Highly Ordered Assembly of π-Stacked Distyrylbenzenes by Oligoadenines
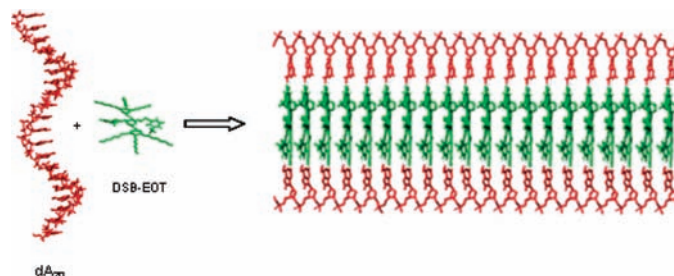
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ABSTRACT

A well-defined nanofibrous structure with lengths of several hundred nanometers and cross-sectional width of a single size ($\sim6 \pm 0.5$ nm) was self-assembled by oligoadenines, dA_{20}, and thymine-appended distyrylbenzene through binary complementary A−T hydrogen bond formation and the strong $\pi-\pi$ stacking interactions. This demonstrated a useful supramolecular self-assembling approach to control the packing order of π-conjugated molecules and provided a practical means to enhance the optical properties of a material.

There has been tremendous progress in designing π-conjugated molecules/polymers for various technologically useful functional properties such as light-emission,[1] optical non-linearity,[2] photovoltaic response,[3] and charge mobility;[4] however, the device performance of these materials is greatly dependent on the supramolecular organization of molecules/polymer chains at the molecular level or the morphology of these materials. Thus, the ability to control the molecular arrangement and packing order provides a useful means to tune and optimize the material performance in a device, apart from the chemical structure modification.[5] It has been shown that covalently organized π-conjugated aggregates and supramolecularly assembled dye aggregates can exhibit enhanced optical and electronic properties[6] due to intra- or interchromophoric interaction that may potentially be useful in the optoelectronic and photonic devices. There has been increasing attention to explore strategies and tools to control the molecular order and arrangement of an aggregate as well as shape, size, and length of nanostructure in the past years.[7] Supramolecular self-assembly is a widely used and most promising approach to construct well-defined molecular

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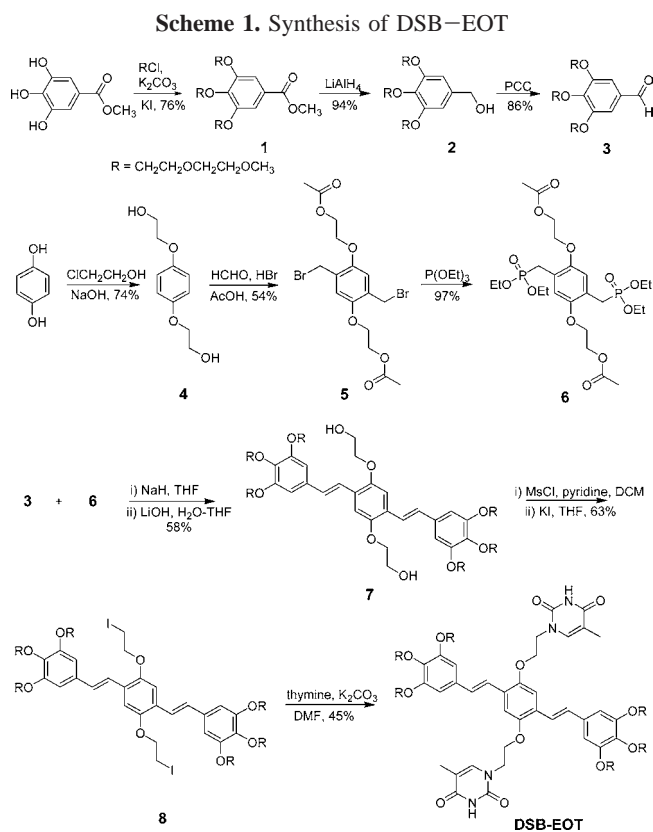
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assemblies, nanostructures, and materials.[8] Among various supramolecular building blocks, oligonucleotides[9] with pre-defined structural architectures are particularly useful templates to arrange and organize functional molecules, construct nanostructures, and control the size of the supramolecular structures. Several groups have used the ssDNA as a template or building block for the assembly of functional π-conjugated molecules to form well-defined aggregates or nanostructures.[10]

We have demonstrated a useful supramolecular self-assembling approach that can be used to properly control the packing order of π-conjugated molecules, which in turn provides a practical means to enhance the optical properties. We report herein an investigation of the supramolecular assembly of oligoadenines, dA_{20}, and thymine-appended distyrylbenzene through binary complementary adenine−thymine (A−T) hydrogen-bond formation and the π−π stacking interactions leading to the highly ordered assemblies, where the distyrylbenzene cores are closely π−π stacked in a cofacial fashion, hence resulting in greatly enhanced fluorescence properties. This exemplifies a practical supramolecular assembly principle that can be used to precisely position π-conjugated molecules into highly ordered aggregates capable of exhibiting enhanced functional properties.

A highly planar π-conjugated system, distyrylbenzene, laterally tethered with two thymine moieties by the short ethoxy chains and equipped with water-solublizing, multiple poly(ethylene glycol)s at both ends, namely DSB−EOT, was synthesized as outlined in Scheme 1. By adapting the convergent approach established previously,[11] double Wadsworth−Emmons reaction of 3,4,5-tris[2-(2-methoxyethoxy)ethoxy]benzaldehyde and *p*-xylylene(bis(phosphonate)) derivative was used as the key step to synthesize the water-soluble *trans*-distyrylbenzene skeleton. Alkylation of 3,4,5-trihydroxybenzoate with 1-chloro-2-(2-methoxyethoxy)ethane in the presence of potassium carbonate in DMSO afforded 3,4,5-tris[2-(2-methoxyethoxy)ethoxy]benzoate, **1**, in 76% yield. Reduction of benzoate **1** with LiAlH$_4$ in dry THF at rt afforded benzyl alcohol **2** in an excellent yield. Oxidation of alcohol **2** using PCC in DCM afforded 3,4,5-tris[2-(2-

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Scheme 1. Synthesis of DSB−EOT

methoxyethoxy)ethoxy]benzaldehyde, **3**, in 86% yield. On the other hand, alkylation of *p*-hydroquinone with 2-chloroethanol in the presence of sodium hydroxide in water solution afforded dialcohol **4** in 74% yield. Bromomethylation of **4** with formaldehyde and concd HBr in acetic acid at rt afforded dibenzyl bromide **5** in 54% yield. Michaelis−Arbuzov reaction of **5** with triethyl phosphite gave bisphosphonate **6** in 97% yield. Double Wadsworth−Emmons reaction of benzaldehyde **3** and bis-phosphonate **6** in THF in the presence of NaH afforded *trans*-distyrylbenzene which was subsequently hydrolyzed using lithium hydroxide in THF and water solution affording compound **7** in 58% yield in two steps. Mesylation of **7** with MsCl and pyridine in DCM followed by nucleophilic substitution with KI in THF afforded diiodo product **8** in 63% yield in two steps. Double substitution of **8** with thymine in the presence of potassium carbonate at 60 °C afforded the desired product DSB−EOT in 45% isolated yield, which was fully characterized with spectroscopic techniques and found to be in good agreement with its structure (see the Supporting Information).

The absorption spectrum of DSB−EOT exhibits a significant decrease in absorption, spectral broadening, and blue shift of absorption maximum (λ^{abs}_{max}) in aqueous solution (λ^{abs}_{max} = 350 nm) relative to that in CHCl$_3$ (λ^{abs}_{max} = 396 nm). The fluorescence spectrum also shows notable spectral broadening with less vibronic structures in aqueous solution. (Figure S1, Supporting Information). Its fluorescence quantum efficiency (Φ_{PL}) is greatly reduced from 58% in CHCl$_3$ to 31% in phosphate buffer solution. In addition, after the

aqueous solution of DSB−EOT was heated to 353 K and then slowly cooled to 283 K over 6 h, both of its absorption and emission spectra showed an apparent decrease in absorptivity and fluorescence intensity, respectively. All these findings consistently suggest that DSB−EOT is solvated in $CHCl_3$ but self-assembles into π-stacked aggregates in aqueous solution where the hydrophobic π-conjugated units, i.e., distyrylbenzene cores and thymine moieties, are relatively tightly packed, with $\pi-\pi$ interactions, and the hydrophilic poly(ethylene glycol) chains are pointed into the aqueous medium.[12] The temperature dependence of aggregate formation of DSB−EOT in water was also examined. Interestingly, there was an increase in absorption of DSB−EOT at 275 nm and a slightly blue shift and a decrease in absorption at 350 nm upon heating from 10 to 60 °C. No such temperature dependence spectral changes were observed for DSB−EOT in $CHCl_3$ (Figure S2, Supporting Information). These observations further affirm that the DSB−EOT aggregates can be thermally dissociated in water resulting in a reduction of the π-stacking interactions among the π-conjugated moieties.

Upon an addition of adenine (4×10^{-7} M) into the DSB−EOT (2×10^{-7} M) solution, initially there is no significant change in the spectral characteristics of DSB−EOT indicating that aggregation prevents the appended thymines from interacting with adenines. However, upon heating and prolonged cooling treatment, in addition to the spectral shift, the absorption and fluorescence ($\Phi_{PL} = 8\%$) of DSB−EOT show a substantial decrease in intensity, which hints that the deaggregated DSB−EOT may bind with adenines through the complementary hydrogen bonding interactions (Figure S3, Supporting Information). The complementary binding of DSB−EOT and adenine is further affirmed by the high-resolution ESI-MS measurements in which the spectrum of the mixture of DSB−EOT and adenine shows peaks at m/z 742.8412 and 799.3753 with expected isotopic distribution that correspond to $[DSB−EOT + adenine + Na + H]^{2+}$ and $[DSB−EOT + 2adenine + 2H]^{2+}$ ions, respectively (Figure S4, Supporting Information).

To make use of such strong binary complementary A−T base pair interactions and the strong $\pi-\pi$ stacking interactions of the planar π-conjugated system, a highly organized, plane-to-plane π-stacking aggregate can be constructed by the self-assembly of DSB−EOTs with oligoadenines. Upon mixing of oligoadenines dA_{20} (0.4 nmol) with DSB−EOT (0.2 nmol) in 1 mL of the buffered solution, the initial spectral change is not so prominent. Nevertheless, after heating and prolonged cooling treatment, there are remarkable changes in various spectroscopic characteristics. The absorption at 258 nm, corresponding to the absorption of oligoadenine, shows a dramatic decrease in intensity, and the absorption around 354 nm, corresponding to the absorption of the distyrylbenzene core, shows a strong increase in absorbance concomitant with spectral shift. In addition to the red shift of emission spectrum, there is a 2-fold and 3-fold

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enhancement in fluorescence of the distyrylbenzene moiety as compared to that of DSB−EOT solution and the assembly of DSB−EOT−adenine, respectively (Figure 1b). Further-
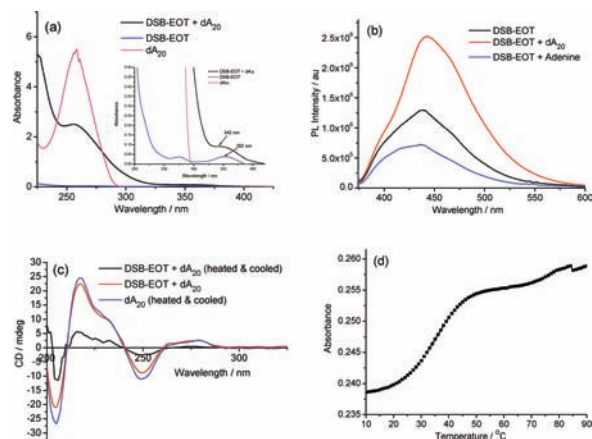

Figure 1. (a) Absorption spectra of DSB−EOT (2×10^{-7} M), dA_{20} (4×10^{-7} M), and DSB−EOT + $2dA_{20}$ (2×10^{-7} M) measured in phosphate buffer solution after heating and cooling treatment. (b) Comparison of emission spectra of DSB−EOT, DSB−EOT−adenine, and DSB−EOT−dA_{20} after heating and cooling treatment. (c) CD spectra of dA_{20} and DSB−EOT + dA_{20} with and without heating and cooling treatment. (d) Plot of temperature dependent absorbance of DSB−EOT−dA_{20} assembly measured at 260 nm versus temperature.

more, the circular dichroism spectrum of dA_{20} exhibits almost completely diminished Cotton effect indicating that dA_{20} unfolds itself in the presence of DSB−EOT. Native polyacrylamide gel electrophoresis (PAGE) analysis of dA_{20} and a mixture of 1:2 of DSB−EOT and dA_{20} revealed that upon mixing and heat−cool treatment, the identity of dA_{20} disappeared but a new band with very low mobility was observed (Figure S5, Supporting Information), suggesting the association of the dA_{20} to the DSB−EOT molecules to form a polymeric assembly. The temperature-dependent UV−vis profile of DSB−EOT−dA_{20} complex shows an abrupt increase in 260 nm absorbance upon heating with a "thermal denaturation" temperature (T_m) of 35 °C (Figure 1d) reminiscent of the dissociation of double helix DNA $dsAT_{20}$ duplex ($T_m = 42$ °C) (Figure S6, Supporting Information). This result further affirms the presence of a cooperative self-assembly of A−T hydrogen-bonded complexes. All these findings consistently point to the fact that oligoadenines unfold themselves and bind with the deaggregated DSB−EOTs through the complementary hydrogen-bonding interactions, and then the bound DSB−EOTs stack up in a parallel fashion leading to a highly ordered assembly. In contrast, when the noncomplementary ssDNA oligothymine, dT_{20}, is mixed with DSB−EOTs under the same experimental conditions, there are no changes in absorption and fluorescence spectra indicating DSB−EOT binds specifically to dA_{20} (Figure S7, Supporting Information). The cause of the spectral changes of DSB−EOT such as the strong fluorescence enhancement upon self-assembling into highly

ordered aggregates is attributed to the excitonic coupling of proximate $\pi-\pi$-stacked chromophores,[13] which gives rise to the increase in the absorption of DSB−EOT (Figure 1a) and, hence, the fluorescence enhancement, although the fluorescence quantum efficiency (Φ_{PL}) of DSB−EOT−dA$_{20}$ assembly is only 19%. Even when the compound is kept at low temperature ($\sim$10 °C) for more than 6 months, the spectral characteristics of these DSB−EOT−dA$_{20}$ assemblies are prevalent, indicating the highly stability of these nanofibrous structures.

To further investigate the morphology of the resulting hydrogen-bonded DSB−EOT−dA$_{20}$ assembly, we carried out an atomic force microscopy (AFM) study in air which distinctly shows the formation of long, stable, and well-defined nanofibers with lengths extending over several hundred nanometers. Lateral cross-sectional analysis of the nanofibers shows them to be of a similar height, indicating a well-defined nanofibrous assembly of a single size (Figure 2a). However, sample preparation of the DSB−EOT−dA$_{20}$
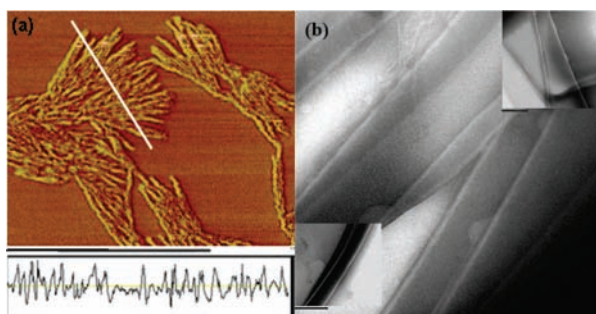

Figure 2. (a) Tapping mode AFM images of DSB−EOT−dA$_{20}$ assembly on a mica plate (bar = 1 μm). Bottom: lateral cross-sectional profiles of DSB−EOT−dA$_{20}$ assemblies along the line. (b) TEM images of DSB−EOT−dA$_{20}$ assembly stained with the Nanovan at pH 8 (bar = 200 nm).

assembly for AFM imaging resulted in nanofibers that are somewhat embedded on the mica surface. Thus, it was difficult to obtain accurate values for the width of the nanofibers using AFM height images.

In addition, DSB−EOT−dA$_{20}$ assemblies were examined under dry conditions using transmission electron microscopy (TEM) after being stained with the Nanovan at pH 8. Again, the self-assembled nanofibers were evident (Figure 2b). The experimentally obtained cross-sectional width analyzed on

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the nanofiber using the TEM images is found to be 6 $\pm$ 0.5 nm, which is consistent with the proposed molecular modeling nanostructures of closely $\pi-\pi$ stacked DSB−EOT molecules bound to two oligoadenine chains in a side by side fashion. The proposed molecular model of hydrogen-bonded DSB−EOT·dA$_{20}$ assembly calculated by Hyperchem 7.0 is shown in Figure 3. In contrast, AFM and TEM analyses
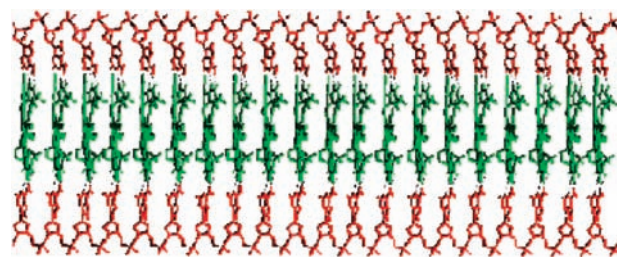

Figure 3. Proposed molecular model of hydrogen-bonded DSB−EOT·dA$_{20}$ assembly (DSB−EOT in green and dA$_{20}$ in red) calculated by Hyperchem 7.0.

of samples containing only DSB−EOT molecules find no such long supramolecular nanofibrous structures. Furthermore, another DSB derivative (DSB−POT) bearing the longer flexible ethoxyethoxy thymine-linkers show no nanofibers formation upon mixing with oligoadenine under the same experimental conditions.

In summary, we have demonstrated that using a predefined template (e.g., oligoadenines) to direct the supramolecular organization of π-conjugated molecules into highly ordered nanostructures which give rise to a strong fluorescence enhancement provide a useful means to tune and modify the material performance. This also highlights the importance of the ability to control the supramolecular packing order of π-conjugated molecules to enhance the optical properties of a material.

Supporting Information Available: Synthesis and experimental details, characterization data, and spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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