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ARTICLE TYPE

# A Supramolecular Ladder Polymer by Hydrogen Bonding-Mediated Self-Assembly of a Metallomacrocycle

Chun-Fai Ng,\*<sup>a</sup> Hak-Fun Chow\*<sup>a</sup>

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A defect-free supramolecular ladder polymer was prepared by H-bond-mediated self-assembly of a metallocycle **1** as determined by NMR, viscometry and dynamic laser light scattering studies. This ladder polymer further self-assembled into thicker bundles which subsequently folded into uniform-sized spheres in the solid state.

Self-assembly involving metal ions and appropriate ligand fragments has become a versatile method to produce a wide variety of shape-persistent molecules such as metalocycles and metalocages.<sup>1</sup> To achieve the next level of synthetic control on the preparation of larger size molecular architectures, further self-assembly using these molecular modules is the next logical step. Indeed, several recent reports have already showcased the possibility of using functionalized metalocycles to form larger-size macromolecular structures. For example, platinum-based metalocycles functionalized with two quadruple H-bonding ureidopyrimidinone side arms further self-assembled into supramolecular polymers with fibril structures.<sup>2</sup> Amphiphilic platinum-based metalocycles with oligo(ethyleneglycol) appendages were shown to self-assemble into ribbon structures via  $\pi$ - $\pi$  stacking and solvophobic interactions.<sup>3</sup> Herein we wish to report that a metallo-rectangle **1**, functionalized with two Gong's quadruple DADA H-bonding arrays<sup>4</sup> in parallel orientation on the opposite side of the rectangle, self-assembled to give a defect-free ladder polymer in the solution state.<sup>5</sup> Due to the highly fidelity of the quadruple H-bonding dimerization process, chain branching and incompletely cyclized structures, two key problems often encountered in the synthesis of ladder polymers,<sup>6</sup> are essentially eliminated using this approach (Fig. 1). It was also shown that this ladder polymer further assembled into uniform-sized spheres with a molecular dimension of 5  $\mu\text{m}$  in the solid state, thus demonstrated that such shape persistent metalocycles are robust building blocks towards the preparation of well-defined mesoscopic-sized macromolecular architectures.

Synthesis of the target metallomacrocycle **1** required the preparation of an intermediate **2** which contained the DADA quadruple H-bond array for further self-assembly (See Supporting Information (SI), section 1.2). The C3-positions of two aromatic rings in compound **2** were functionalized with an acetylene unit in order to form the metallo-rectangle **1** via Pt-acetylene linkages (Scheme 1). Due to the rigid structure and the strong association properties of the DADA H-bond motif, long alkyl chains were required to install at the two ends of the

oligoamides in order to endow them reasonably good solubility in organic solvents, but the target metallomacrocycle **1** still showed inferior solubility in non-polar organic solvents. Treatment of the acetylene **2** (2.0 equiv) with *trans*-Pt(PtEt<sub>3</sub>)<sub>2</sub>Cl<sub>2</sub> (1.0 equiv) produced an organoplatinum(II) complex **3** with two triisopropylsilyl (TIPS)-protected acetylene units in 98% yield. The TIPS groups on **3** were then removed by TBAF to give a terminal bisacetylene **4** in 92% yield. Finally, formation of the macrocycle **1** was accomplished by reacting *trans*-Pt(PtEt<sub>3</sub>)<sub>2</sub>Cl<sub>2</sub> with compound **4** in 1:1 stoichiometry under diluted concentration (0.7 mM). As it turned out, the undesirable open-chain oligomers showed better solubility in THF than the target macrocycle **1**, hence the latter could be obtained in good purity (62% yield) by simply washing the crude reaction mixture with THF. On the other hand, attempts to prepare an organic diacetylene-linked macrocycle **5** via Hay coupling failed, highlighting such metallomacrocycles are more easily accessible targets than the non-metal containing ones (SI, section 1.5).

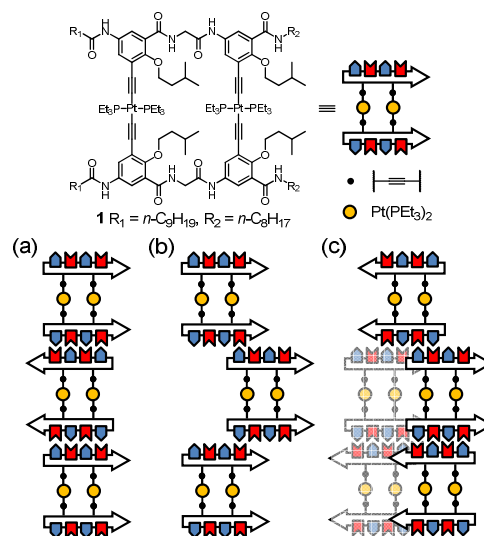
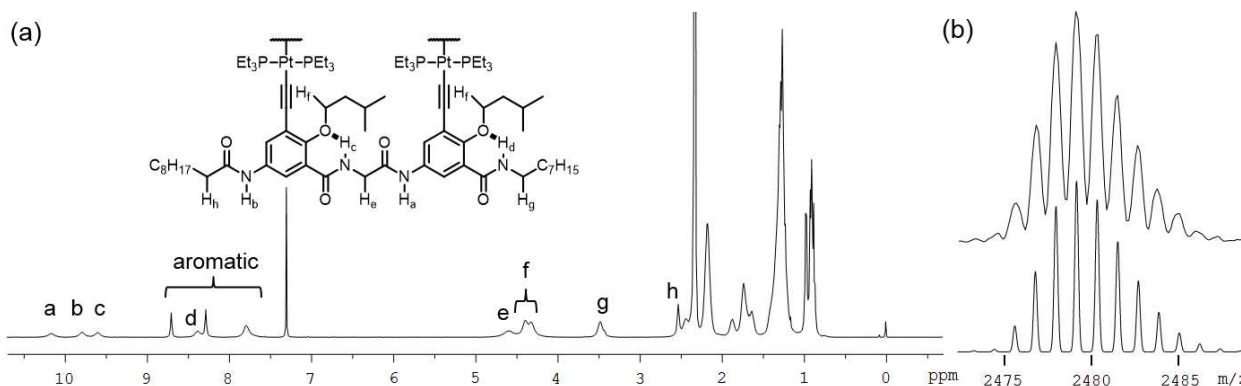
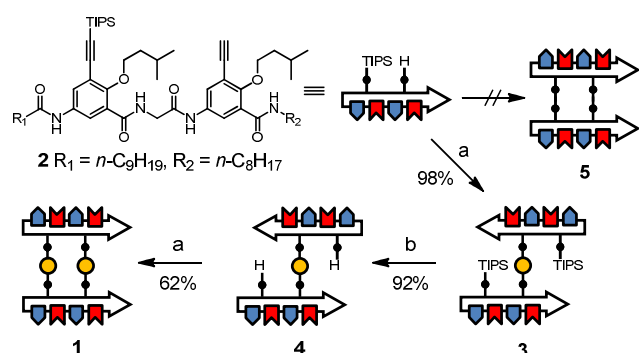


Fig. 1. Structure of the metallo-rectangle **1** and its possible self-assembly modes into (a) a defect-free ladder polymer, (b) a defective ladder polymer with uncyclized structures, and (c) a defective ladder polymer with branching. Processes (b) and (c) are thermodynamically highly-unfavorable and hence process (a) is the predominant self-assembly pathway.



**Fig. 2** (a)  $^1\text{H-NMR}$  spectrum (400 MHz, 4%  $\text{CD}_3\text{OH}/\text{CDCl}_3$ , 25  $^\circ\text{C}$ ); (b) experimental (top) and theoretical (bottom) isotopic distribution of the molecular ion peaks ( $\text{M} + \text{Na}$ ) $^+$  of supramolecular ladder polymer **1**.



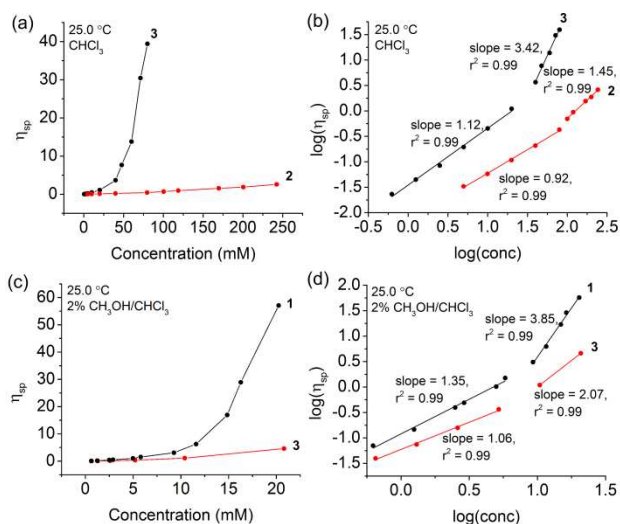
**Scheme 1** Synthesis of metallo-rectangle **1** from **2**. Reagents and conditions: (a)  $\text{trans-PtCl}_2(\text{PPEt}_3)_2$ ,  $\text{CuI}$ ,  $\text{DIPA}$ ,  $\text{CH}_2\text{Cl}_2$ ; (b)  $\text{TBAF}$ ,  $\text{THF}$ .

The structures of all synthesized compounds were characterized by  $^1\text{H}$ ,  $^{13}\text{C}$ -NMR spectroscopies, mass spectrometry, and/or elemental analysis, and for phosphorous-containing compounds,  $^{31}\text{P}$ -NMR spectroscopy. All obtained data were consistent with the proposed structures. However, for compounds containing two DADA H-bonding motifs (*i.e.* **1**, **3** and **4**),  $^1\text{H-NMR}$  signal broadening in non-polar solvents such as pure  $\text{CDCl}_3$  was noted (SI, Fig. S1). This was consistent with the formation of supramolecular polymers from **3** and **4**, and supramolecular ladder polymer from **1**. As expected, addition of 0.5–5% of  $\text{CD}_3\text{OH}$  into the  $\text{CDCl}_3$  solution resulted in a sharpening of signals, indicating the dissociation of the supramolecular polymers into shorter fragments. For the target metallomacrocyclic **1**, the  $^1\text{H-NMR}$  spectral data in 4%  $\text{CD}_3\text{OH}/\text{CDCl}_3$  were consistent with the proposed structure (Fig. 2a). Its  $^{31}\text{P}$ -NMR spectrum showed the presence of two  $^{31}\text{P}$  signals, indicating the non-equivalence of the two Pt linkers (SI, Fig. S2). The mass spectral isotopic distribution of the molecular ion peak ( $[\mathbf{1} + \text{Na}]^+$  = 2479.3136, theoretical = 2479.3133) of metallomacrocyclic **1** also matched well with the calculated one (Fig. 2b). The size exclusion chromatogram of compound **1** (THF at 40  $^\circ\text{C}$  under diluted concentration to suppress self-association) showed one major peak with a polydispersity index of 1.01, thus confirming its high structural purity (SI, Fig. S16).

The H-bond mediated self-assembly properties of the supramolecular ladder polymer **1**, the dimeric complex **2** and the supramolecular polymer **3** were then compared to unravel the changes of self-association properties with regard to their structural features. The dimerization mode of other DADA quadruple H-bond analogues of **2** had previously been firmly established by Gong,<sup>4</sup> and as expected, the dimeric structure of compound **2** was confirmed by ROESY experiments (SI, section 2.3), and the dimerization constant<sup>8</sup> ( $K_{\text{dim}}$ ) was found to be  $5000 \pm 2000 \text{ M}^{-1}$  in pure  $\text{CDCl}_3$  at 25  $^\circ\text{C}$  by concentration dependent NMR spectroscopy (SI, section 3).<sup>7</sup> Likewise, the supramolecular polymer nature of compound **3** via self-association of the DADA H-bond units was also confirmed by the presence of a strong NOE cross-signal between the methylene protons on the nonyl ( $\text{R}_1$ ) and octyl ( $\text{R}_2$ ) chains in the ROESY study. Further ROESY experiments on metallomacrocyclic **1** (carried out at 7 mM in 2%  $\text{CD}_3\text{OH}/\text{CDCl}_3$  to avoid signal broadening) also identified an NOE cross-signal between the relevant methylene protons (SI, section 2.3). This cross-peak had a weaker intensity as compared to that of supramolecular polymer **3** because of low sample concentration and in the presence of a H-bond competing solvent. Nonetheless, the self-assembly of the metallomacrocyclic **1** through its self-complementary quadruple DADA H-bond to form a supramolecular ladder structure was confirmed. Due to the poor solubility of compound **1** in  $\text{CDCl}_3$ , association constant measurements ( $K_{\text{ass}}$ )<sup>8</sup> had to be carried out in 2%  $\text{CD}_3\text{OH}/\text{CDCl}_3$  at 25  $^\circ\text{C}$ . In this H-bond competing solvent, the  $K_{\text{dim}}$  value of the dimer **2** dropped to  $300 \pm 100 \text{ M}^{-1}$ , while the  $K_{\text{ass}}$  values of polymers **1** and **3** were determined to be  $700 \pm 200 \text{ M}^{-1}$  and  $490 \pm 90 \text{ M}^{-1}$ , respectively. These values revealed that the self-association property of the supramolecular ladder polymer **1** was stronger than that of the supramolecular polymer **3**. Hence, it was safe to assume that the  $K_{\text{ass}}$  values in pure  $\text{CDCl}_3$  should be much higher and this should guarantee the self-association species were supramolecular polymers instead of oligomers.<sup>9</sup> Differential scanning calorimetry studies also showed that ladder polymer **1** had a much higher melting temperature at 382  $^\circ\text{C}$  and remained stable up to 430  $^\circ\text{C}$ , while that of the polymer **3** showed a melting transition at around 287  $^\circ\text{C}$ , accompanied with a decomposition process beginning at 331  $^\circ\text{C}$  (SI, section 5). This result further

confirmed the higher thermostability of the structurally more rigid ladder polymer.

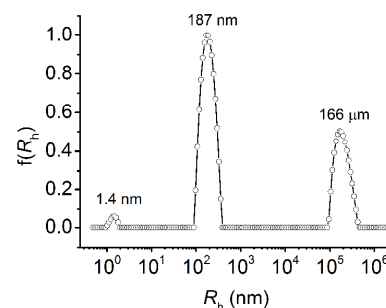
To trace the concentration effect on the extent of self-association, viscometry measurements on compounds **1–3** at different sample concentrations were carried out. For the dimeric **2** vs supramolecular polymer **3** pair in pure  $\text{CHCl}_3$  (Fig. 3a), a non-linear dependence of specific viscosity ( $\eta_{\text{sp}}$ ) upon changes in the concentration of the supramolecular polymer **3** was noted, while that of the dimeric species **2** showed a much smaller increase in viscosity even when the concentration was increased 50 fold (from 5 to 250 mM). According to literature precedents, supramolecular polymers are typified by a change of slope in the double-logarithm plot of  $\eta_{\text{sp}}$  vs concentration.<sup>10</sup> In general, a slope of  $>3$  at the higher concentration region implied the presence of significant intermolecular association. For supramolecular polymer **3**, a change of slope from 1.1 to 3.4 was found at  $\sim 30$  mM (Fig. 3b). The high value of the slope (3.4) at the high concentration region confirmed that it was a supramolecular polymer. For the supramolecular **3** vs the supramolecular ladder **1** pair, again the measurements needed to be conducted in 2%  $\text{CH}_3\text{OH}/\text{CHCl}_3$  to ensure solution homogeneity (Fig. 3c). In this H-bond competing solvent system, it could be seen that the slope at the high concentration region of the supramolecular polymer **3** dropped from 3.4 to 2.1 (Fig. 3d), while that of the supramolecular ladder polymer **1** attained an even higher value of 3.9. The finding that the supramolecular ladder polymer **1** self-associated stronger than the supramolecular polymer **3** was consistent with their measured  $K_{\text{ass}}$  values.



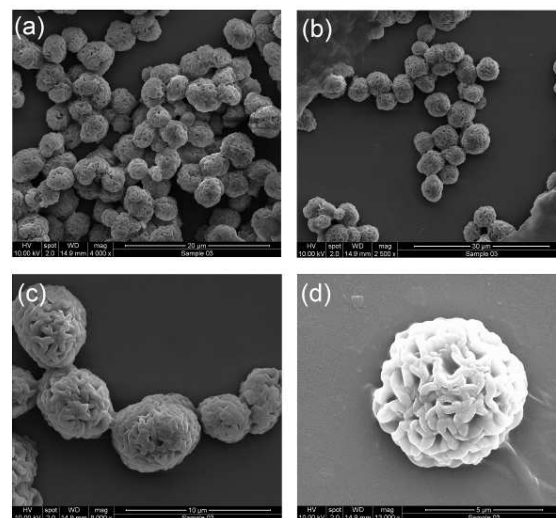
**Fig. 3** (a) Plot of specific viscosity ( $\eta_{\text{sp}}$ ) of dimeric **2** and supramolecular polymer **3** in pure  $\text{CHCl}_3$ ; and (b) the corresponding double-logarithm plot; (c) plot of specific viscosity of supramolecular polymer **3** and supramolecular ladder polymer **1** in 2%  $\text{CH}_3\text{OH}/\text{CHCl}_3$ ; and (d) the corresponding double-logarithm plot.

Dynamic light scattering (DLS) study was conducted to determine the molecular size distribution of the self-assemblies of metallomacrocyclic **1** (at 2 mM) in 2%  $\text{CH}_3\text{OH}/\text{CHCl}_3$  at 25 °C (Fig. 4). Three peaks at 1.4 nm, 18.7 nm and 166  $\mu\text{m}$  were observed, reflecting the coexistence of various sized species in the solution. The smallest peak at a hydrodynamic radius  $R_h$  of

1.4 nm gave the least intense signal, which corresponded to the discrete metallomacrocyclic **1**, whereas the peak at  $R_h$  of 18.7 nm could be attributed to the supramolecular ladder polymer of **1**. The largest peak at  $R_h$  166  $\mu\text{m}$  indicated further assembly of the supramolecular ladder polymer into micron-sized aggregates. Moreover, increasing the percentage of  $\text{CH}_3\text{OH}$  in the solvent system caused a reduction of the scattering intensity (SI, Fig. S18), which supported the formed self-assembly was based on H-bonding and readily dissociated in the presence of  $\text{CH}_3\text{OH}$ .



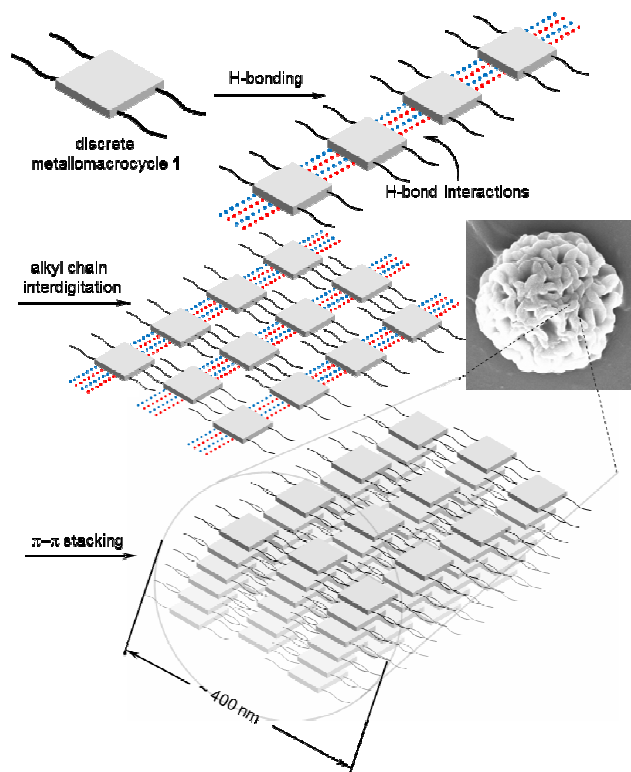
**Fig. 4** Hydrodynamic radius distribution of metallomacrocyclic **1** as determined by DLS study (2 mM, 30 °C) in 2%  $\text{CH}_3\text{OH}/\text{CHCl}_3$ .



**Fig. 5** (a)–(d) SEM images of supramolecular ladder polymer **1** on a silica wafer.

Scanning electron microscopy (SEM) of the rectangular-shape metallomacrocyclic **1** was then performed to reveal its morphology in the solid state. The sample was prepared by drop-casting a 30 mM solution of **1** in 2%  $\text{CH}_3\text{OH}/\text{CHCl}_3$  on a silica wafer. A cluster of uniform-sized spheres (diameter  $\sim 5$   $\mu\text{m}$ ) with a highly folded substructure was found (Fig. 5). The elemental composition of the spheres were determined by energy-dispersive X-ray (EDX) spectroscopy, and the results were consistent with the molecular formula of the metallomacrocyclic **1** (SI, section 8). The formation of such highly ordered micron-sized structures instead of fibril structures expected for ladder polymers deserved further comments, and was consistent with the further assembly of individual ladder polymer chains into thicker bundles

commonly observed for polymer fibrils.<sup>2,10e</sup> It was proposed that discrete metallomacrocyclic **1** first self-assembled to form a supramolecular ladder polymer chain through quadruple DADA H-bonding (Fig. 6). At the same time, the long hydrophobic alkyl chains interdigitated with each other through van der Waal's interaction.<sup>11</sup> Furthermore, the flat metallo-rectangles could stack upon each other to form *J*-aggregates<sup>12</sup> via  $\pi$ - $\pi$  interaction. As a result, a worm-like strand of ~400 nm in diameter was formed, which further coiled up and packed into uniform spheres. It should be emphasized here that these three self-assembling processes needed not take place in the sequence described above, but could occur in a random manner.



**Fig. 6** Self-assembly model of metallomacrocyclic **1** into micron-sized spheres.

In summary, we described here a new approach for the synthesis of a supramolecular ladder metallo-polymer based on the quadruple H-bond mediated self-assembly of a bifunctional metallomacrocyclic **1**. Due to the high fidelity of the quadruple H-bonding process, the synthesized supramolecular ladder should be free from structural defects. It was also demonstrated that supramolecular ladder polymer **1** possessed higher thermostability than its analogous supramolecular polymer **3**. The advantages of using shape-persistent metallocycles for further self-assembly are also demonstrated here. First, they can be easily prepared in good yields and homogeneity as compared to non-metal containing macrocycles. Second, the H-bonding motif is compatible with the organometallic framework, and therefore this approach is applicable to other metallo-macrocycles of different geometric parameters, which in turn provides a facile synthetic entry to other 'super-sized' self-assemblies with new hierarchical structures.

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## Notes and references

<sup>a</sup> Department of Chemistry and Institute of Molecular Functional Materials UGC-AoE, The Chinese University of Hong Kong Shatin, NT, Hong Kong SAR. Tel: +852 3943 6341; E-mail: hfchow@cuhk.edu.hk

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