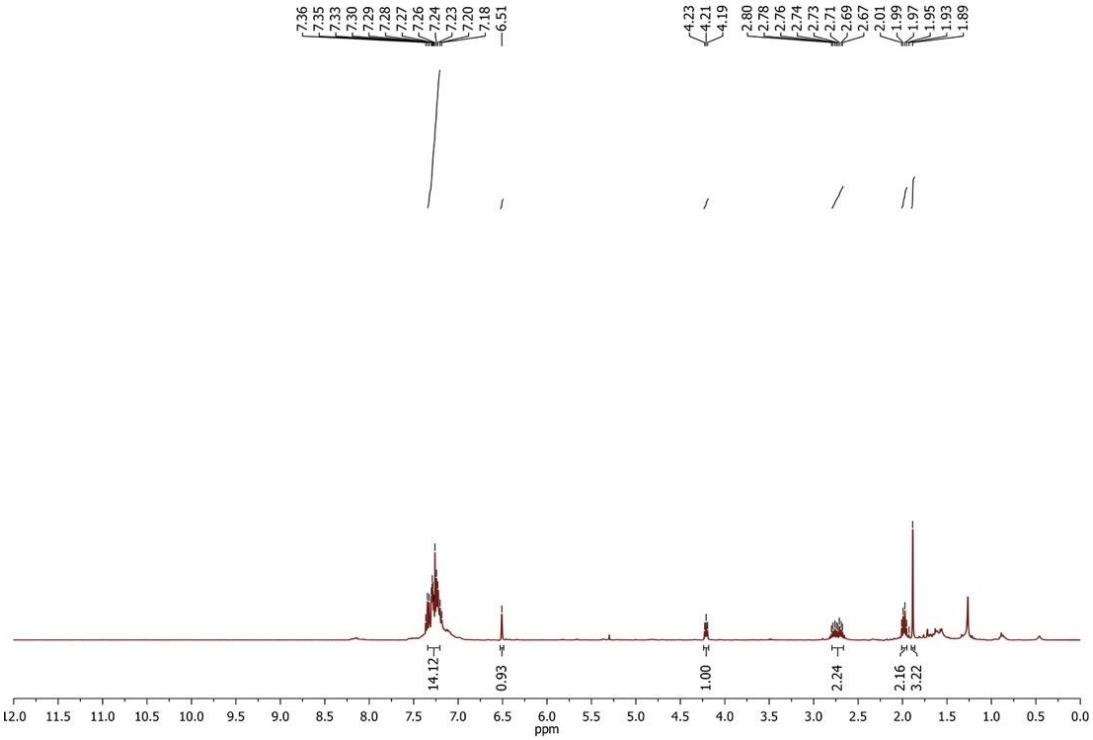
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



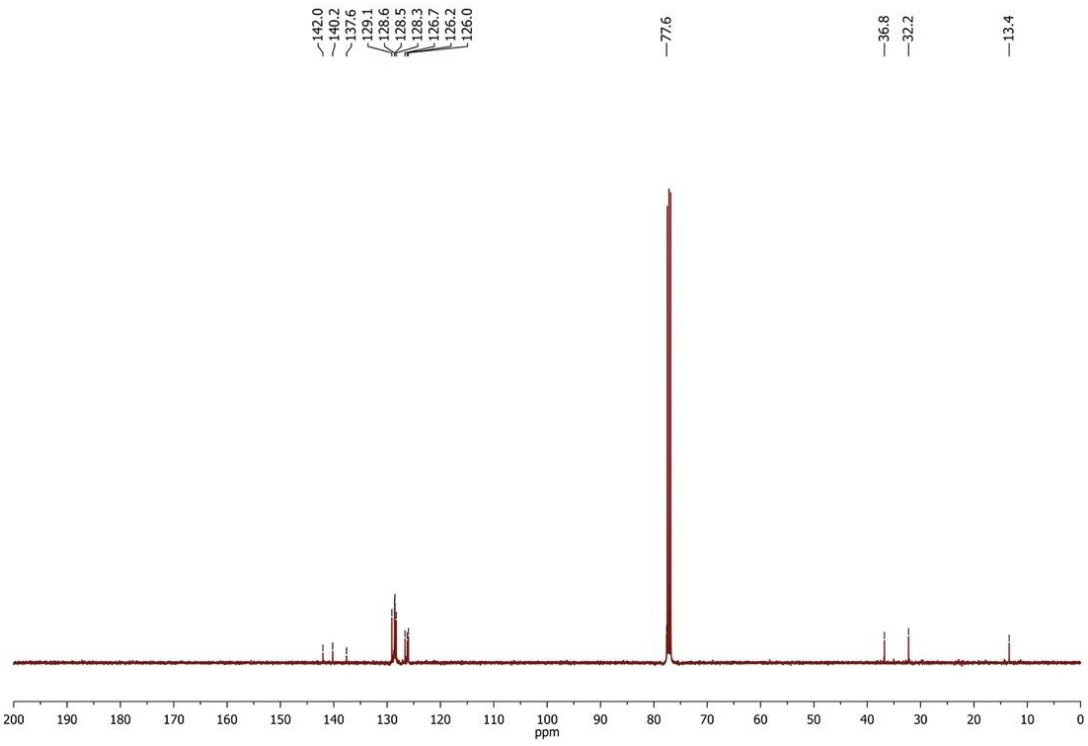


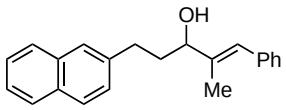
3n:**3n'**

^{1}H NMR (401 MHz, $CDCl_3$)



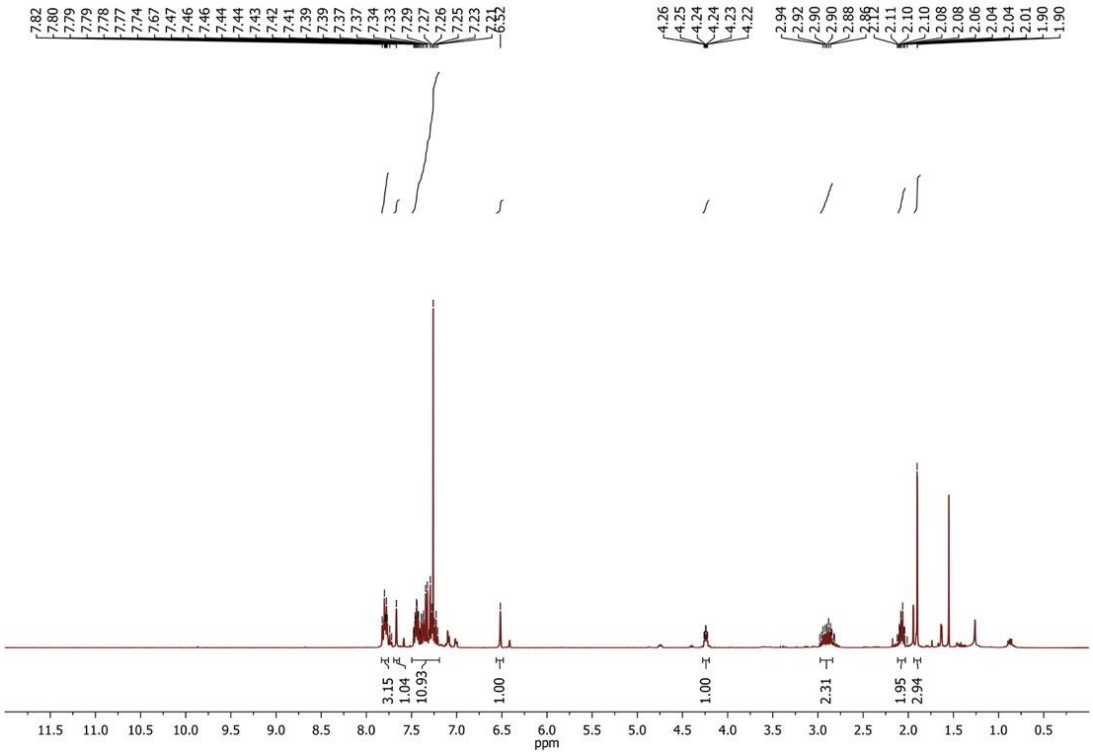
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



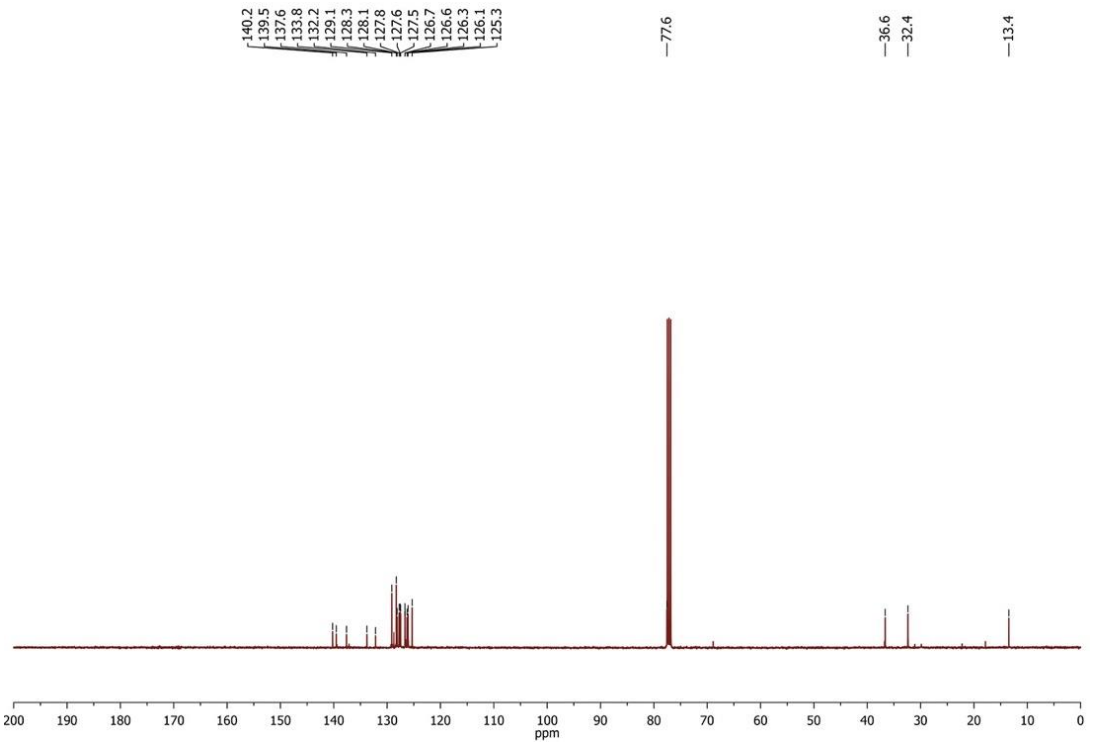


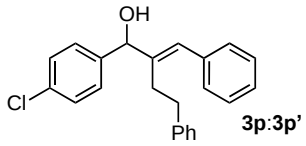
3o:**3o'**

^{1}H NMR (401 MHz, $CDCl_3$)



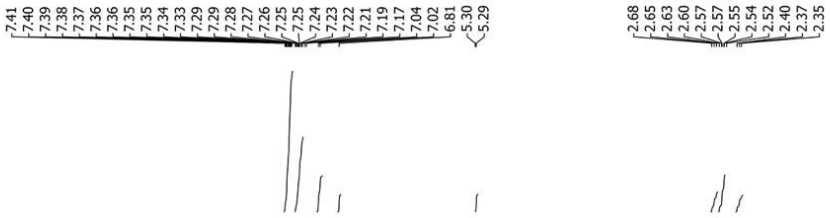
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)

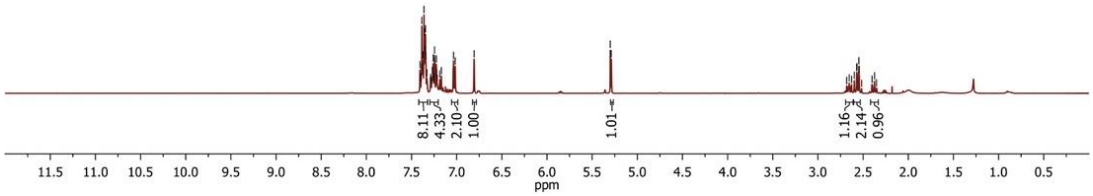


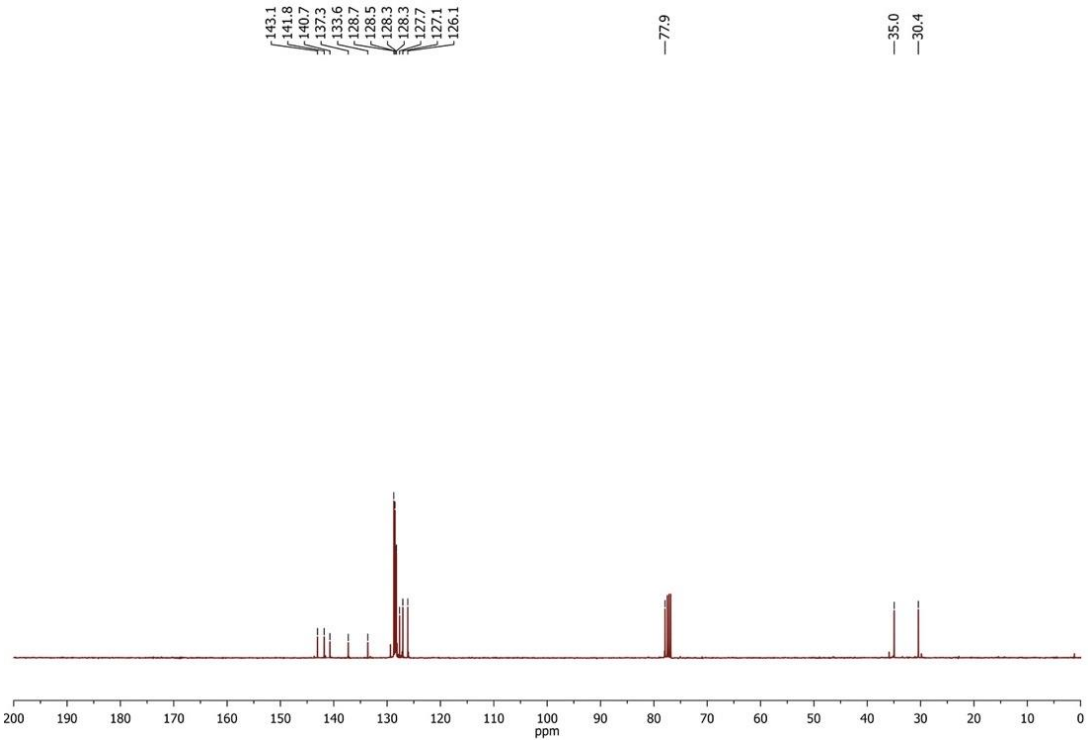


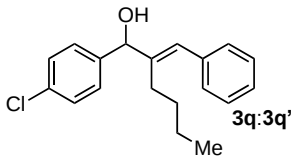
3p:**3p'**

^{1}H NMR (401 MHz, $CDCl_3$)



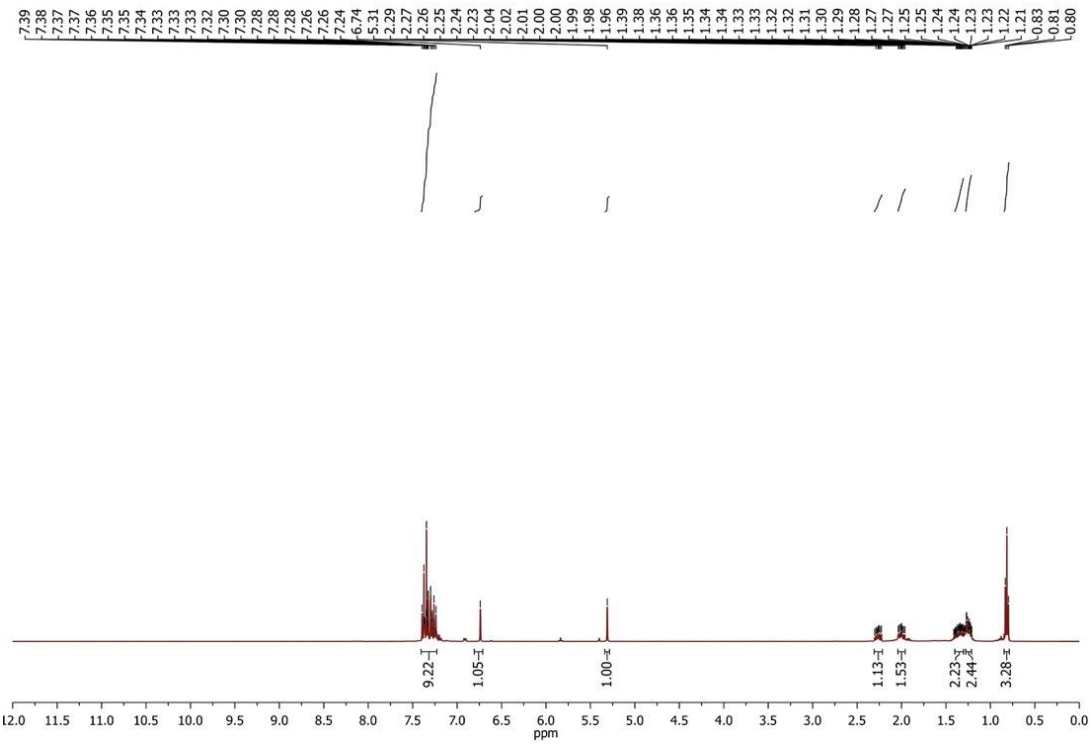




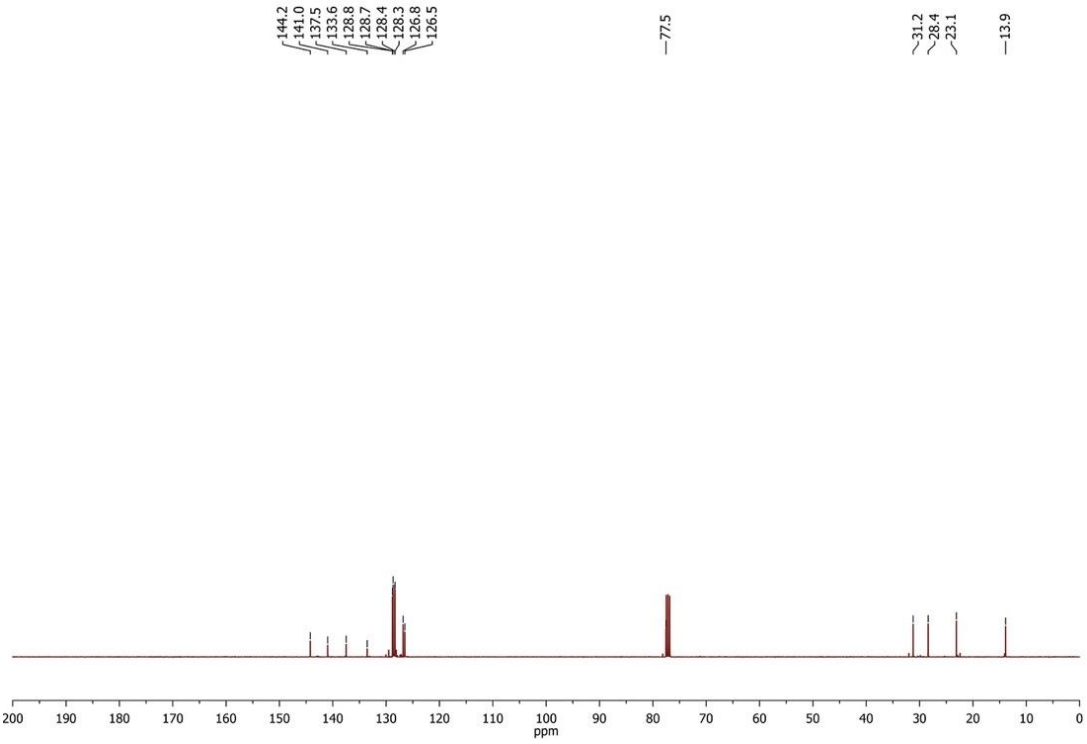


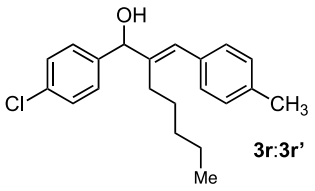
3q:**3q'**

^{1}H NMR (401 MHz, $CDCl_3$)



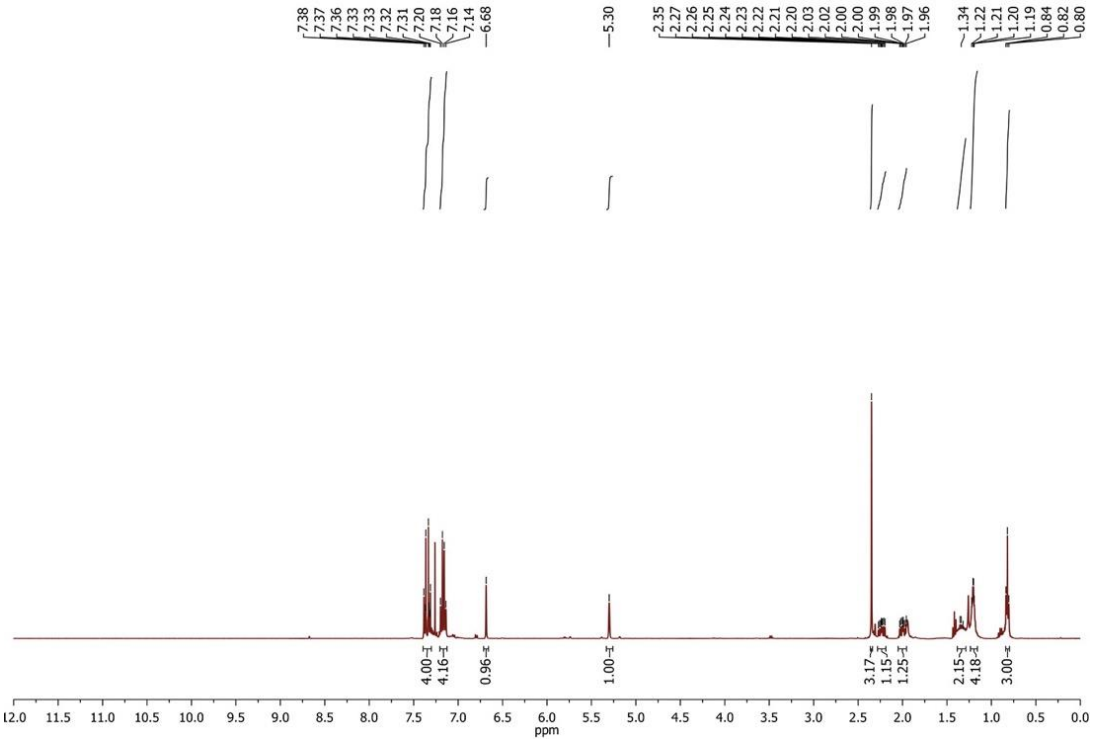
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



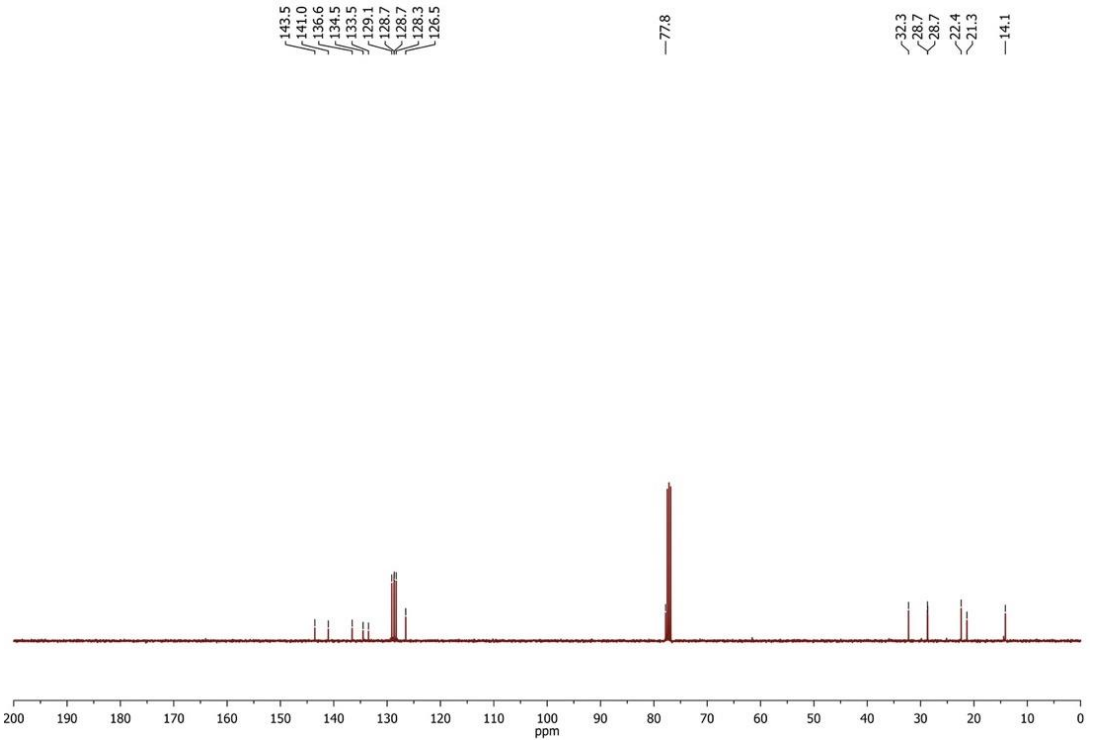


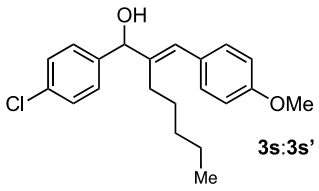
3r:**3r'**

^{1}H NMR (401 MHz, $CDCl_3$)



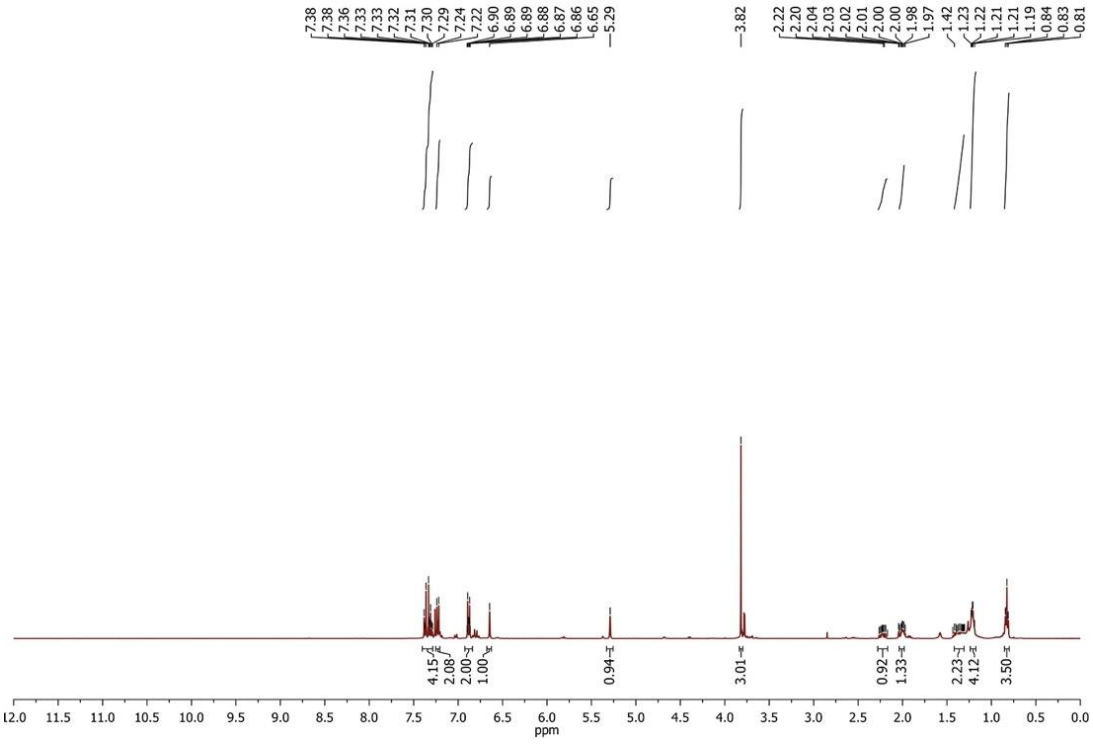
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



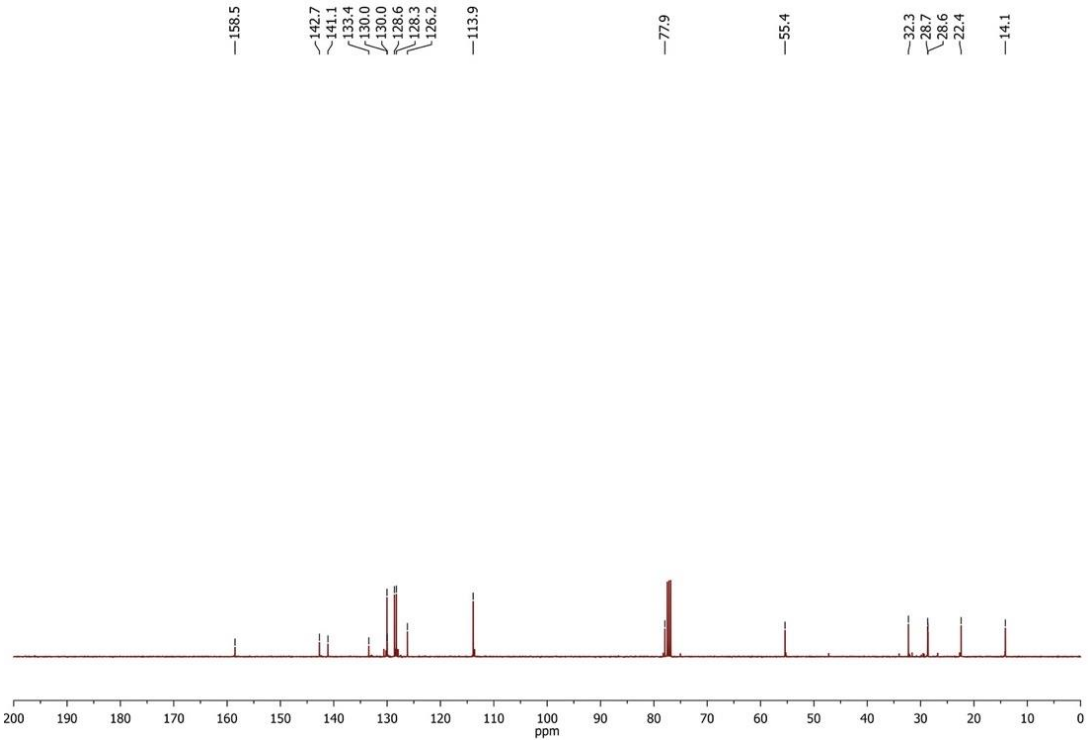


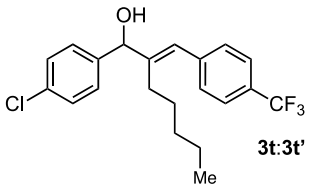
3s:**3s'**

^{1}H NMR (401 MHz, $CDCl_3$)



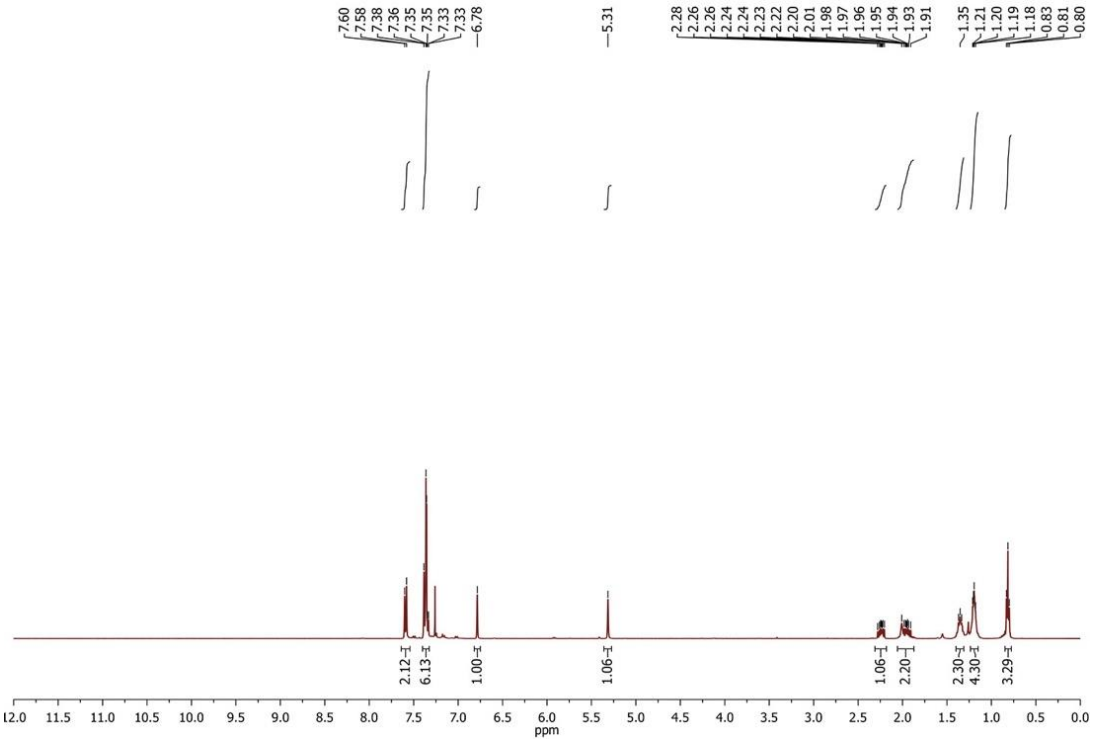
^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



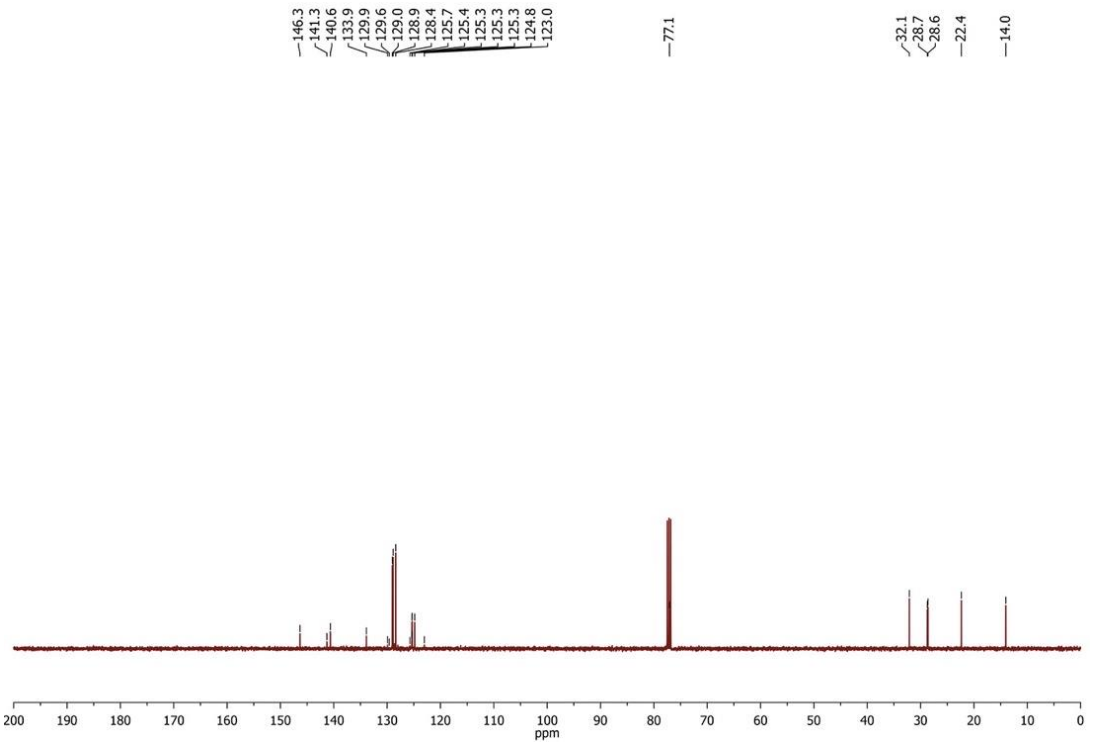


3t:**3t'**

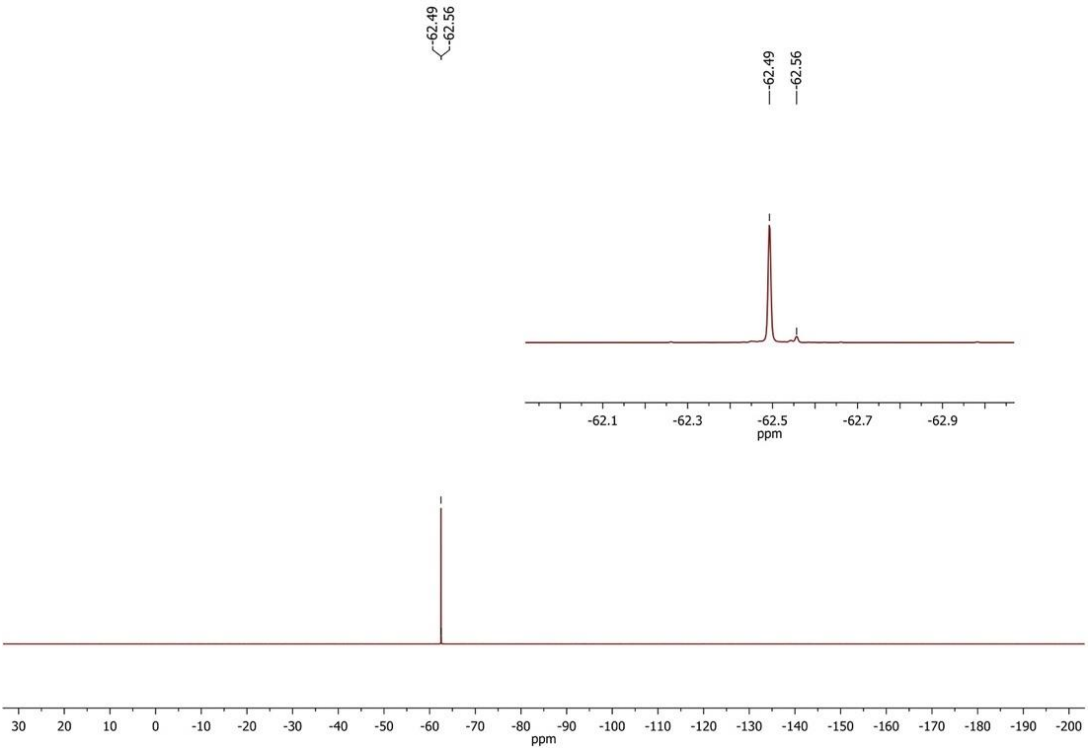
^{1}H NMR (401 MHz, $CDCl_3$)

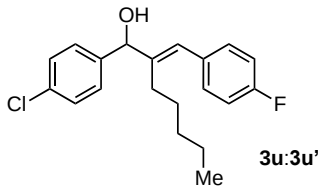


^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



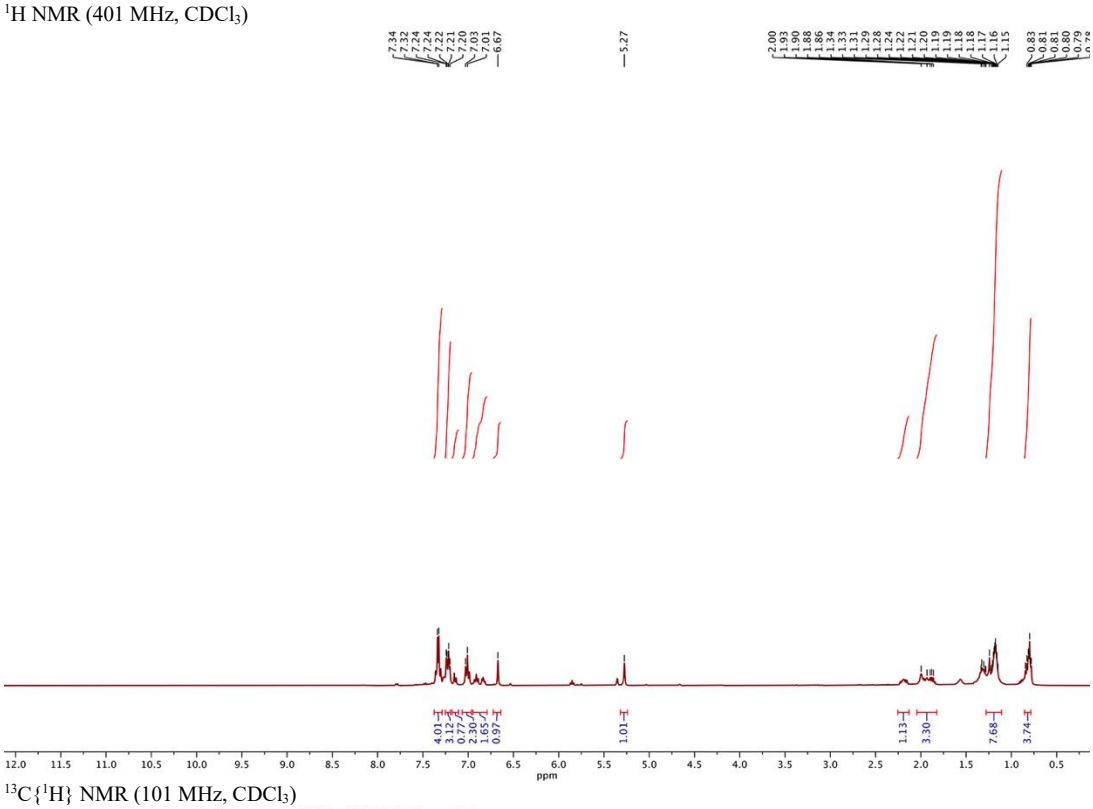
^{19}F NMR (376.5 Hz, $CDCl_3$)



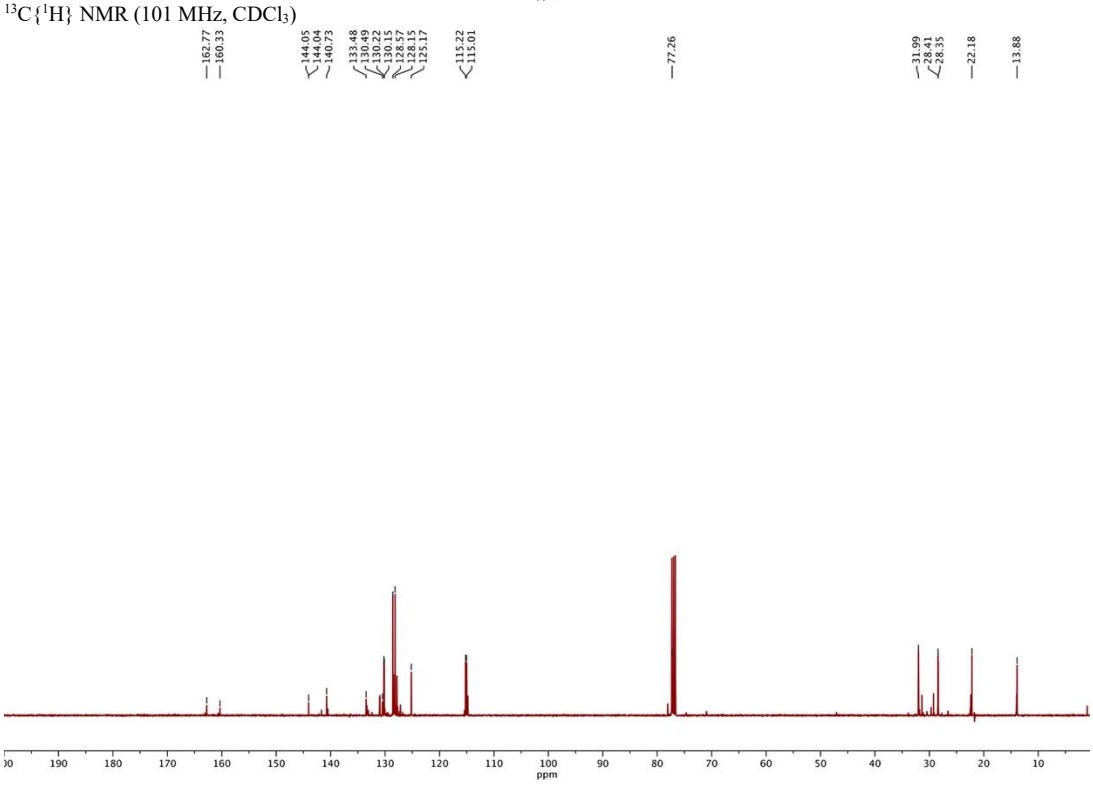


3u:**3u'**

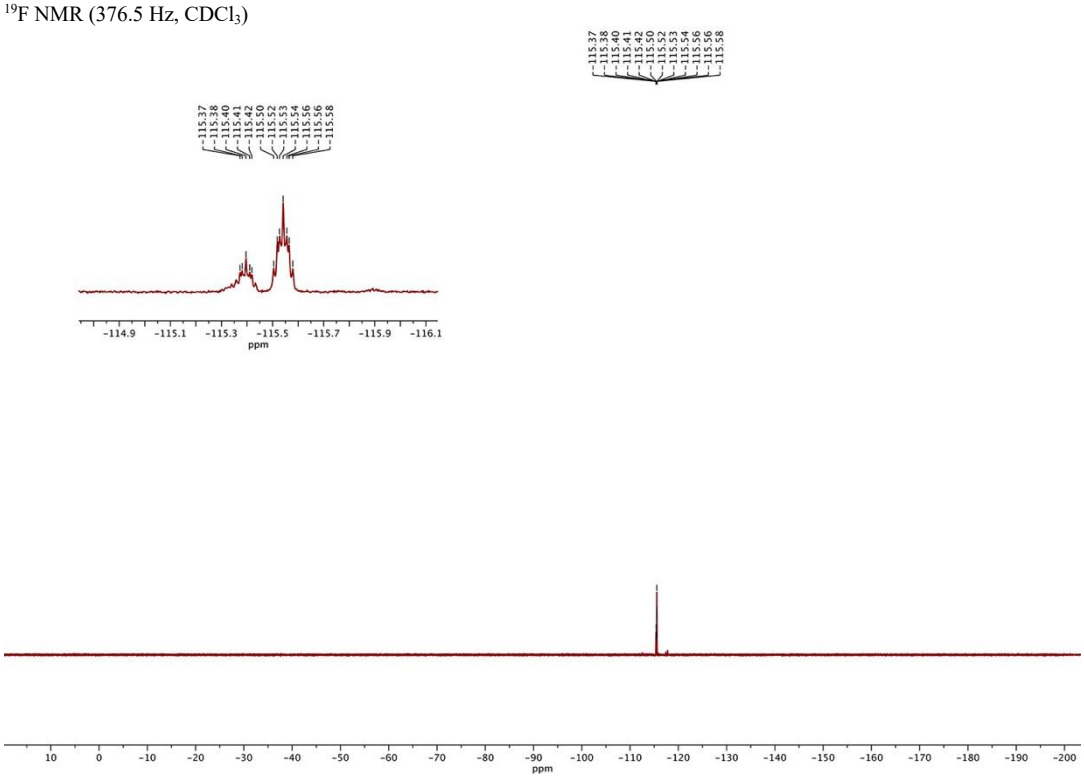
^{1}H NMR (401 MHz, $CDCl_3$)



^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)



^{19}F NMR (376.5 Hz, $CDCl_3$)



References

[1] https://www.kessil.com/science/PR160L.php

[2] E. Speckmeier, T. G. Fischer, K. Zeitler, *J. Am. Chem. Soc.* **2018**, *140*, 15353–15356.

[3] a) P. Rai, K. Maji, B. Maji, *Org. Lett.* **2019**, *21*, 3755–3759; b) A. Hamze, O. Provot, J.-D. Brion, M. Alami, *Synthesis* **2007**, 2025–2036; d) M. Chen, X. Zheng, W. Li, J. He, A. Lei, *J. Am. Chem. Soc.* **2010**, *132*, 4101–4103; e) D.-Q. Chen, C.-H. Guo, H.-R. Zhang, D.-P. Jin, X.-S. Li, P. Gao, X. Wu, X.-Y. Liu, Y.-M. Liang, *Chem. Sci.*, **2016**, *15*, 4176 - 4180.

[4] Y.-L. Li, S.-Q. Zhang, J. Chen, J.-B. Xia, *J. Am. Chem. Soc.* **2021**, *143*, 7306–7313.

[5] G. A. Crosby, J. N. Demas, *J. Phys. Chem.* **1971**, *75*, 991–1024.