

Confined Rhodium catalyst by self-assembly for asymmetric hydroformylation of unfunctionalized, internal alkenes.

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Materials

All chemicals were used as received from commercial sources. Rh(acac)(CO)₂ (Strem Chemicals Inc.), acetone and methylenechloride (Biosolve B.V.). Toluene was freshly distilled under argon over sodium and kept under Argon.

Instrumentation

Elemental analysis was performed by Microanalytisches Laboratorium Kolbe (Mülheim an der Ruhr, Germany) after drying under vacuum at room temperature. ¹H NMR and ³¹P NMR spectra were recorded on a Varian INOVA 500 NMR spectrometer (500 MHz for ¹H, 125 MHz for ¹³C, and 202 MHz for ³¹P). ¹H NMR chemical shifts were reported in ppm against residual solvent resonance as the internal standard (δ(acetone) = 2.05 ppm). Gas Chromatography (GC) analyses were performed on a Shimadzu GCT17A instrument (split/splitless injector, J&W Scientific, DBT1 J&W 30 m column, film thickness 3.0 μm, carrier gas 70kPa He, FID Detector). Chiral GC separations were conducted on an Interscience HR GC instrument with a Supelco βTdex 225 capillary column. Electrospray ionization (positive mode) was done with a Q-ToF1 mass spectrometer of Micromass (Waters). Circular dichroism (CD) spectra were recorded on a OLIS DSM-1000 CD-Spectrometer.

Preparation and Characterization of Supramolecular Structures

Compounds **2**¹ and **3**² were prepared via literature procedures.

1. Compound 1.

To an Erlenmeyer flask charged with compound **2** (83 mg, 0.16 mmol) and **3** (180 mg, 0.16 mmol), acetone was added until all solids were dissolved. The flask was allowed to sit overnight, at which point red powder/crystals had precipitated out. The solid was collected by filtration, rinsed with acetone, and dried under reduced pressure (224mg, 68 mmol, 85% yield). ³¹P NMR (500 MHz, acetone-*d*₆): δ 144 (s). ¹H NMR (500 MHz, acetone-*d*₆): δ 9.21 (8H, **3** ArH), 9.08 (2H, **2** ArH), 8.92 (2H, **2** ArH), 8.56 [6H (4H, **3** ArH)+(2H, **2** ArH)], 8.44 (2H, **2** ArH), 8.27 (2H, **2** ArH), 7.92 (2H, **2** ArH), 7.70 (4H, **2** ArH), 7.45 [10H (8H, **3** ArH)+(2H, **2** ArH)], 7.05 (8H, **3** ArH), 7.02 (2H, **2** ArH). EA: Calculated for evacuated **1** (C₁₉₆H₂₃₆N₁₄O₁₂P₂Zn₄): (%) C, 71.26; H, 7.20; N, 5.94. Found: C, 69.44; H, 7.20; N, 5.59.

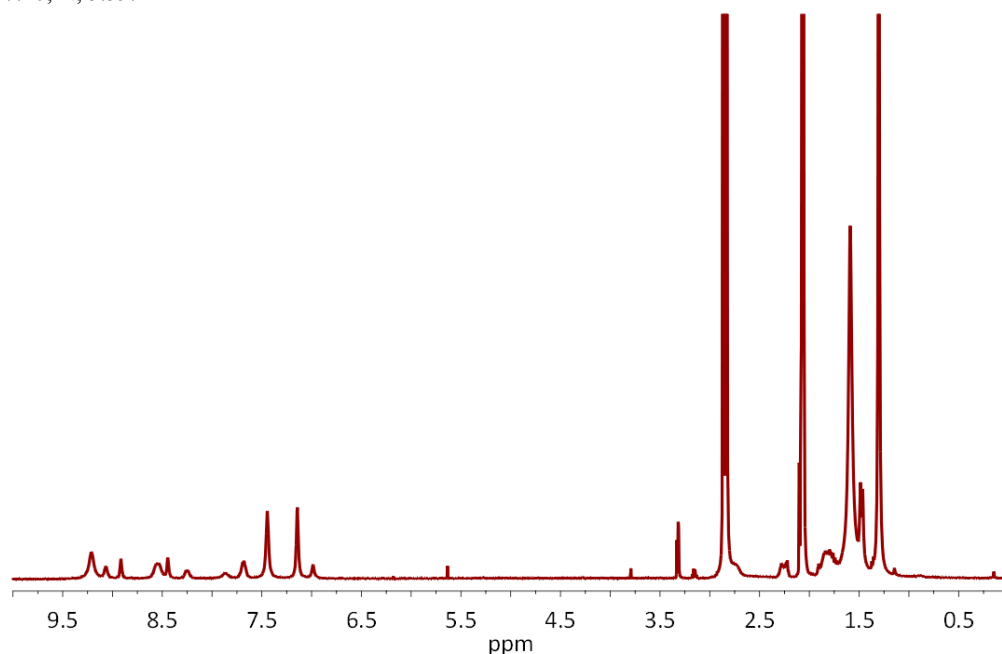


Figure S1. ¹H NMR spectrum of **1**.

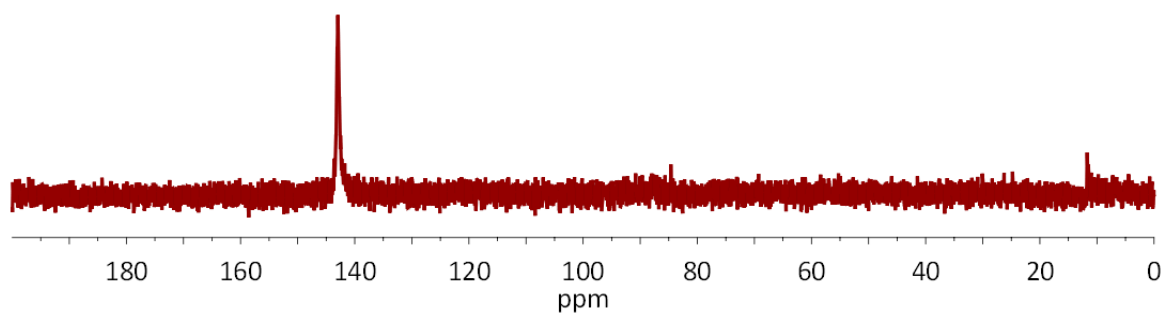


Figure S2. ^{31}P NMR spectrum of **1**.

Titration of **3** against **2** monitored by CD spectroscopy

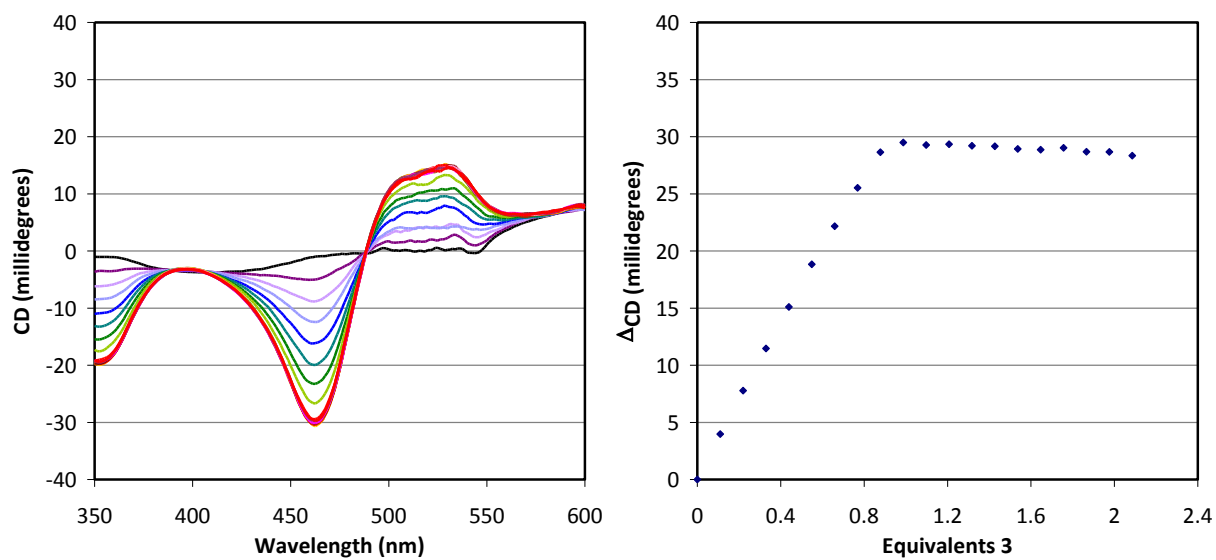


Figure S3. CD spectral titration curves for the assembly of **1** (left) $\Delta\text{mOD } 463.75\text{nm}$ (right). Fixed concentration of **2** ($2.46 \times 10^{-5}\text{M}$ in acetone), 1.00mm path length quartz cuvette.

Diffusion NMR data for **1**

The diffusion NMR experiments were carried out using the diffusion bipolar pulse pair stimulated echo (DBPPSTE) method. Measurement of T_1 was carried out before each experiment. $\Delta = 100$ ms and $\delta = 2$ ms, and $T = 298.15$ K. Samples were 8.3 mM in d_6 -acetone.

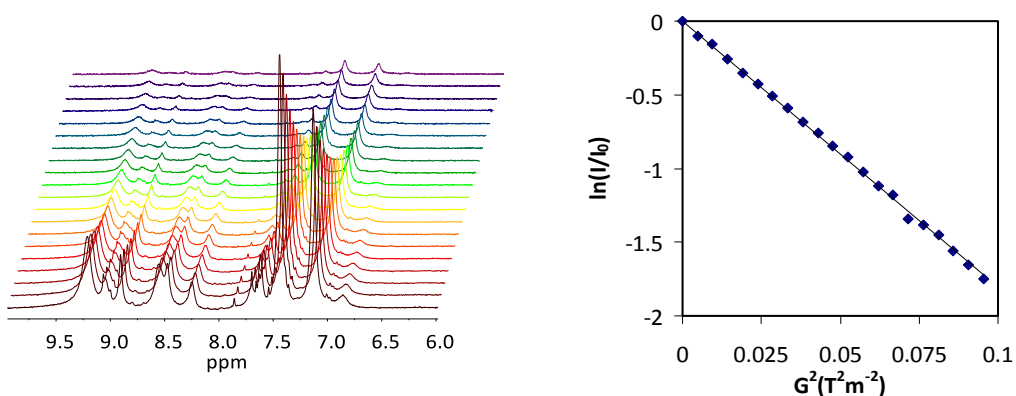


Figure S4. A stacked plot of the aromatic area of the ^1H NMR spectrum of **1** as a function of applied gradient strength (left). A linear fit of the diffusion (right).

$$\ln\left(\frac{I}{I_0}\right) = -18.071G^2 \quad \Rightarrow \quad \left[\gamma^2\delta^2\left(\Delta - \frac{\delta}{3}\right)D\right] = 18.071T^{-2}m^2$$

$$\Rightarrow D = \frac{18.071T^{-2}m^2}{\gamma^2\delta^2\left(\Delta - \frac{\delta}{3}\right)} = \frac{18.071T^{-2}m^2}{\gamma^2\delta^2\left(\Delta - \frac{\delta}{3}\right)} = \frac{18.071T^{-2}m^2}{2.84 \times 10^{10}T^{-2}s} = 6.356 \times 10^{-10}m^2s^{-1}$$

$$r_H = \frac{K_bT}{6\pi\eta D} = \frac{4.12 \times 10^{-21}m^2s^{-2}kg}{4.07 \times 10^{-12}ms^{-2}kg} = \underline{1.01 \times 10^{-9}m}$$

2. Compound **1-Rh**.

To a Schlenk flask charged with compound **1** (100 mg, 30 μmol) and $\text{Rh}(\text{acac})(\text{CO})_2$ (7.8 mg, 30 μmol), and equipped with a magnetic stir-bar, distilled toluene (5 mL) was added under a nitrogen atmosphere. The flask was allowed to stir overnight at 80 $^\circ\text{C}$, after which an unlocked ^{31}P NMR spectrum of the crude reaction reveals the absence of the singlet corresponding to compound **1**, and the presence of a new doublet. The reaction is then brought to room temperature, and the solvent removed under reduced pressure. The resulting solid was then characterized without further purification. ^{31}P NMR (500 MHz, acetone- d_6): δ 159.5 (d, $J_{\text{Rh-P}} = 292$ Hz). ESI-MS: Calculated ($\text{C}_{201}\text{H}_{245}\text{N}_{14}\text{O}_{14}\text{P}_2\text{Rh}_1\text{Zn}_4$): m/z (%) 1752.72 (100.0%), 1752.22 (96.4%), 1753.22 (90.2%). Found: 1752.85, 1752.36, 1753.34.

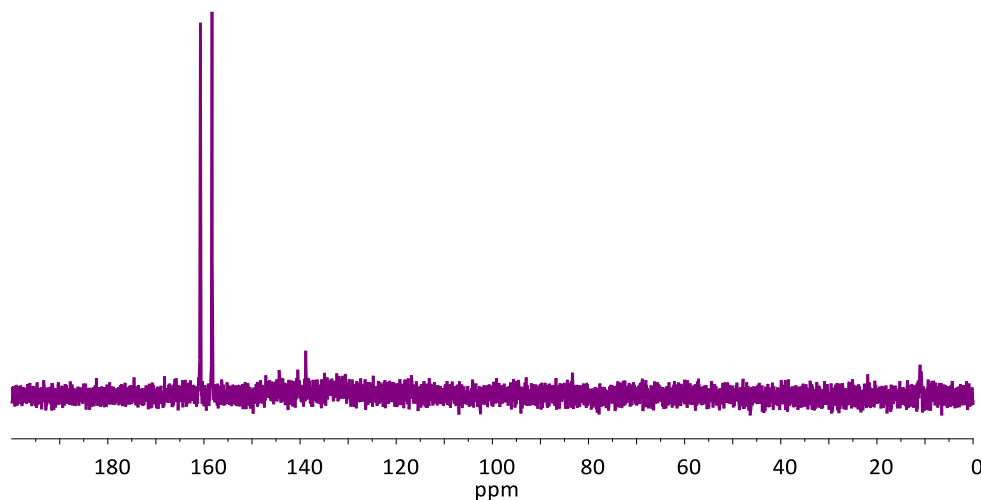


Figure S5. ^{31}P NMR spectrum of **1-Rh**.

ESI-TOF MS spectra for **1-Rh**

An offline spray was made by filling a glass standard coated Econo10 tip (New Objective) with a solution of the constructed supramolecular complexes in Toluene. Ions visible within the m/z window of 400-1800 were selected from the ToFMS spectrum. A collision-induced dissociation was performed with the selected ions. Masslynx software was used for the processing of the acquired data and modeling of the isotope pattern.

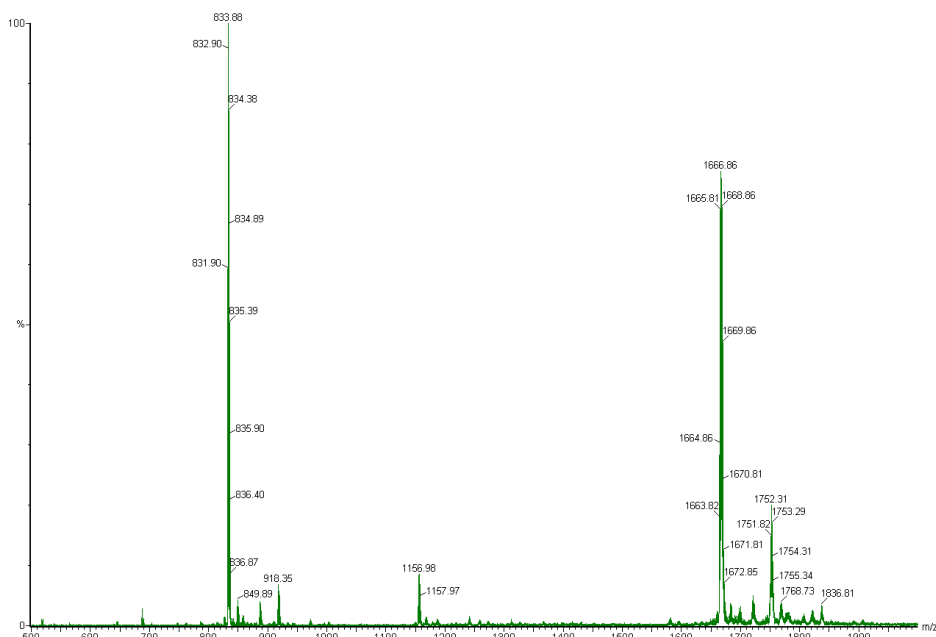


Figure S6. ESI-TOF MS of **1-Rh**.

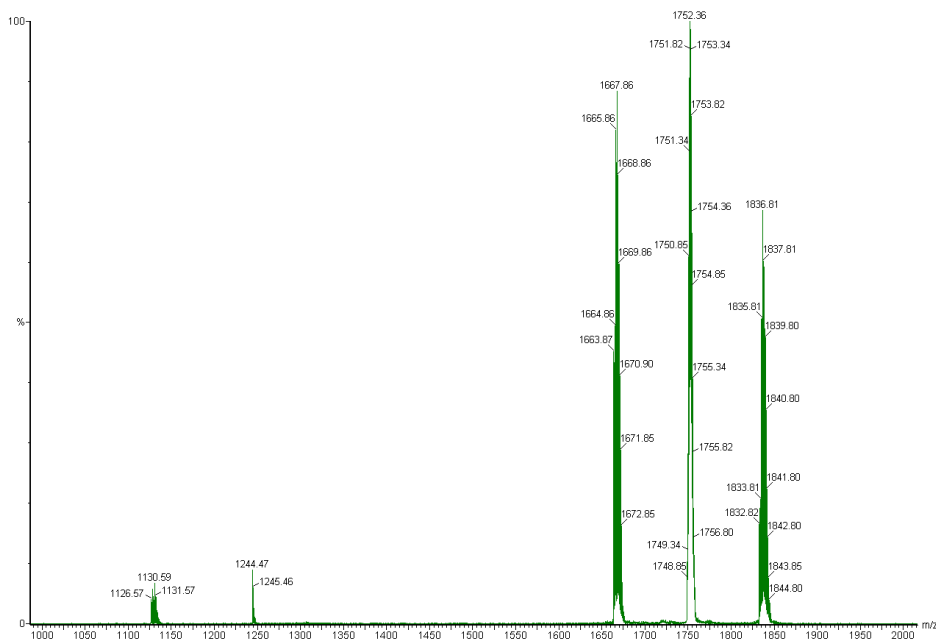


Figure S7. MS-MS of ESI-TOF MS peak at 1752 (Figure S6).

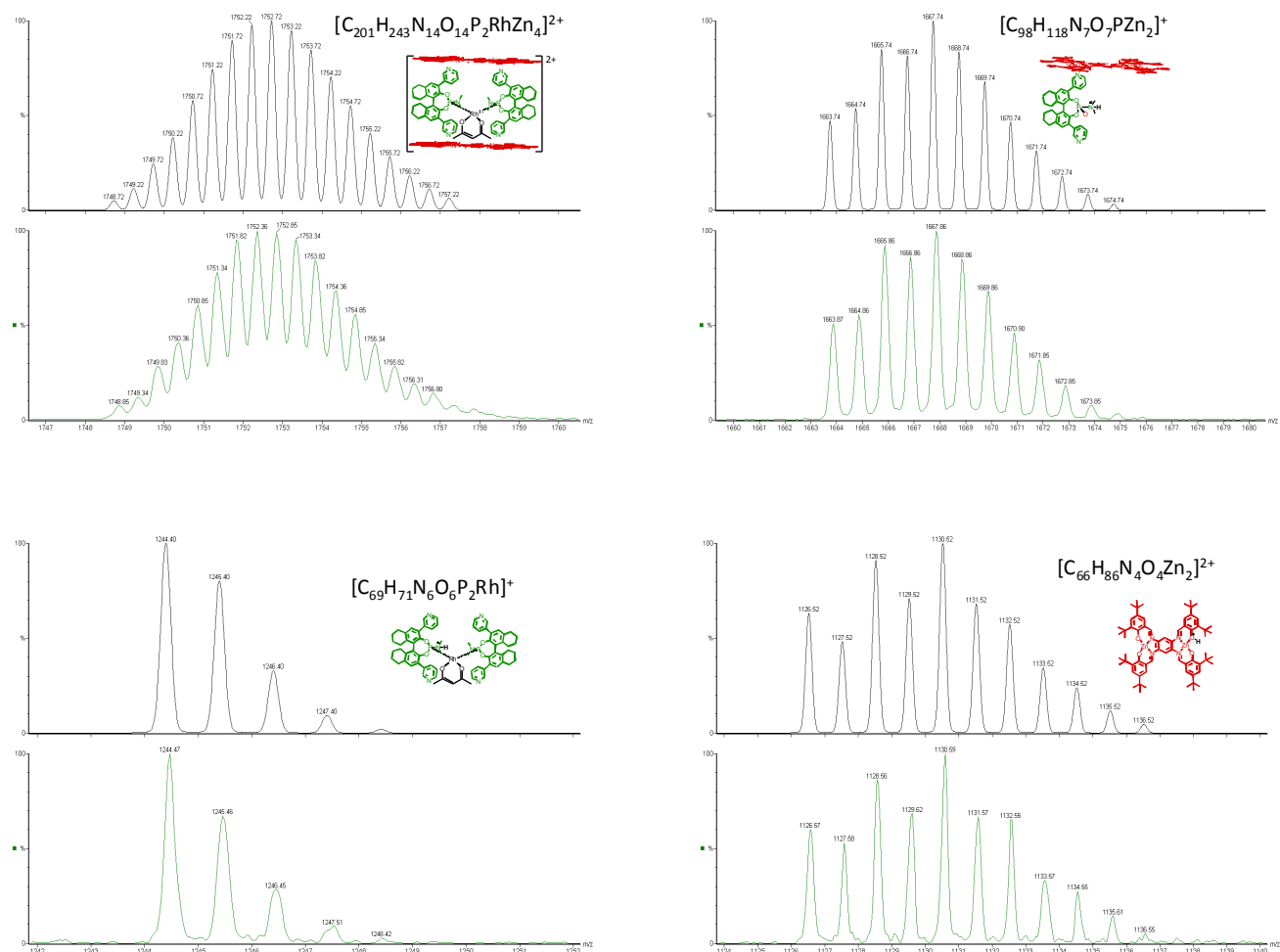
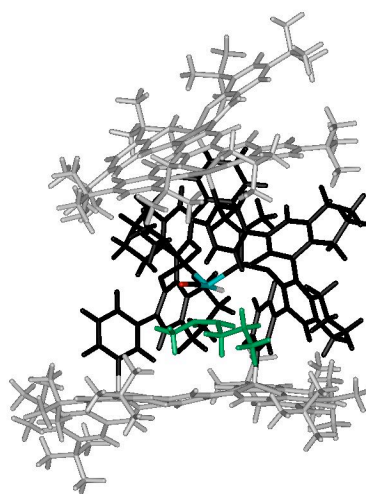


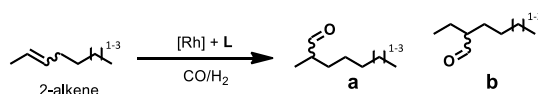
Figure S8. Magnification of MS-MS peaks. Black: model calculated in Masslynx. Green: Experimental.

Computational details



The structure was generated in Spartan 08, using the previously obtained X-ray structure of **2** as a starting point.² After generating the structure **1-CORhH-octene**, the assembly was first optimized using constraints on the salen building blocks (**2**), and in the final PM3 optimization no constraints were applied.

Catalysis Procedures and Results:



A stainless steel autoclave (150 mL) was fitted with an insert capable of holding multiple GC vials (1.5 mL) to run reactions in parallel. Each vial, equipped with a Teflon stir bar, was charged with the appropriate ligand (9 μmol ligand **2**, 5 μmol all bidentate ligands), $\text{Rh}(\text{acac})(\text{CO})_2$ (1 μmol), the substrate (200 μmol), decane (20 μL), and then distilled toluene (1 mL) was added, all under ambient conditions. Each vial was then capped with a septum cap, which was then punctured with a needle (25G x $\frac{5}{8}$ "), which was left piercing through the cap throughout the catalysis. The autoclave was sealed and purged (3 x 10 bar) with syngas ($\text{H}_2/\text{CO} = 1:1$), then pressurized to 20 bar, and the vials left stirring for 84 h. The autoclave was then vented to 1 atm and each reaction quenched with a drop of tri-*n*-butylphosphite. Aliquots were diluted with CH_2Cl_2 for GC analysis.

Table S1. Evaluation of the substrate scope of ligand **2**.^a

Entry	Substrate	% conv ^b	% inner	er ^c
1	<i>trans</i> -2-nonene	30	40	62:38
2	<i>cis</i> -2-nonene	37	38	52:48
3	<i>trans</i> -2-octene	22	42	61:39
4	<i>cis</i> -2-octene	35	39	48:52
5	<i>trans</i> -2-heptene	24	42	59:41
6	<i>cis</i> -2-heptene	38	39	47:53
7	<i>trans</i> -3-hexene	10	na	45:55
8	<i>cis</i> -3-hexene	23	na	44:56
9	1-octene	8	32	nd
10	styrene	8	>99	47:53 ^d

^aAll reactions were performed at 25 °C in toluene with 20 bar 1:1 CO/H_2 , 0.5 mol % $\text{Rh}(\text{acac})(\text{CO})_2$, 2.5 mol % **1** and 84 h reaction time. ^bGC conversions reported. ^cThe er values were determined by chiral GC only for the innermost aldehyde. ^dS:R.

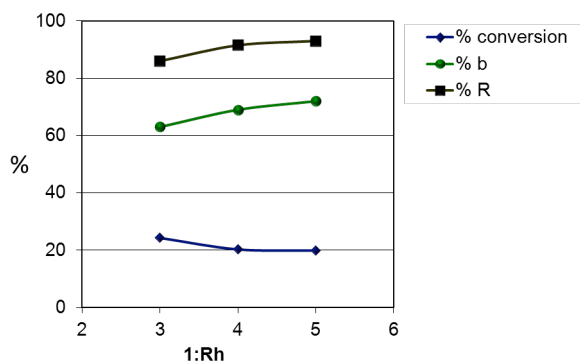


Chart S1. Optimization of ligand **1** to Rh ratio.

Table S2. High temperature (70°C) catalysis results for **1**.

Entry	Ligand	Substrate	% conv	% isomerization products	% b	er b (<i>R:S</i>)
1	2	<i>trans</i> -2-octene	66	3	30	58:42
2	2	<i>cis</i> -2-octene	79	6	27	52:48
3	1	<i>trans</i> -2-octene	12	3	28	82:18
4	1	<i>cis</i> -2-octene	20	5	40	88:12

Gas chromatography details

Gas Chromatography (GC) analyses were performed on a Shimadzu GCT17A instrument (split/splitless injector, J&W Scientific, DBT1 J&W 30 m column, film thickness 3.0 µm, carrier gas 70kPa He, FID Detector). Initial temp: 70°C, hold 1 min. Ramp 1: 7°C/min to 120°C. Ramp 2: 13°C/min to 250°C, hold 5 min.

Table S3. Response factors of alkenes with decane internal standard.

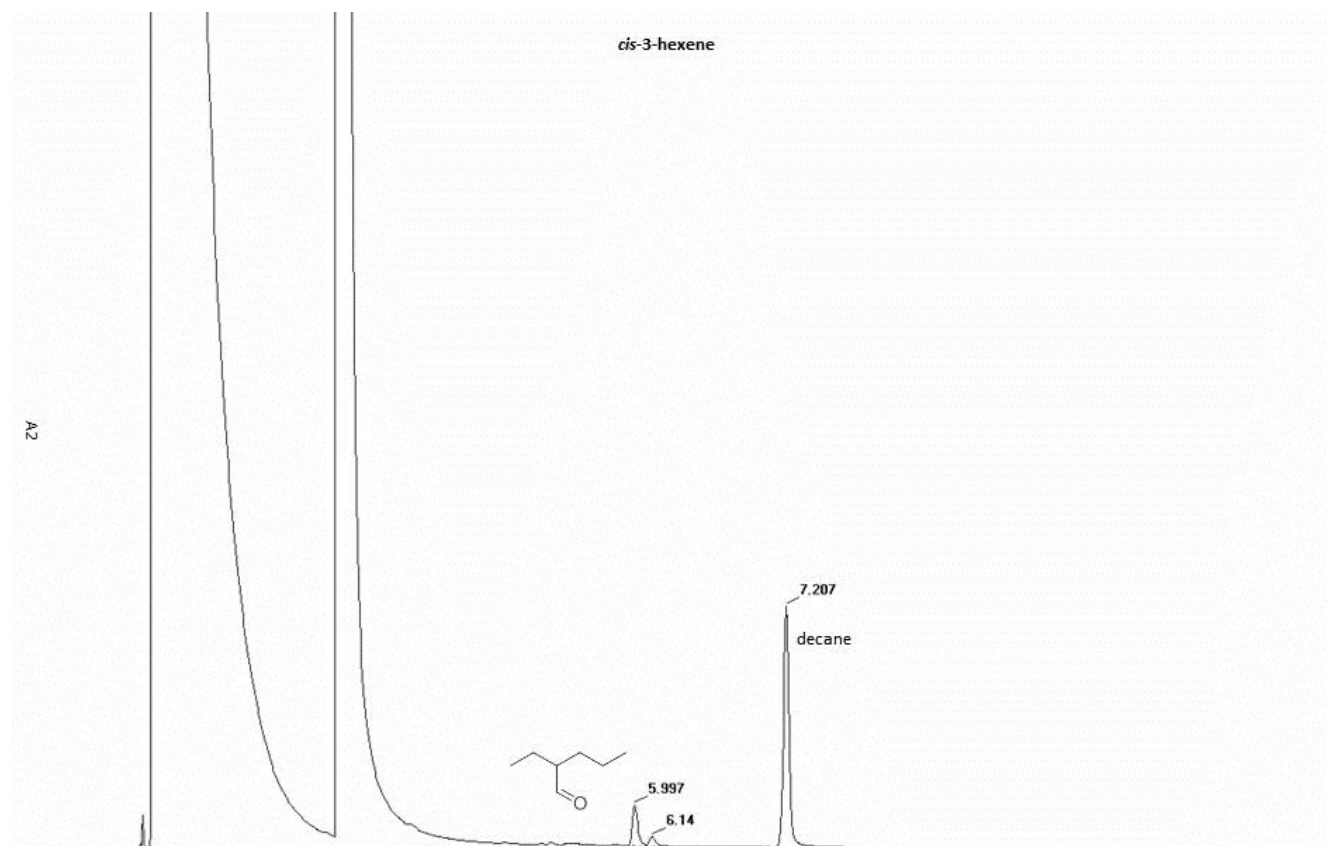
$$\frac{Area_{substrate}}{Area_{decane}} = f \frac{mol_{substrate}}{mol_{decane}}$$

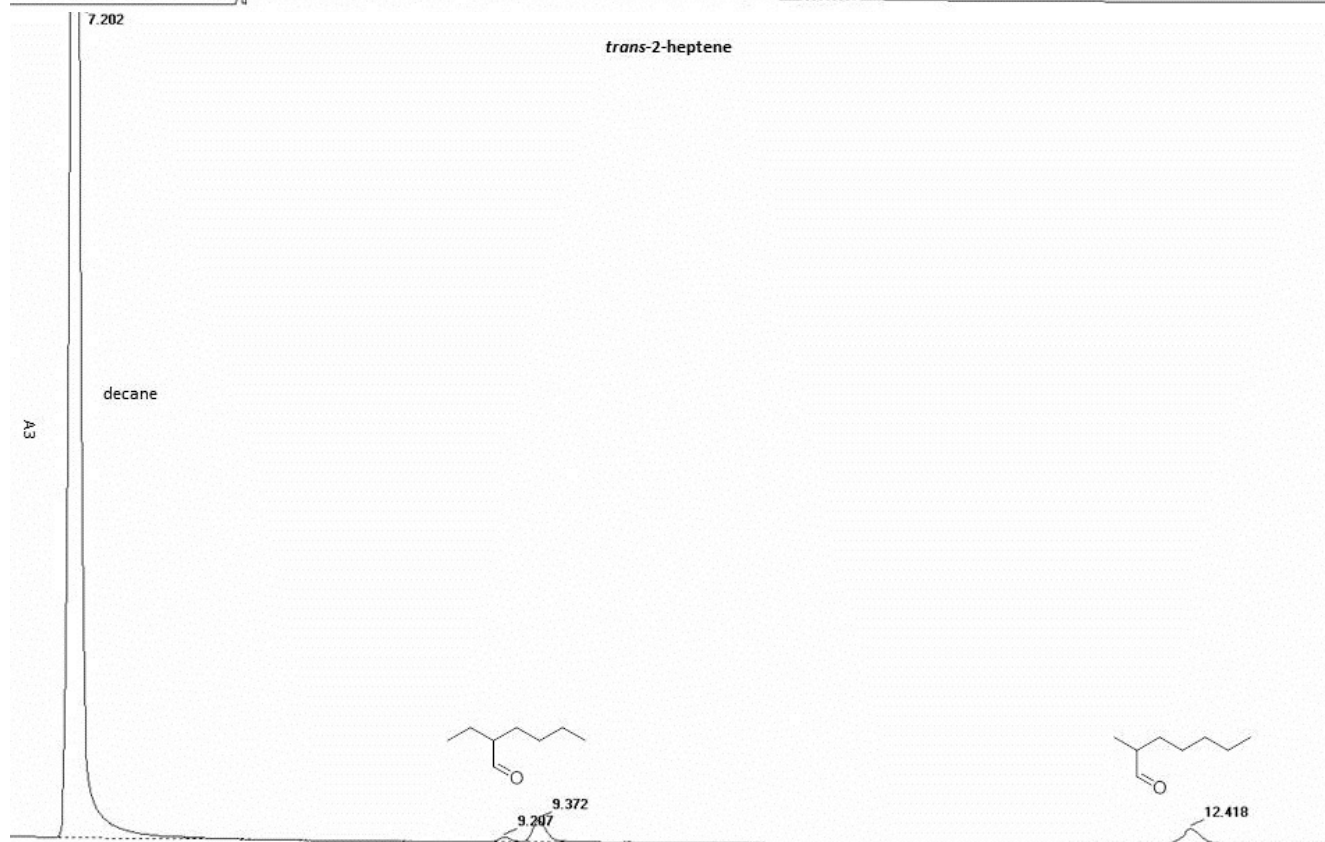
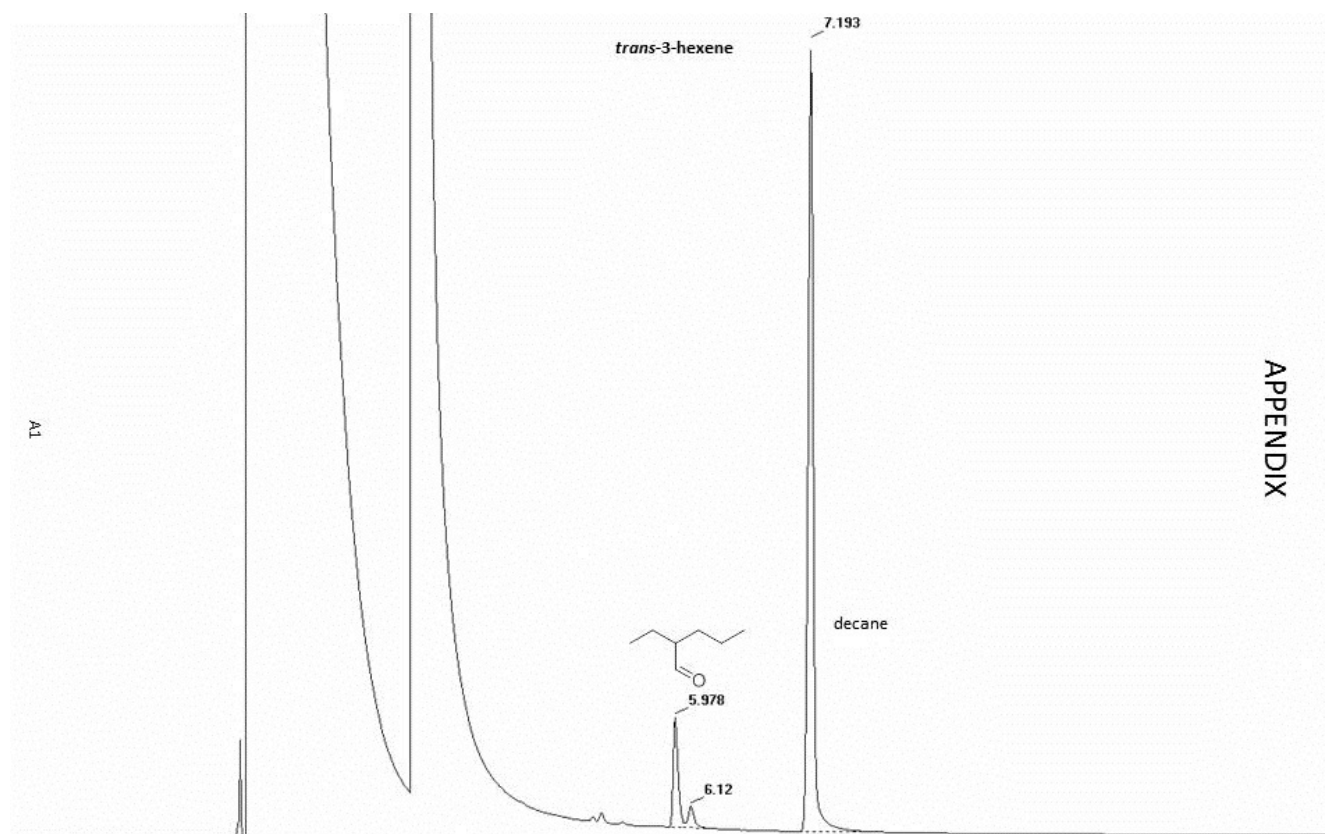
Substrate	<i>f</i>
<i>trans</i> -2-nonene	0,9536
<i>cis</i> -2-nonene	0,8072
<i>trans</i> -2-octene	0,7994
<i>cis</i> -2-octene	0,7052
<i>trans</i> -2-heptene	0,6618
<i>cis</i> -2-heptene	0,6257
<i>trans</i> -3-hexene	0,4743
<i>cis</i> -3-hexene	0,4036
1-octene	0,7461
styrene	0,758

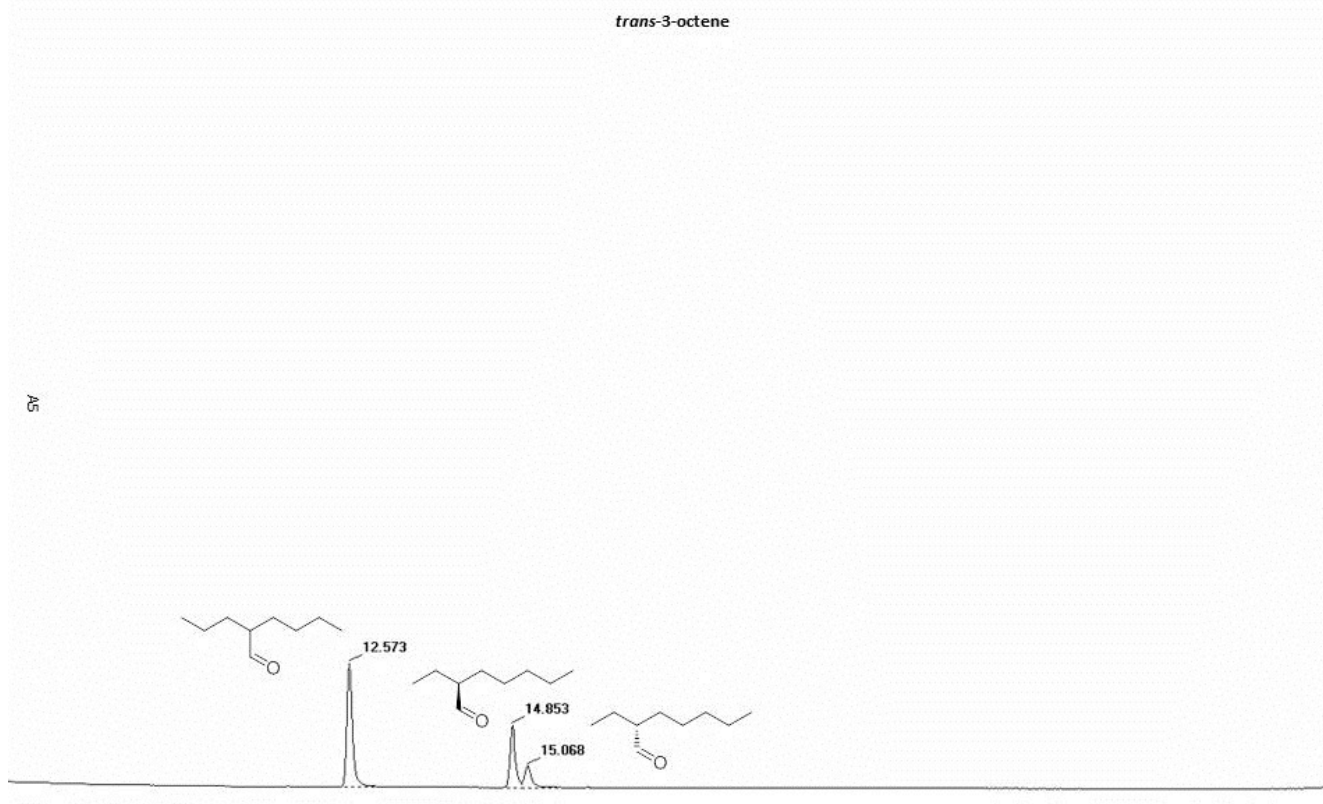
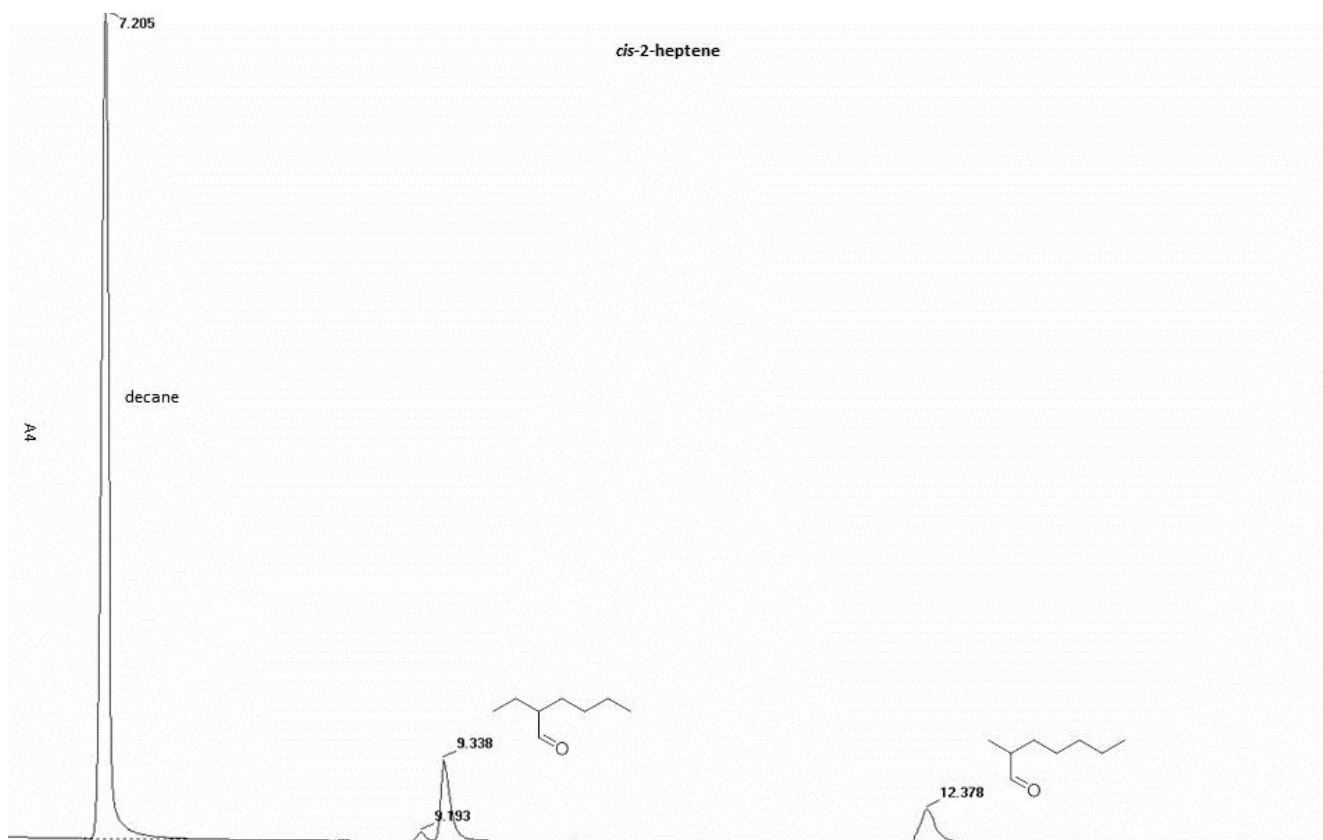
Chiral GC separations were conducted on an Interscience HR GC instrument with a Supelco βTdex 225 capillary column. Initial temp: 80°C. Ramp 1: 1°C/min to 95°C. Ramp 2: 40°C/min to 200°C, hold 2 min. GC traces in Appendix.

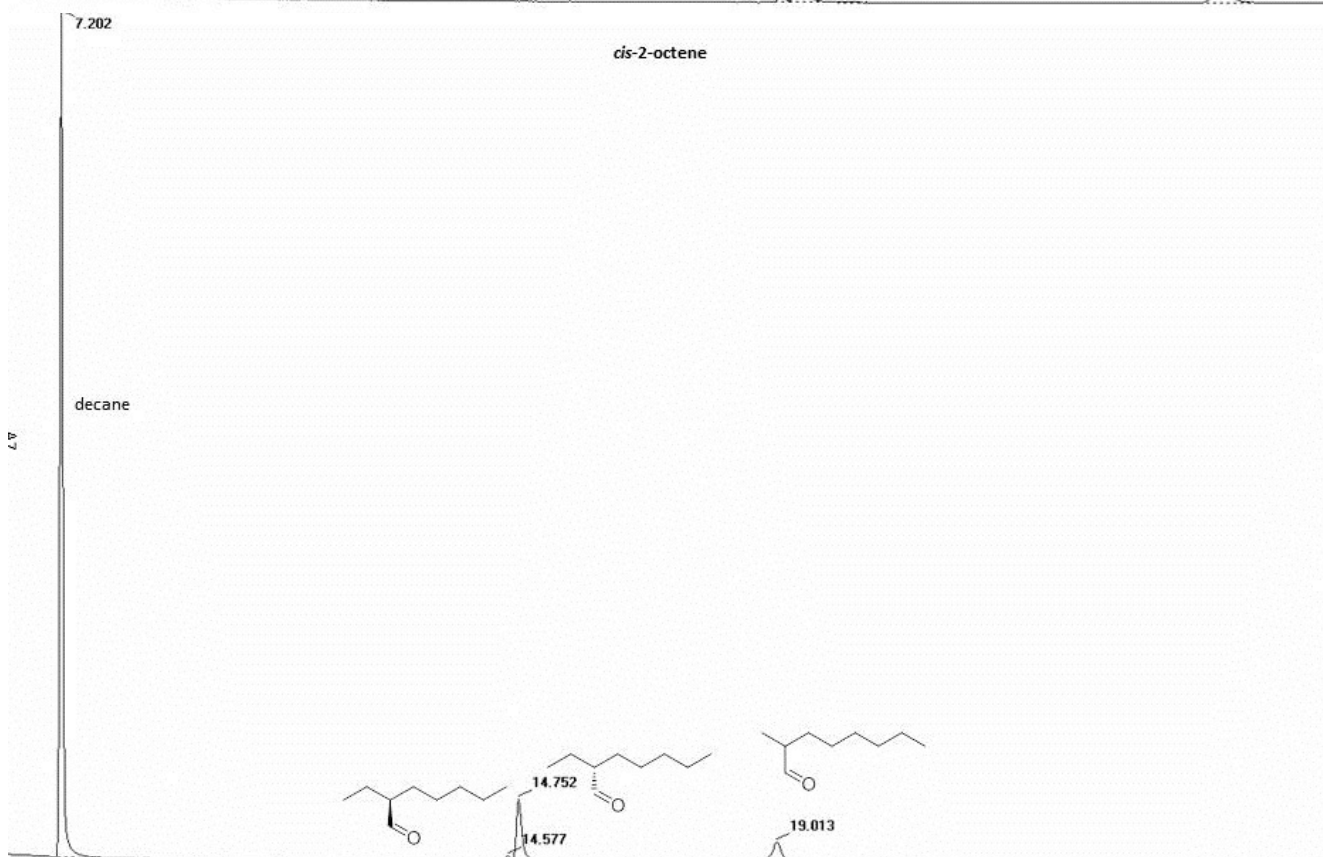
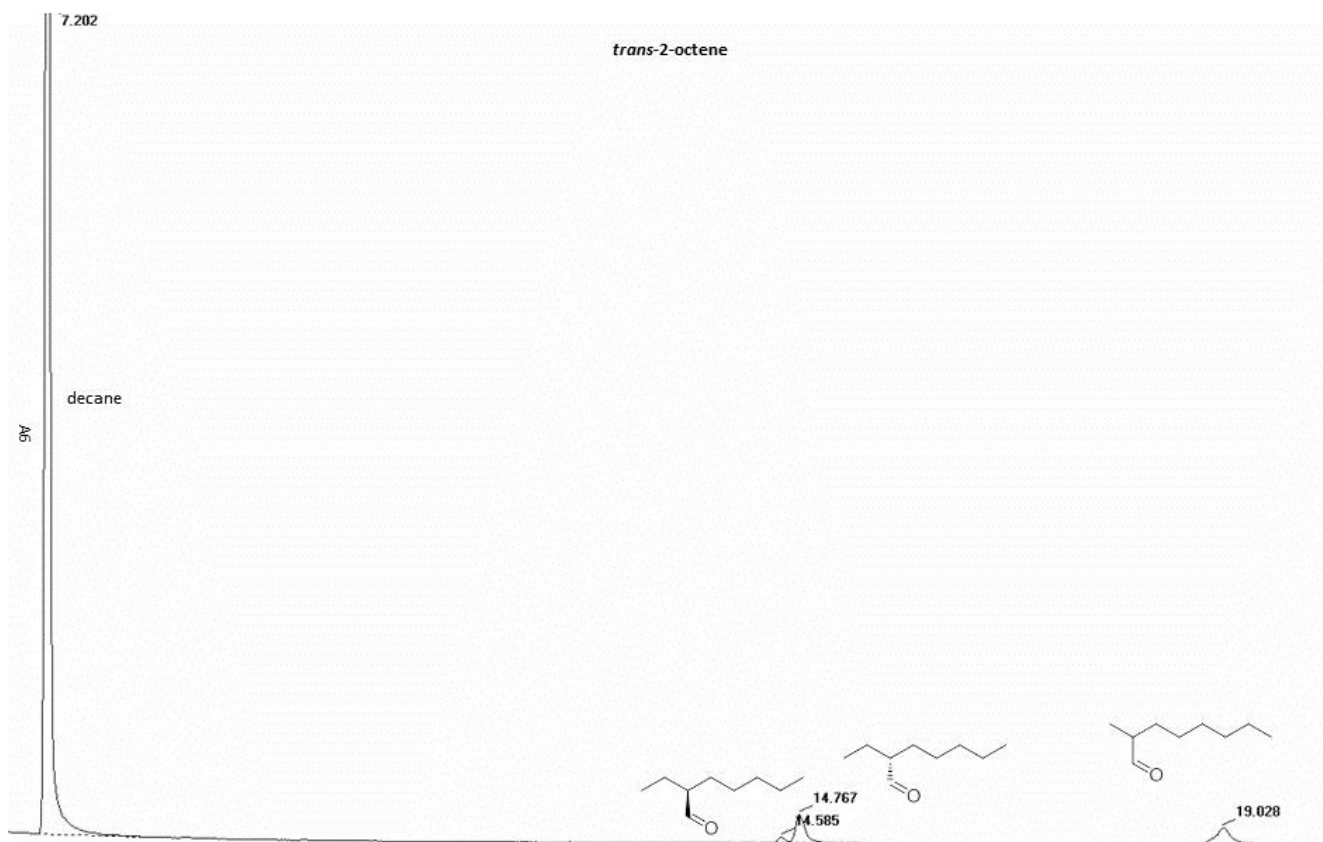
- (1) Bellini, R.; Chikkali, S. H.; Berthon-Gelloz, G.; Reek, J. N. H. *Angew. Chem. Int. Ed.* **2011**, *50*, 7342-7345.
- (2) Kleij, A. W.; Kuil, M.; Tooke, D. M.; Lutz, M.; Spek, A. L.; Reek, J. N. H. *Chem. Eur. J.* **2005**, *11*, 4743-4750.

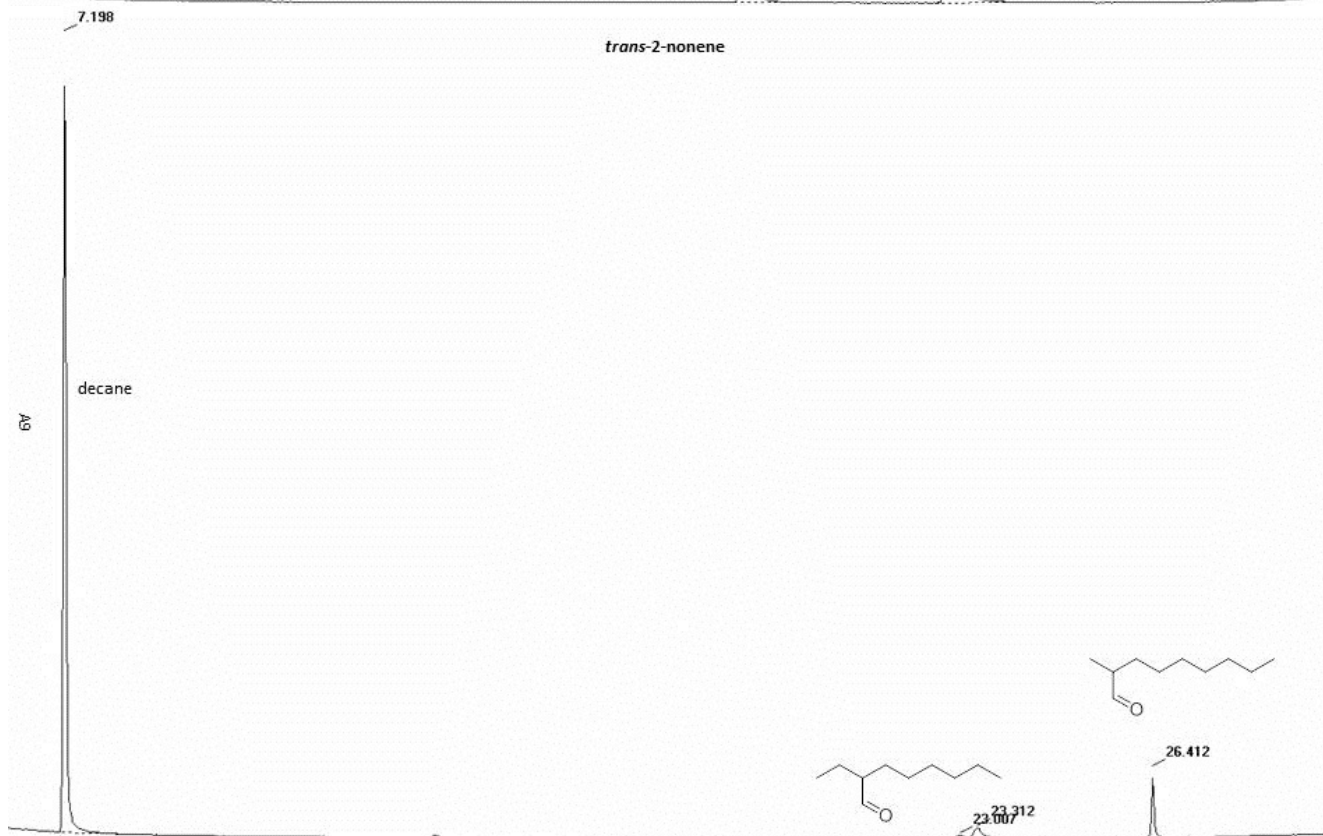
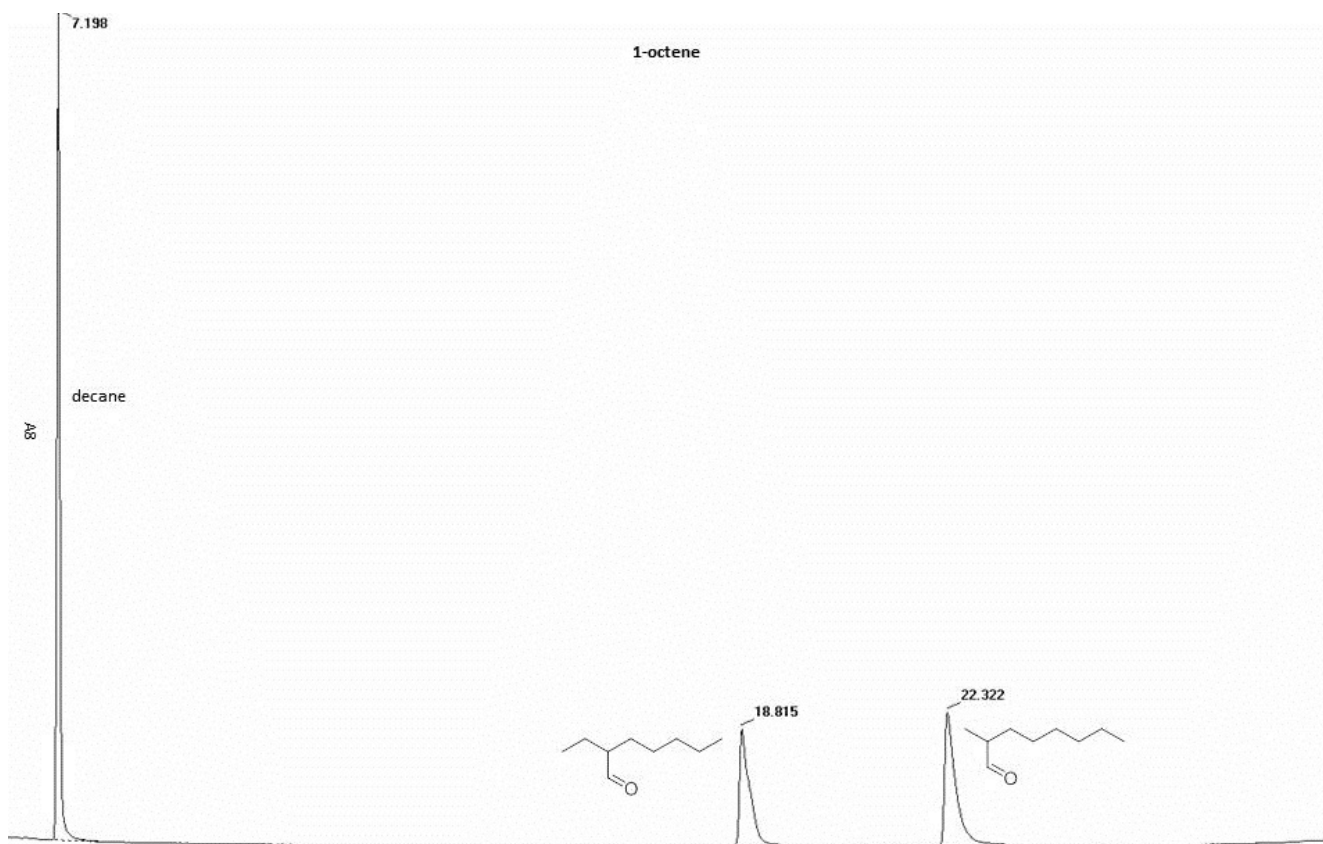
Appendix











cis-2-nonen



styrene

