# Polymerization based on alternating insertion of isocyanide and alkyne into palladium–carbon bond

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## Supporting Information

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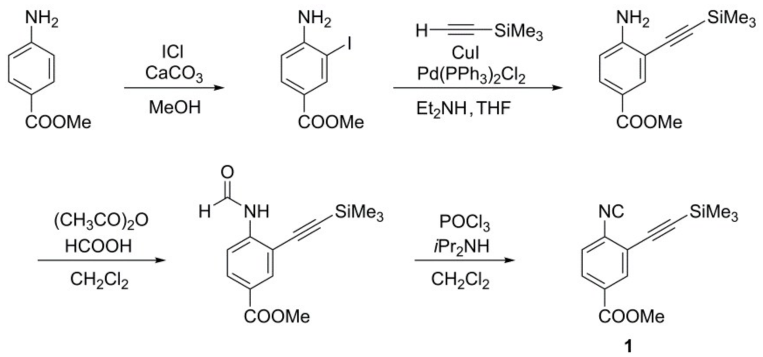
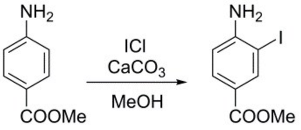
### 1. Synthethis of methyl 4-isocyano-3-((trimethylsilyl)ethynyl)benzoate (1)

Monomer **1** was synthesized following the scheme S1.

**Scheme S1.**



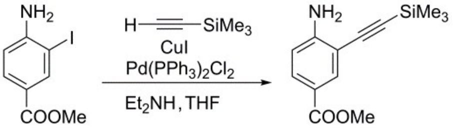
### Methyl 4-amino-3-iodobenzoate



To a solution of methyl 4-aminobenzoate (7.57 g, 50.1 mmol) in MeOH (70 mL) was added a solution of $CaCO_3$ (7.97 g, 80 mmol) in water (20 mL) followed by ICl (2.90 mL, 55.0 mmol). After stirring the mixture at room temperature for 16 h, that was diluted with $Et_2O$ and quenched with water. The aqueous layer was extracted with $Et_2O$ and combined the organic layer. The extract was dried over $Na_2SO_4$ , filtered, and concentrated in vacuo. The residue was purified with silica gel column chromatography (hexane/$Et_2O$ = 7/3) Yield: 12.57 g, 91%

$^1$H NMR ($CDCl_3$): δ 8.33 (d, *J* = 1.9 Hz, 1H, Ar-H), 7.81 (dd, *J* = 8.4Hz, 1.9 Hz, 1H, Ar-H), 7.70 (d, *J* = 8.4 Hz, 1H, Ar-H), 4.52 (br, 2H, $NH_2$), 3.85 (s, 3H, $OCH_3$).

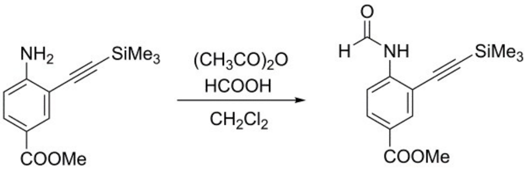
### Methyl 4-amino-3-((trimethylsilyl)ethynyl)benzoate



To a stirred solution methyl 4-formamido-3-iodobenzoate (6.09 g, 20.0 mmol) in diethylamine (100 mL) and THF (50 mL) was added trimethylsilylacetylene (3.06 g, 31.1 mmol) and CuI (74.8 mg, 0.393 mmol) and $PdCl_2(PPh_3)_2$ (145 mg, 0.20 mmol) at room temperature. After 28 h, the reaction mixture was died in vacuo to give dark brown solid. The solid was purified with silica gel column chromatography ($CH_2Cl_2$). Yield: 4.51 g, 91 %

$^1$H NMR (400 MHz, $CDCl_3$): δ 8.01 (d, *J* = 2.0 Hz, 1H, Ar-H), 7.79 (dd, *J* = 8.6 Hz, 2.0 Hz, 1H, Ar-H), 7.70 (d, *J* = 8.5 Hz, 1H, Ar-H), 4.63 (br, 2H, $NH_2$), 3.85 (s, 3H, $OCH_3$), 0.27 (s, 9H, $SiCH_3$). $^{13}$C NMR (100 MHz, $CDCl_3$): δ 166.7, 152.0, 134.8, 131.7, 119.4, 113.3, 107.2, 100.7, 51.9, 0.2.

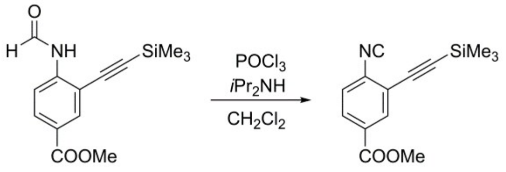
### Methyl 4-formamido-3-((trimethylsilyl)ethynyl)benzoate



A mixture of formic acid (5.0 mL) and acetic anhydride (6.3 mL) was heated at 50 °C for 1h and then cooled to 0 °C. This was added to a solution of methyl 4-amino-3-((trimethylsilyl)ethynyl)benzoate (4.41g, 17.8 mmol) in $CH_2Cl_2$ (100 mL) at 0 °C. After 4 h, the reaction mixture was quenched with saturated $NaHCO_3$ aq. and the aqueous phase was extracted with $CH_2Cl_2$. The extract was washed with saturated $NaHCO_3$ aq. and brine, and dried over $Na_2SO_4$,

filtered and concentration in vacuo to give highly viscous liquid. Yield: 5.11 g, >99%
In solution, the product consists of two isomers in a ratio of 7:3 due to restricted rotation of the C–N bond. $^1$H NMR (400 MHz, $CDCl_3$): δ 8.95 (d, $J$ = 11.0 Hz, 0.3H, CHO), 8.54 (s, 0.7H, CHO), 8.51 (d, $J$ = 8.8 Hz, 0.7H, Ar-H), 7.97 (br, 0.3H, NH), 8.13 (d, $J$ = 1.7 Hz, 0.7H, Ar-H), 8.13 (br, 0.7H, NH), 7.99 (dd, $J$ = 8.8 Hz, 1.7 Hz, 0.7H, Ar-H), 7.97 (s, 0.3H, Ar-H), 7.30 (d, $J$ = 8.5 Hz, 0.3H, Ar-H), 3.91 (s, 3H, $OCH_3$), 0.31 (s, 9H, $SiCH_3$). $^{13}$C NMR (100 MHz, $CDCl_3$): δ 165.9, 165.7, 160.6, 159.0, 141.8, 134.9, 133.8, 131.5, 126.0, 125.6, 119.3, 114.2, 112.6, 112.0, 104.0, 103.6, 98.8, 52.3, 0.0.

**Methyl 4-isocyano-3-((trimethylsilyl)ethynyl)benzoate (1)**



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To a solution of methyl 4-formamido-3-((trimethylsilyl)ethynyl)benzoate (1.85 g, 6.1 mmol) in $CH_2Cl_2$ (50 mL) was added diisopropylamine (3 mL) and phosphoryl chloride (1.68 g, 11.0 mmol) at 0 °C. After 2 h, the reaction mixture was quenched with saturated $NaCO_3$ aq. The organic layer was washed twice with brine, dried over $Na_2SO_4$, filtered and concentration in vacuo. The residue was purified with silica gel column chromatography (hexane/EtOAc = 1/9) to give white solid. Yield: 1.87 g, >99%
$^1$H NMR (400 MHz, $CDCl_3$): δ 8.19 (d, $J$ = 1.9 Hz, 1H, Ar-H), 7.99 (dd, $J$ = 8.3 Hz, 1.9 Hz, 1H, Ar-H), 7.43 (d, $J$ = 8.3 Hz, 1H, Ar-H), 3.94 (s, 3H, $OCH_3$), 0.30 (s, 9H, $SiCH_3$). $^{13}$C NMR (100 MHz, $CDCl_3$): δ 170.5, 165.1, 134.0, 130.8, 130.1, 126.7, 104.5, 98.6, 52.8, −0.2. FT-IR (KBr tablet, $cm^{-1}$): 2171 ($\nu_{(C\equiv C)}$), 2119 ($\nu_{(C\equiv N)}$), 1731 ($\nu_{(C=O)}$).

2. **The investigation of the reaction rate constant for the intramolecular insertion of alkyne**

The experiment procedures are written in the main manuscript. The reactions from **II** to **III** were monitored by $^{31}$P NMR spectroscopy. The rate constant were calculated from the first-order plot of ln([**II**]/[**II**]$_0$) against the reaction time.

**IIa to IIIa** (Table 1, entry 1)

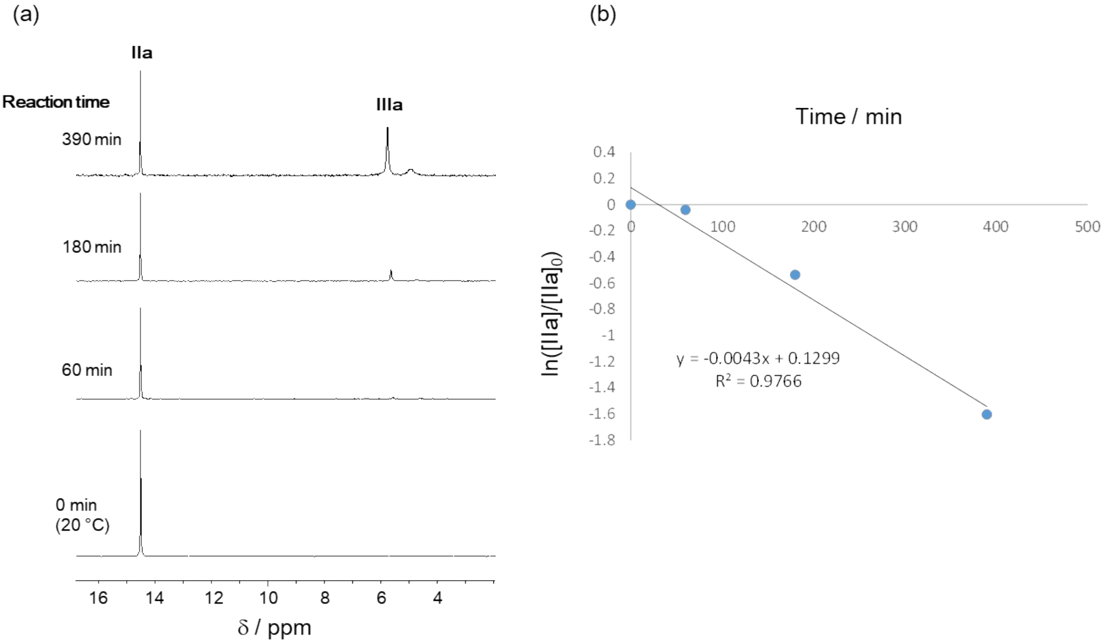


**Fig. S1** The time course of the reaction from **IIa** to **IIIa** (Table 1, entry 1): (a) $^{31}$P NMR spectra (162 MHz, $CDCl_3$, 25 °C) and (b) the plot of ln([**IIa**]/[**IIa**]$_0$) versus time.

**IIb to IIIb** (Table 1, entry 2)

Only using **Ib**, the characteristic double-doublet signals were first observed on $^{31}P$ NMR spectra (Fig. S2). The double-doublet signal is attributed to the *cis*-form bisphosphine palladium complexes. The double-doublet signal decreased as the reaction progress, and one signal appeared. That suggests that the formation of **IIIb** would proceed via the *cis*-form (Scheme S2). The reaction rate was calculated from consumption of **IIb**.

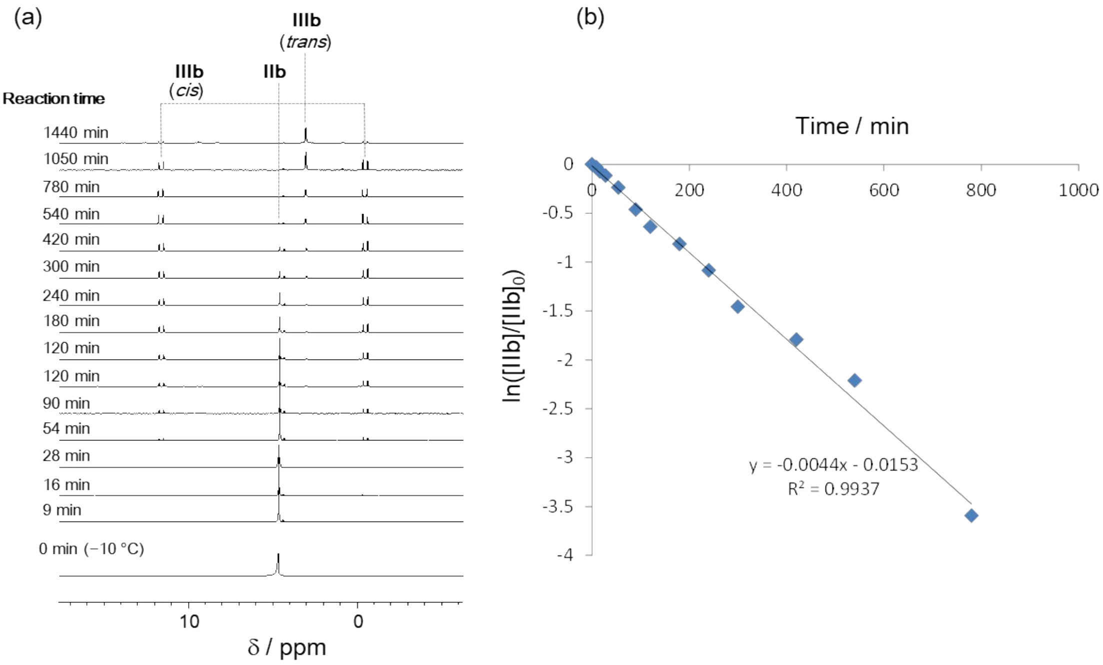
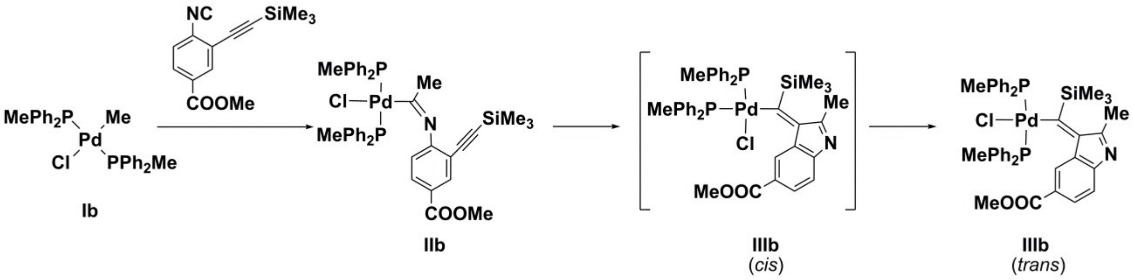


**Fig. S2** The time course of the reaction from **IIb** to **IIIb** (Table 1, entry 2): (a) $^{31}P$ NMR spectra (162 MHz, $CDCl_3$, 20 °C) and (b) the plot of ln([**IIb**]/[**IIb**]$_0$) versus time.

**Scheme S2.**



**IIc to IIIc** (Table 1, entry 3, 4)

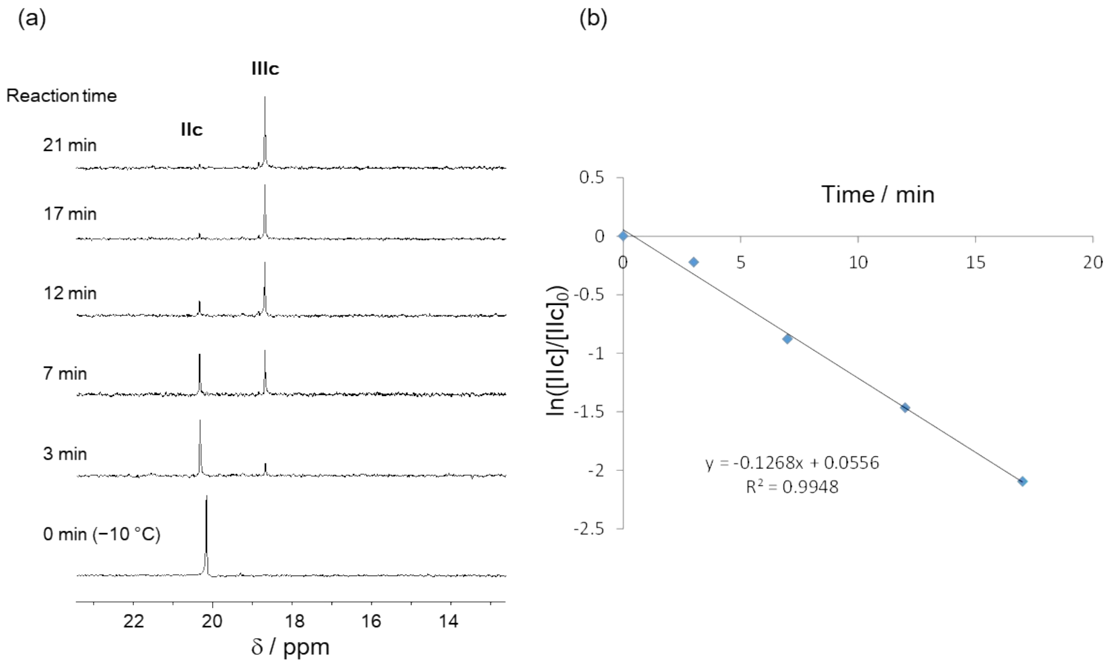


**Fig. S3** The time course of the reaction from **IIc** to **IIIc** (Table 1, entry 3): (a) $^{31}$P NMR spectra (162 MHz, $CDCl_3$, 20 °C) and (b) the plot of ln([**IIc**]/[**IIc**]$_0$) versus time.

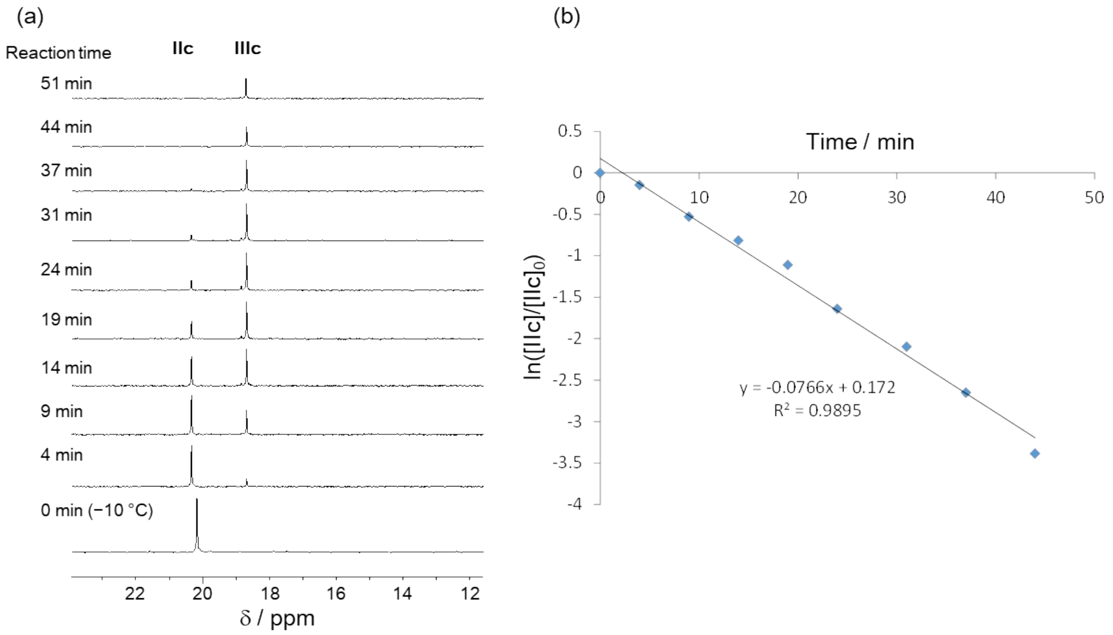


**Fig. S4** The time course of the reaction from **IIc** to **IIIc** in the presence of 0.5 equiv of $PPh_3$ (Table 1, entry 4): (a) $^{31}$P NMR spectra (162 MHz, $CDCl_3$, 20 °C) and (b) the plot of ln([**IIc**]/[**IIc**]$_0$) versus time.

## 3. Determination of the ratio of successive insertion units on poly-1

The ratio of indole structure units in **poly-1** was determined by comparing IR spectrum of **poly-1** with **poly-1’** (Fig. S5). The two spectra were normalized by the area intensity of the absorption ν(C=O), and the absorption ν(C≡C) were compared. The ratio of the intensity of the absorption ν(C≡C) was **poly-1**/**poly-1’** = 33/100. Assuming that the intensities of ν(C≡C) and ν(C=O) don’t depend on the molecular structure, there is 33% of unreacted alkyne moiety in **poly-1**. That suggests the alternating insertion of isocyanide and alkyne proceeded to form indole structure 67% in the polymer.

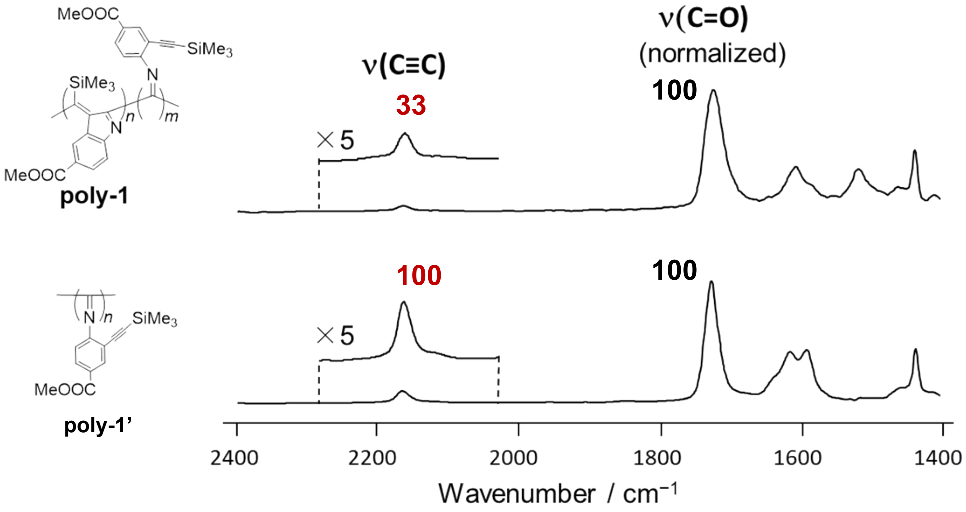
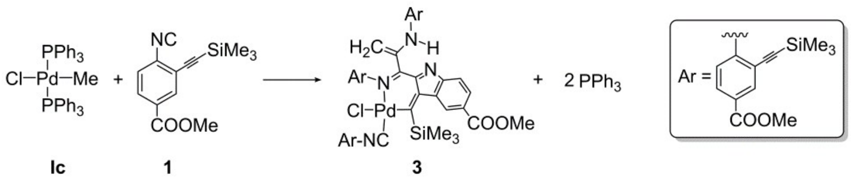


**Fig. S5** IR spectra of **poly-1** and **poly-1’** in $CHCl_3$ normalized with the area intensity of ν(C=O).

## 4. Characterization of compound 3

To investigate complex **3**, the reaction of **Ic** with 5 equiv of **1** ([**Ic**] = 14.7 mM, [**1**]/[**Ic**] = 5) was performed in $CDCl_3$ at 0 ºC (Scheme S3). Detailed experimental procedures are written in the main text. The reaction mixture was analyzed by $^1$H NMR spectroscopy at 0 ºC. Signals owing to **1** were decreased, and a single complex was observed. In the spectrum, four new characteristic signals of equal intensity were observed for the trimethylsilyl and methyl ester groups, respectively (Fig. S6). Additionally, signals corresponding to the terminal alkene ($CH_2$=) protons were observed at 3.80 and 3.53 ppm and amine (NH) proton was observed at 10.64 ppm instead of the methyl proton derived from **Ic** (These protons were confirmed by HSQC spectrum: Two alkene protons interact the same carbon atom, and the amine proton interacts no carbon atom, Fig. S7). As such, these results suggest that the imine-enamine tautomerization of the imino acyl group originated from the initial insertion of the isocyanide moiety of **1** into the methyl group of **Ic**. In the ESI-MS analysis of the reaction mixture, the signals were observed at m/z = 892.1895 and 1149.2765, along with their characteristic isotope distribution patterns for [Pd(**1**)$_3$(Me)]$^+$ and [Pd(**1**)$_4$(Me)]$^+$ (Fig. S8). The IR absorption of the coordinated isocyanide $\nu$(C≡N) was observed at 2184 cm$^{-1}$, while absorption bands corresponding to the acetylene $\nu$(C≡C) and indole $\nu$(C=N) moieties were also observed at 2158 and 1515 cm$^{-1}$ respectively (Fig. S9). From these results and Yamamoto's work, the structure of **3** and its formation mechanism are estimated in Scheme 5. When the reaction was carried out using 4 equiv of **1**, complicated signals was observed on $^1$H NMR spectrum. Compound **3** would be formed stably in the presence of excess **1**.

**Scheme S3**.



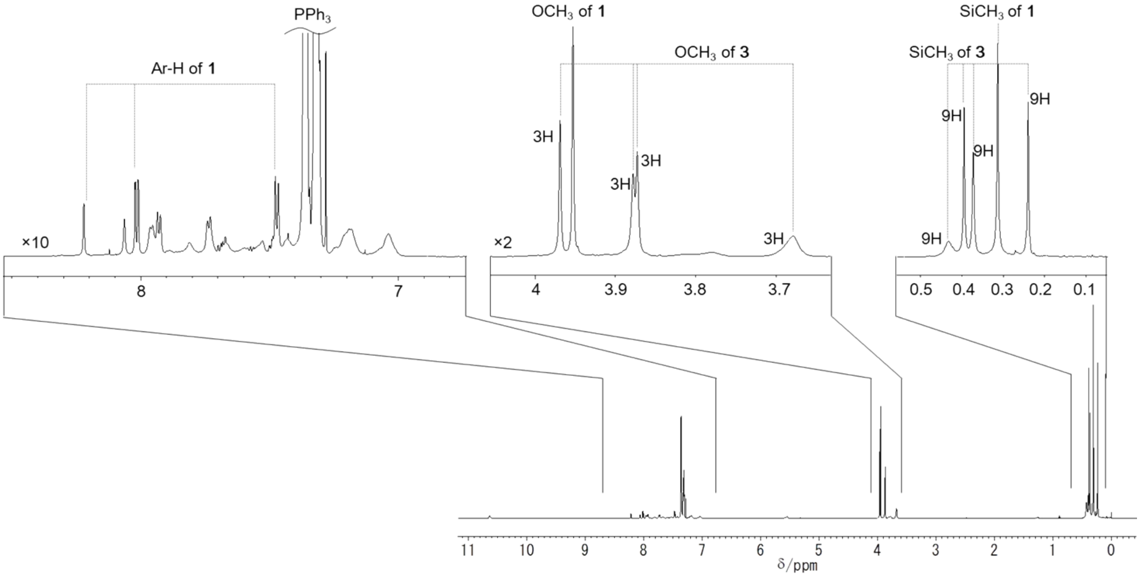


**Fig. S6** $^1$H NMR spectrum of the reaction mixture of **Ic** with 5 equiv of **1** in CDCl$_3$ at 0 °C

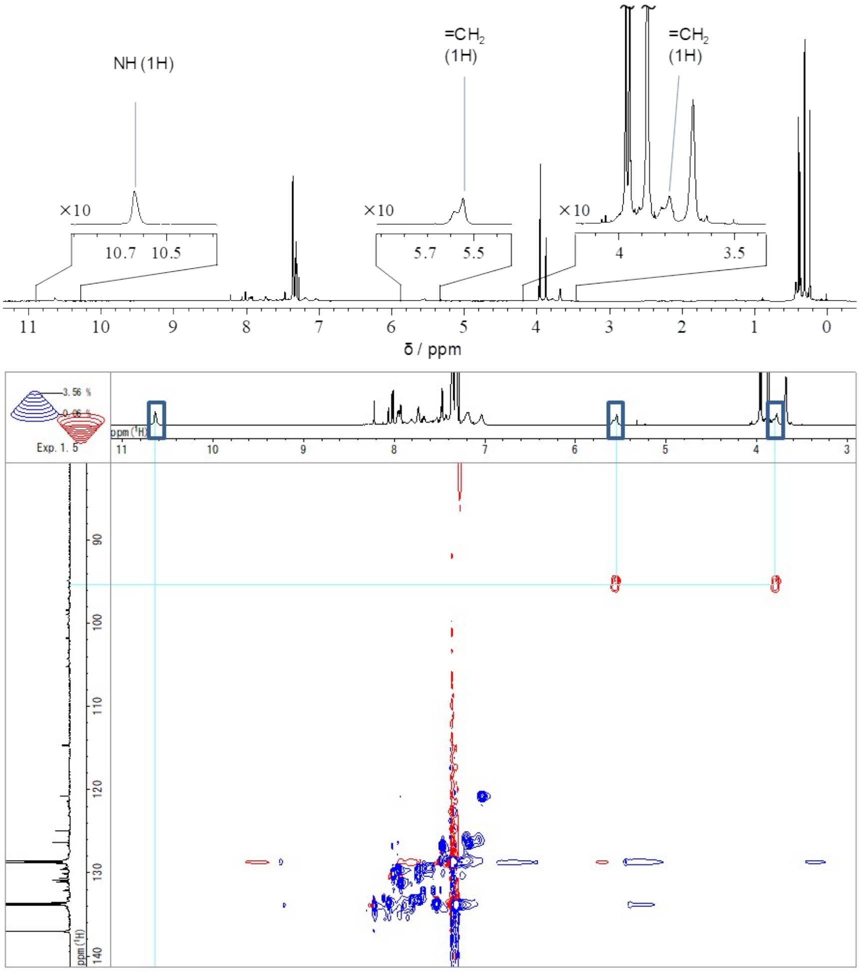


**Fig. S7** HSQC spectrum of the reaction mixture of **Ic** with 5 equiv of **1** in CDCl$_3$ at 0 °C.

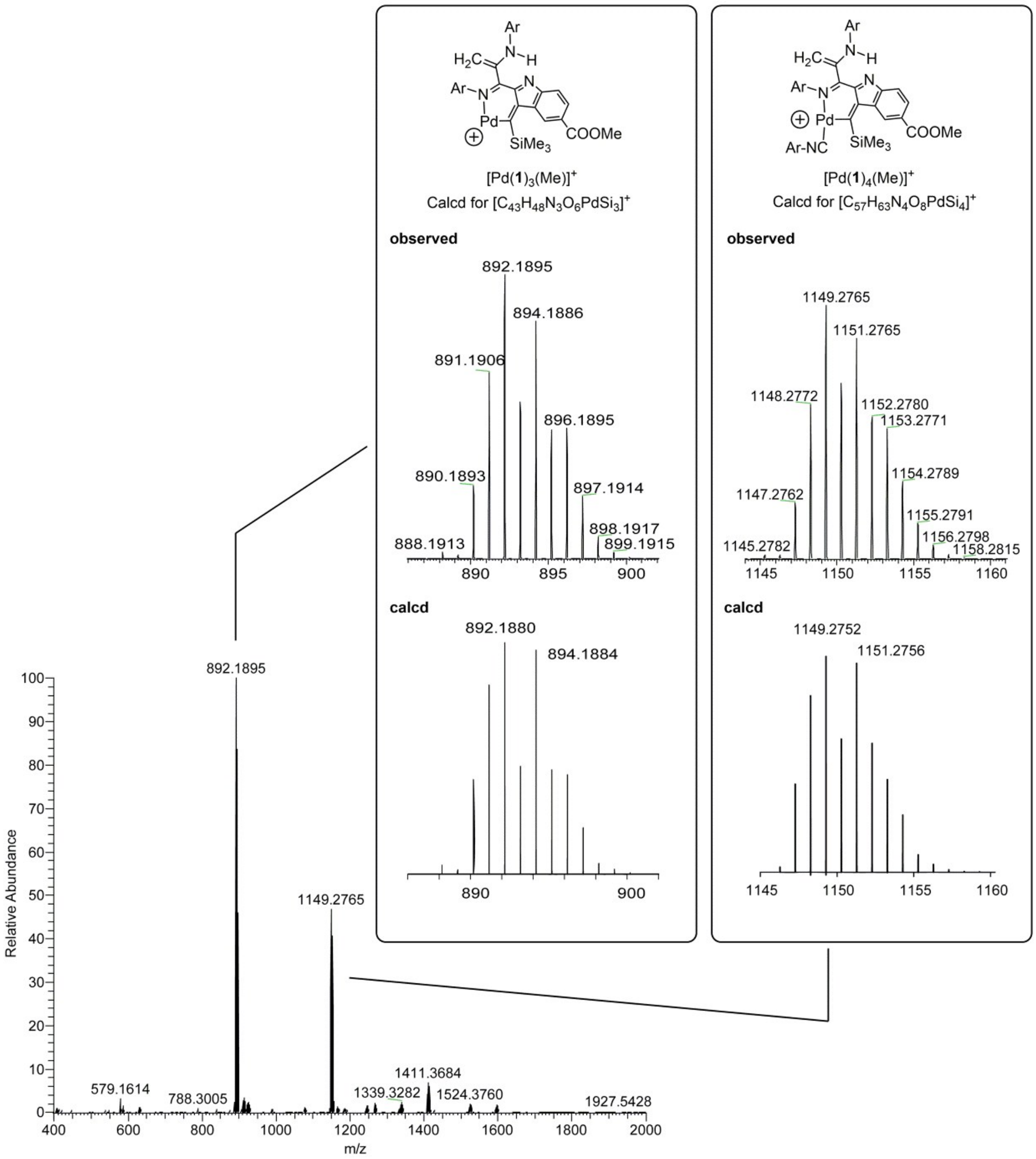


**Fig. S8** ESI-MS spectrum of the reaction mixture of **Ic** with 5 equivof **1**.

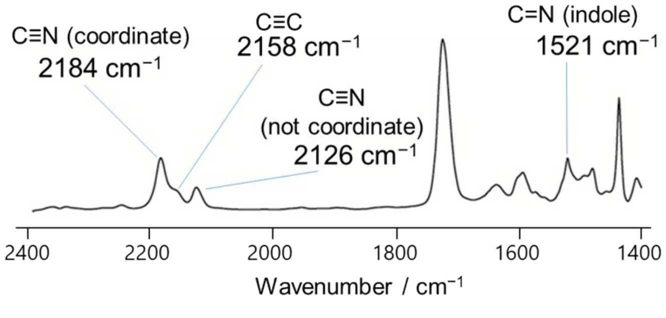


**Fig. S9** IR spectrum of the reaction mixture of **Ic** with 5equivof **1** in $CHCl_3$.

## 5. Spectra and chromatograms

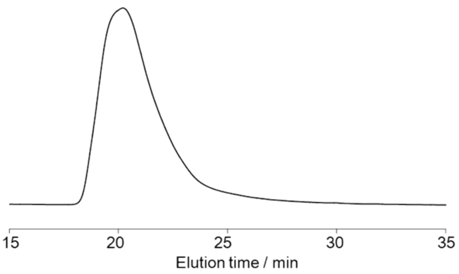


**Fig. S10** SEC curve of **poly-1** after the purification (Table 2, entry 1).

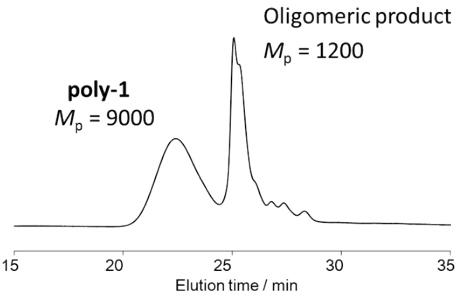


**Fig. S11** SEC curve of the reaction mixture of the polymerization in chloroform (Table 2, entry 2).

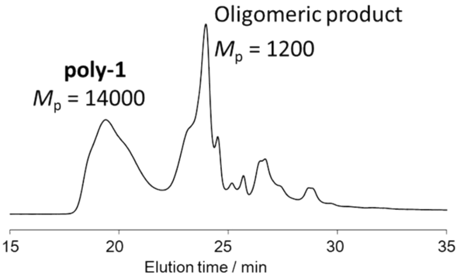


**Fig. S12** SEC curve of the reaction mixture of the polymerization in toluene (Table 2, entry 3).

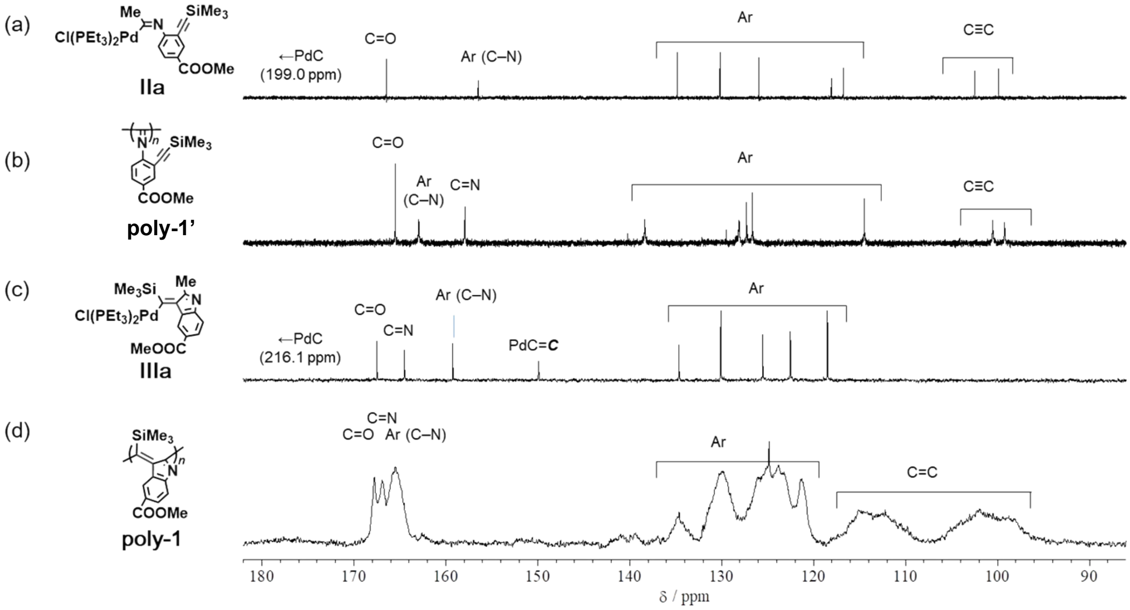


**Fig. S13** $^{13}$C NMR spectra of (a) **IIa**, (b) **poly-1'**, (c) **IIIa**, and (d) **poly-1** ($CDCl_3$, 25 °C).

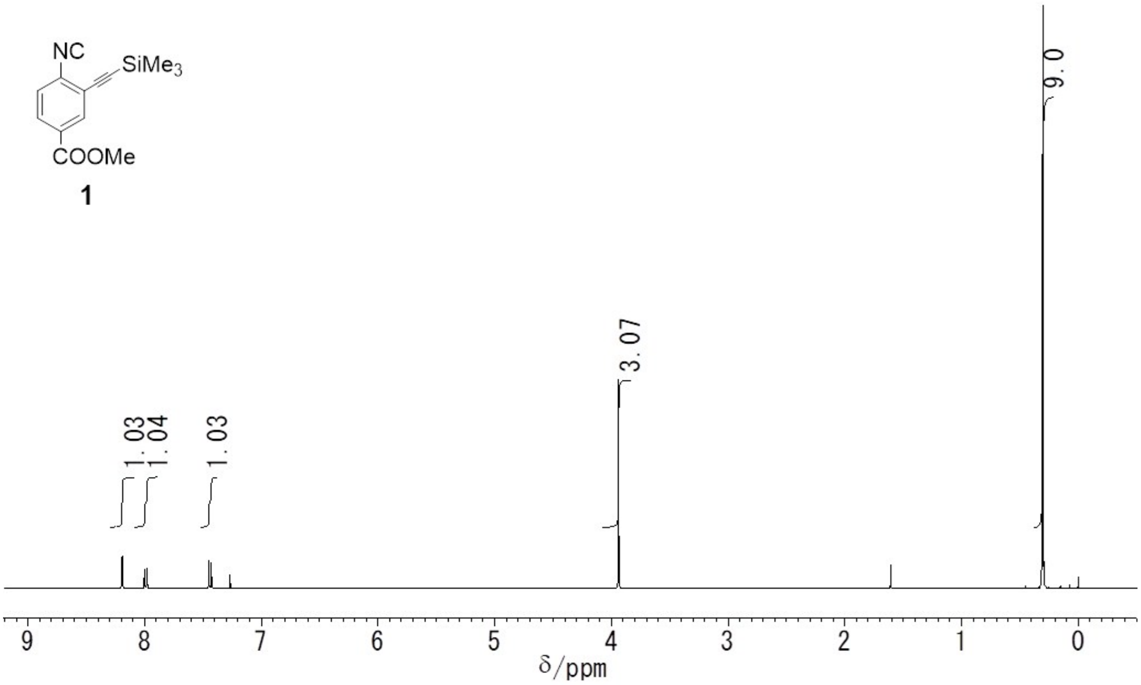


**Fig. S14** $^1$H NMR spectrum of **1** (CDCl$_3$, 25 °C).

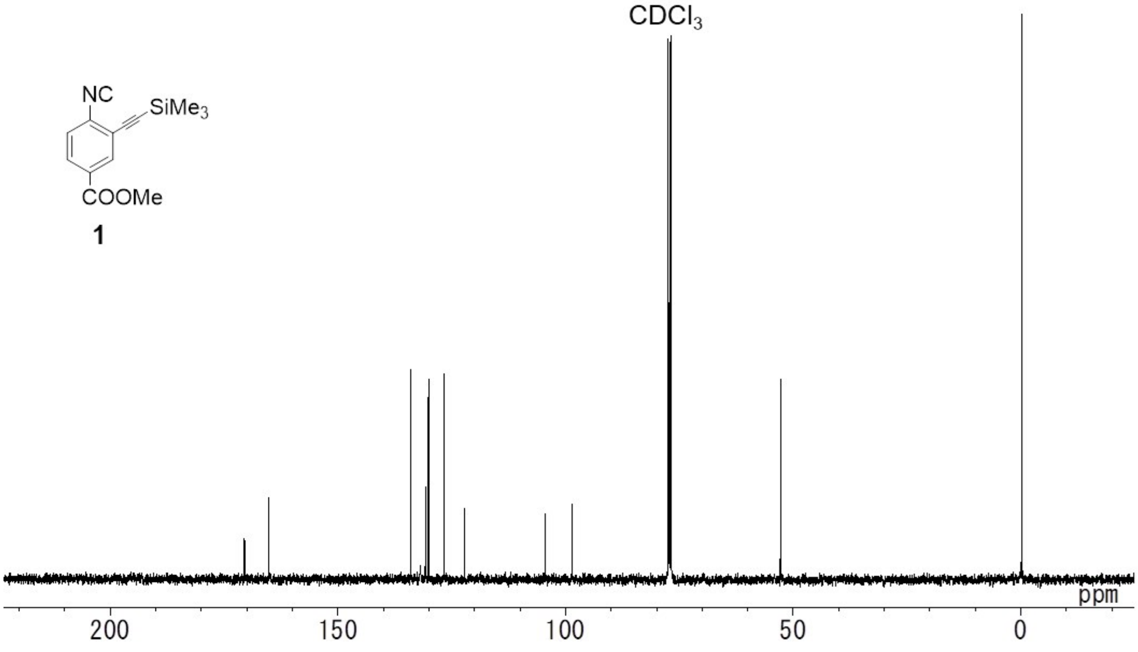


**Fig. S15** $^{13}$C NMR spectrum of **1** (CDCl$_3$, 25 °C).

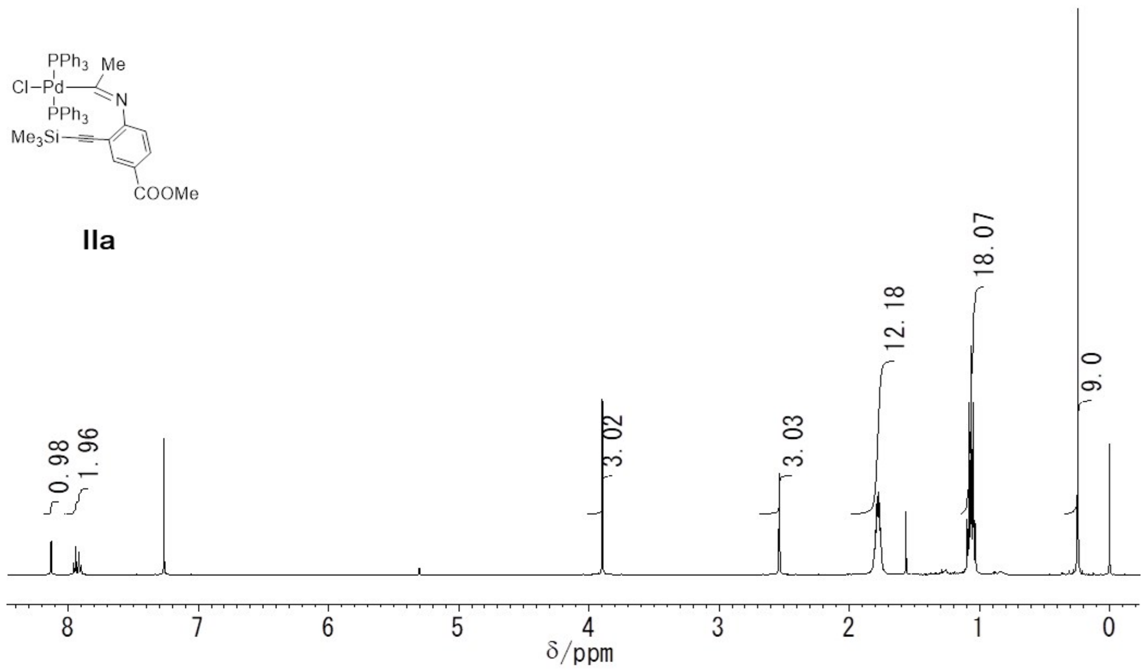


**Fig. S16** $^{1}$H NMR spectrum of **IIa** ($CDCl_3$, 25 °C).

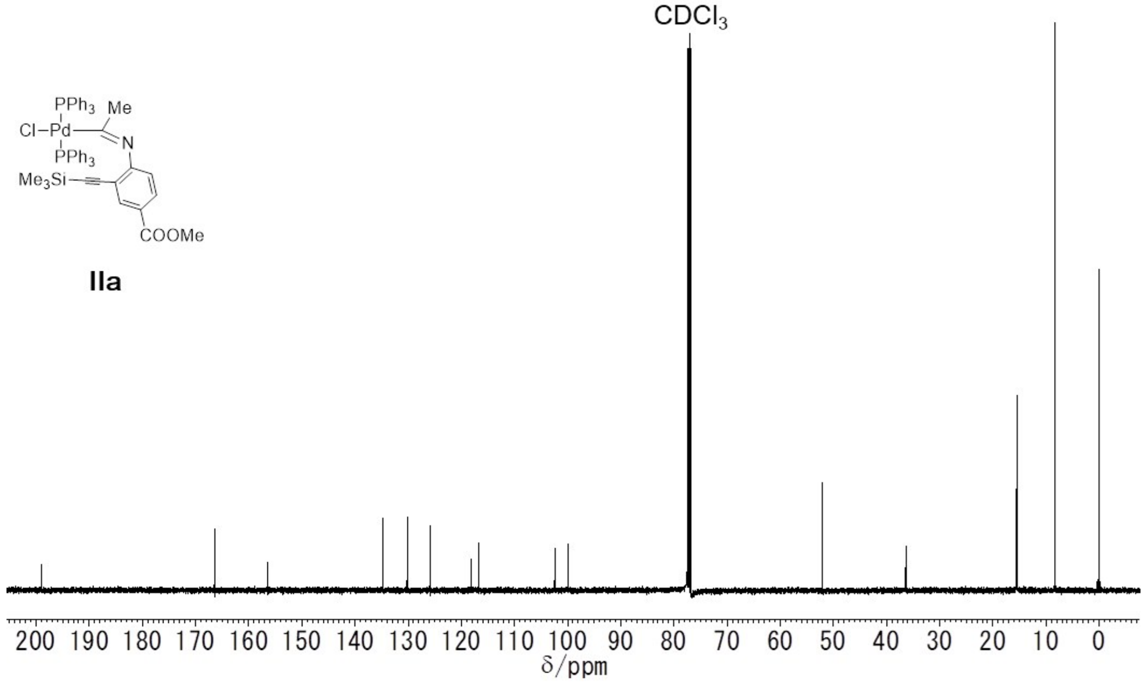


**Fig. S17** $^{13}$C NMR spectrum of **IIa** ($CDCl_3$, 25 °C).

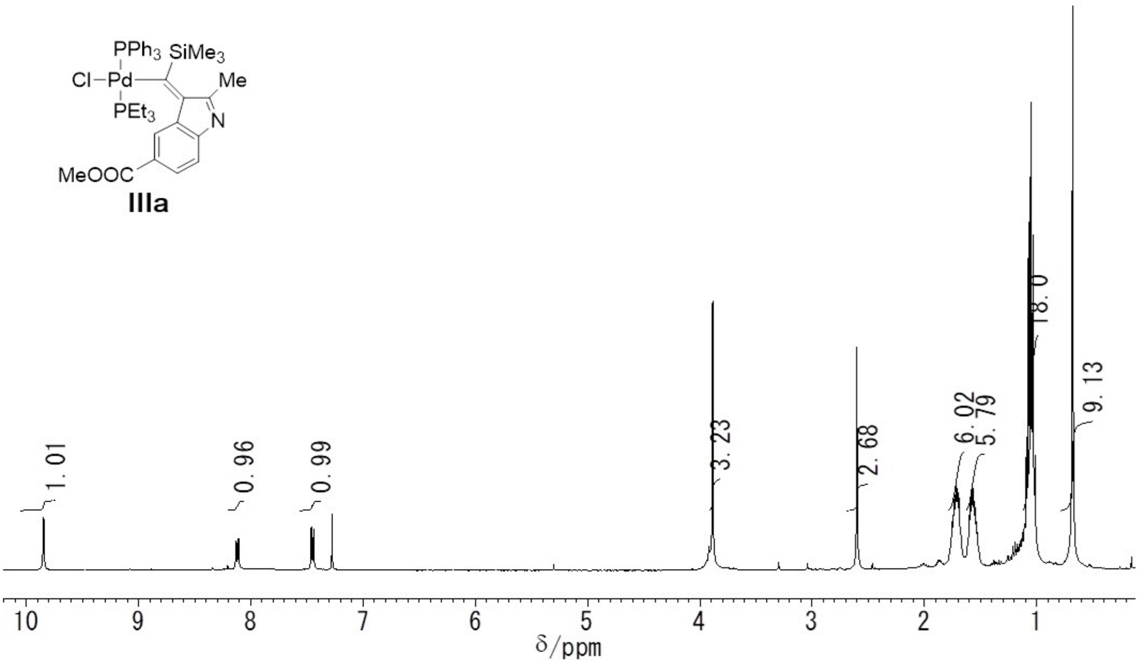


**Fig. S18** $^1$H NMR spectrum of **IIIa** ($CDCl_3$, 25 °C).

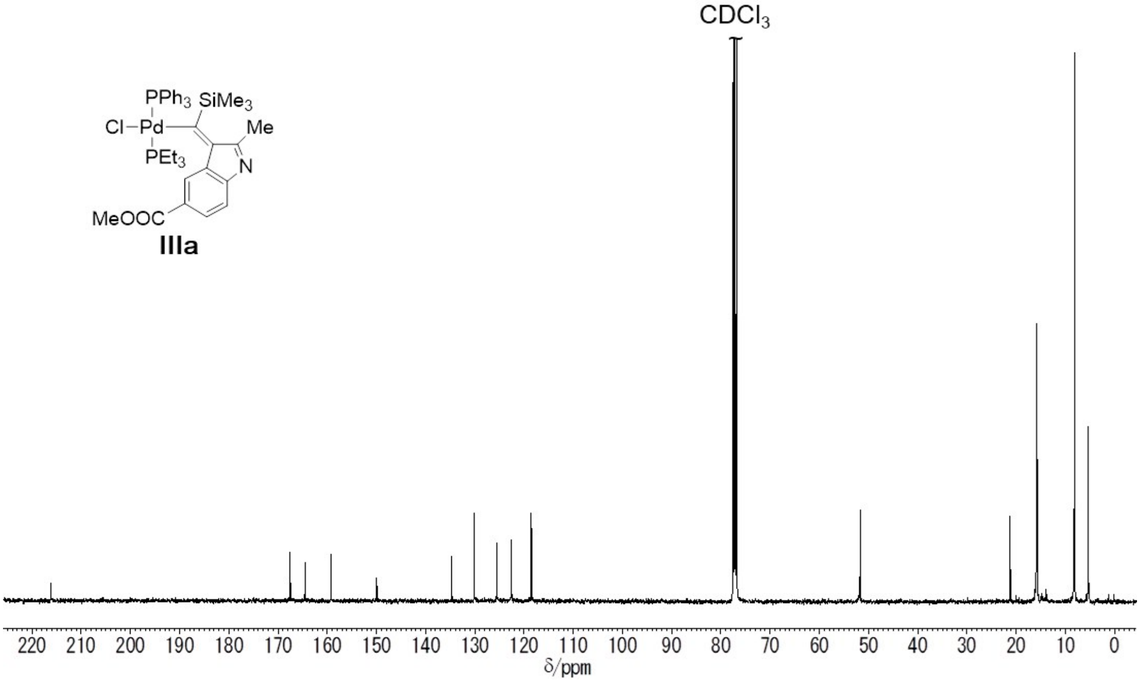


**Fig. S19** $^{13}$C NMR spectrum of **IIIa** ($CDCl_3$, 25 °C).

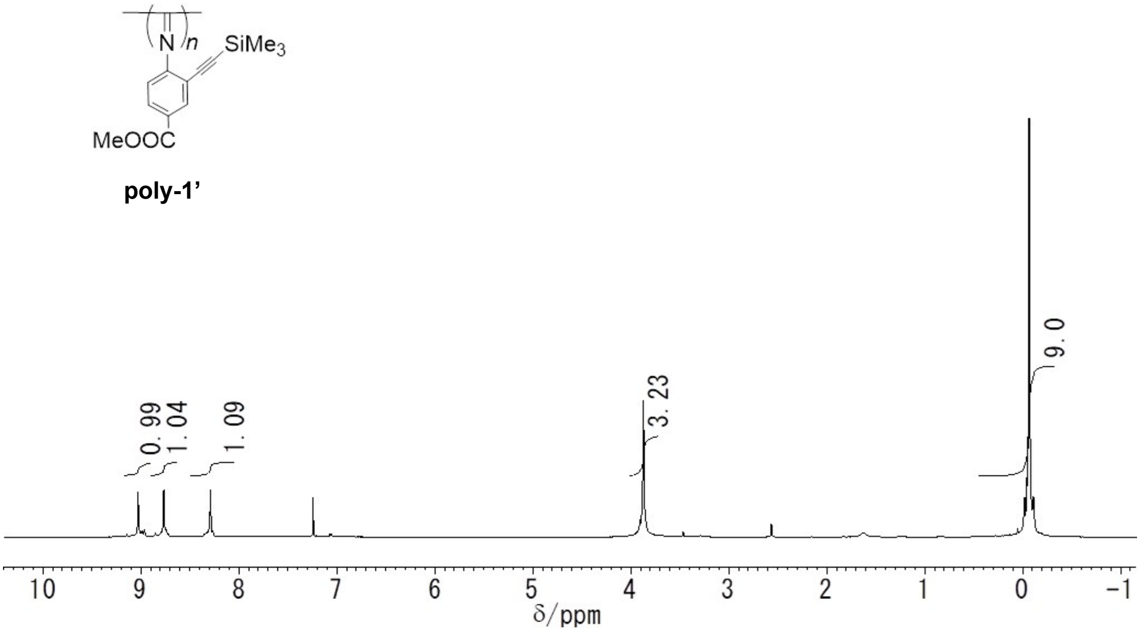


**Fig. S20** $^{1}$H NMR spectrum of **poly-1’** ($CDCl_3$, 25 °C).

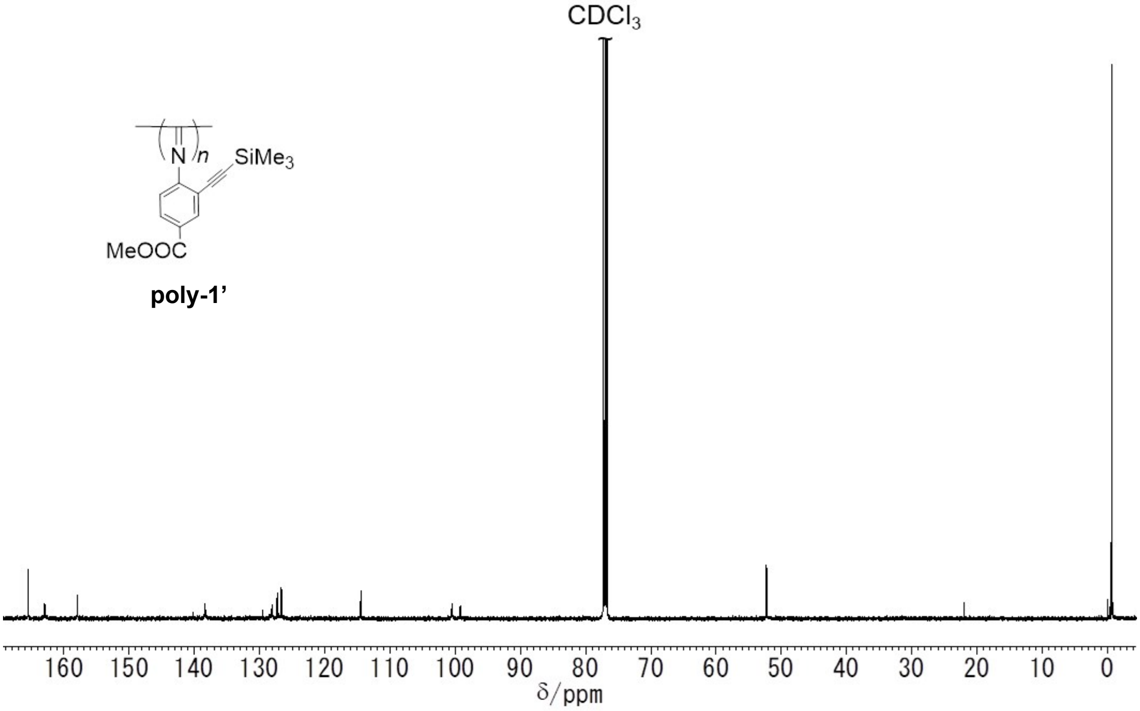


**Fig. S21** $^{13}$C NMR spectrum of **poly-1’** ($CDCl_3$, 25 °C).

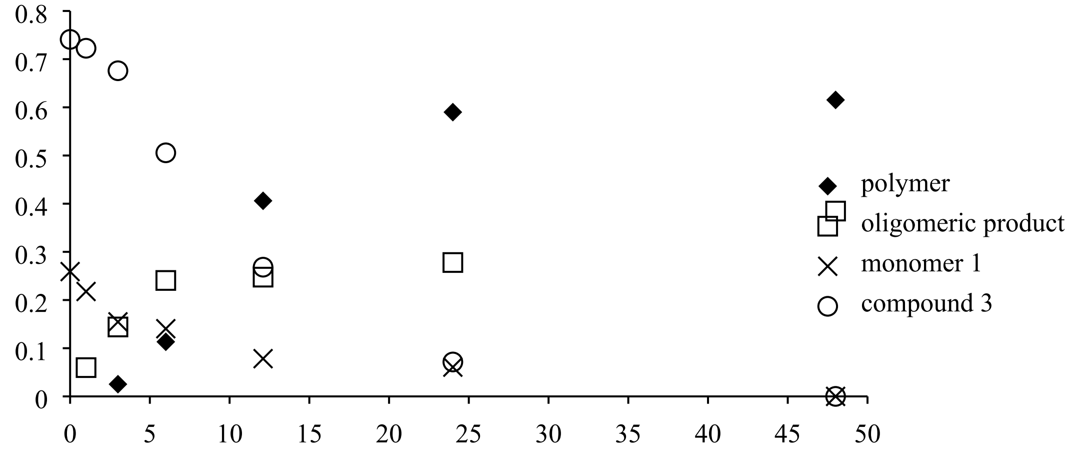


**Fig. S22** Time course of the ratio of polymer (closed diamond), oligomeric products (open square), monomer **1** (cross), and compound **3** (circle) component estimated by the ratio of the area intensity of the SEC curves in Fig. 4.