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Photoactive organic material discovery with combinatorial supramolecular assembly

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Organic semiconductors have received substantial attention as active components in optoelectronic devices because of their processability and customizable properties. Tailoring the organic active layer in these devices to exhibit the desired optoelectronic properties requires understanding the complex and often subtle structure–property relationships governing their photophysical response to light. Both structural organization and molecular orbitals play pivotal roles, and their interactions with each other are difficult to anticipate based upon the structure of the components alone, especially in systems comprised of multiple components. In pursuit of design rules, there is a need to explore multicomponent systems combinatorially to access larger data sets, and supramolecularly to use error correcting, noncovalent assembly to achieve long-range order. This review will focus on the use of supramolecular chemistry to study combinatorial, hierarchical organic systems with emergent optoelectronic properties. Specifically, we will describe systems that undergo excited state deactivation by charge transfer (CT), singlet fission (SF), and Förster resonance energy transfer (FRET). Adopting combinatorial, supramolecular assembly to study emergent photophysics promises to rapidly accelerate progress in this research field.

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1. Introduction

Organic materials are increasingly investigated in solar energy harvesting devices,^{1–3} sensors,^{4–6} field effect transistors,^{7–9} and

catalysts.^{10–13} The active components that drive these applications are organic semiconductors—small molecules or polymers that are conductive following charge injection or upon photoexcitation. Organic semiconductors offer several potential

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advantages over their inorganic counterparts. First, they can be cheaper to prepare because the expensive, high-energy annealing processes needed for inorganic semiconductors are not required for organics.^{14,15} Second, their structures can be altered to vary their frontier molecular orbital (FMO) energies, shapes, absorptions, and solid-state packing, thereby providing a degree of tailorability not available with inorganics.¹⁶ This is a major potential benefit of organic semiconductor systems because systematically altering their substituents could ideally produce relationships between their molecular structures and their responses to light and charge in solution and in films. In reality, however, deriving these relationships is far more complex than this description suggests. The optoelectronic response of organic semiconductors, and particularly multicomponent materials that are often composed of mixtures of n-type and p-type molecules, remains difficult to predict if one were to consider only the molecular structures of the components.^{17,18} The reason is that many important properties, such as the photophysical deactivation pathway—the way in which photoexcited electrons relax through various excited states and intermediates back to the ground state—excited state lifetimes, film conductance, and light absorption, are ensemble properties that are dependent upon the interactions between two or more molecules. As such, the properties of organic semiconducting films are sensitively dependent on the relative orientations and spacing of the components. So, predicting and optimizing the optoelectronic responses of organic semiconductors so they can realize their promise as active elements for various devices and advanced applications remains a particularly unwieldy problem. This is primarily because of the sensitive dependence of their ensemble properties on Ångstrom-scale perturbations and the necessity of reproducing these orientations across micrometer or even millimeter length scales. Meeting the structural and electronic requirements of organic optoelectronic devices becomes even more challenging in multicomponent active layers where different constituent molecules must be brought together in a specific geometry to achieve a desired function.

The magnitude of the challenges involved in optimizing the photoresponse of a multicomponent organic system can be understood by considering the active layer of bulk

heterojunction (BHJ) organic photovoltaics.^{19,20} The BHJ is an OPV device geometry where organic electron donor molecules and electron acceptor molecules are blended together into a film that is sandwiched between two electrodes (Fig. 1B). In this layer, electrons in the donor or acceptor chromophores are photoexcited to create coupled electron-hole pairs (excitons). These excitons migrate to a donor-acceptor interface where they charge separate—electrons are thermodynamically driven into the acceptor phase and holes into the donor phase.²¹ Following this charge separation event, charge carriers must migrate to the opposing electrodes so that they can be harnessed as electricity (Fig. 1A). When the films are cast from solution, the donor and acceptor components tend to phase-segregate,^{3,19,22} reducing heterojunction (*i.e.* donor-acceptor contact) area. As the amount of heterojunction interface decreases, the number of charge separation events decrease and/or pathways to electrodes do not form so the charges cannot be collected. Alternatively, too much mixing increases unproductive recombination events because the length of the percolation pathways to the electrodes can exceed charge carrier diffusion lengths. Ideally, the active layer could adopt a geometry (Fig. 1C) that maximizes the donor-acceptor interface, while providing contiguous and short pathways for charge migration to the electrodes.

These operational criteria for organic photovoltaics dictate that the FMO energy levels and electronic coupling, which govern the dynamics of charge transfer, and film morphology are treated as equally important considerations in the design of the components of the BHJ layer, but this is not commonly reflected in practice. Rather, the donor and acceptor components are typically designed such that upon photoexcitation, the relative energies of the FMOs favor electron transfer from donor to acceptor, while morphology is an afterthought that is optimized *via* trial and error.^{20,23,24} Typically, two component systems are spin-coated together to create blended active layers, and the most common strategies for improving the mixing of donors and acceptors during this process include installing



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Fig. 1 Donor-acceptor heterojunction morphologies. (A) Bilayer structure showing process of charge collection in OPV devices. (B) Bulk heterojunction (BHJ) and (C) heterojunction optimized to increase junction area, while providing contiguous pathways for charges to migrate to the electrodes.



solubilizing side chains on the components,^{19,25} solvent annealing,²⁶ adding insulating polymer fillers,²⁷ adding peptide side chains,^{28,29} or, alternatively, covalently linking the two together to create architectures such as diads,³⁰ triads,³¹ donor-acceptor alternating polymers,³² and double-cable polymers.³³ Though these covalent strategies may improve heterojunction interface area, drawbacks include their cumbersome and time consuming syntheses, which limit the ability to establish structure-activity relationships, and their inability to predictably control molecular orientation on the nanoscale and film structure on the micrometer length scale, which are both necessary to create contiguous and uniform percolation pathways from the site of charge separation to the electrodes. An ideal approach towards exploring and optimizing both charge-transfer efficiency and film geometry would involve the synthesis of a library of simple components and a method to control their orientation across the molecular-to-micrometer continuum. Such an approach would inform how subtle structural modifications affect system performance, and, in turn, rapidly produce quantitative and predictive relationships between them.

Programmed supramolecular assembly of multicomponent systems is a promising approach for overcoming the phase segregation conundrum, while providing a mechanism for rapidly deriving structure-activity relationships. Supramolecular assemblies use noncovalent bonding—*e.g.* H-bonding, C-H $\cdots\pi$ interactions, $\pi\cdots\pi$ stacking, van der Waals forces, and metal-ligand coordination—to bring molecules together in a prescribed orientation (Fig. 2A).^{34–36} Co-assembly—where distinct components noncovalently bond with each other—can be programmed into photoresponsive organic semiconductors by incorporating complementary noncovalent bonding motifs (Fig. 2B).³⁷ Multicomponent systems programmed to co-assemble can be combinatorial in that the photoactive cores of similar molecules can be altered with the same noncovalent bonding group so they share the same assembly with a set of complimentary components. The benefits of using supramolecular assembly to achieve order in donor-acceptor films are that (1) the cumbersome syntheses required to covalently link donor and acceptor components can be circumvented, (2) from a few donor and acceptor components with conserved noncovalent bonding groups, many combinations are attained by simply mixing different components together so structure-activity relationships can be derived, and (3) self-correcting, supramolecular assembly can also achieve hierarchical superstructures with long-range order (Fig. 2C). Because supramolecular systems are naturally combinatorial, the larger data sets that are attainable when using them to study photoactive films can provide better predictive insight into how subtle changes in molecular structure or FMO energies affect active layer performance.

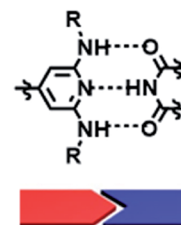
Combinatorial approaches are used extensively to address some of the most vexing challenges in drug discovery,³⁸ material science,³⁹ and nanotechnology.⁴⁰ Combinatorial science involves synthesizing libraries of components that differ in some key structural aspect, and screening them for a particular property.³⁸ This strategy results in large data sets that are used

A. Noncovalent bonding

$\pi\cdots\pi$ Stacking



H-bonding



B. Assembly types

Self-assembly



Co-assembly



C. Hierarchical superstructures



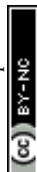
Heteroaggregates



Homoaggregates

Fig. 2 Supramolecular assembly. (A) Examples of noncovalent binding. (B) Self-assembly between like compounds or co-assembly between complementary components. (C) Superstructures with hierarchical order.

to unearth trends and outliers without devoting exorbitant resources to time-consuming design, and, as a result, naturally lends itself to solving complex scientific challenges. Combinatorial approaches have been increasingly adopted for understanding subtle structure-activity relationships in photoresponsive organic materials, where the ability to rationally design ensemble properties continues to elude researchers.^{41–43} Deactivation pathways such as charge transfer (CT),^{44,45} singlet fission (SF),^{46,47} and Förster resonance energy transfer (FRET)^{48,49} are all in competition following the photoexcitation of organic donor-acceptor mixtures, and the factors that determine whether one occurs preferentially over another is the result of an interplay between kinetic and thermodynamic driving forces as well as the orientation of the components and the long-range film order. Here, we focus on



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geometries that result in periodically aligned donor–acceptor configuration with 1D nanopores. Calculated, optimized unit cell geometries of the donor–acceptor superstructures show the most stable structure is a slip-stack geometry, which is largely dependent on the π -extension of the acceptors, and to a lesser extent, the metal centers in the donors. COFs with naphthalene diimide (NDI) and perylene diimide (PDI), allow for interlayer H-bonding, which further improves stacking stability. Transient absorption (TA) spectroscopy and time-resolved electron spin resonance (TR-EPR) were used to interrogate the lifetimes of the charge separated states. It was found that Cu metal centers enhanced CT lifetimes compared to Ni or Zn, while lattice size from changing acceptor units played a less critical role. Importantly, in this system, similar hierarchical structures are achieved for all metal/acceptor combinations, so a correlation could be drawn as to how structural and, in turn, electronic changes to individual components contribute to deactivation properties.

Another example of achieving CT with a combinatorial, supramolecular library of donor and acceptor components was reported by Mallia *et al.* who studied a series of nonparallel stacked dyad chromophores.⁶⁵ A Suzuki–Miyaura cross-coupling reaction was used to bring together covalently naphthalimide (NI) acceptors with either naphthalene (N) or phenyl

(Ph) donors (Fig. 4A). Superstructure assembly was promoted by C–H $\cdots\pi$, $\pi\cdots\pi$, and C–H \cdots O interactions, while donors and acceptors tilted with respect to one another; N and Ph at 68° and 63° with respect to the NI plane, respectively. Additionally, these interactions and resulting assembled structures whose geometries were found through simulation, suggest both donor and acceptor $\pi\cdots\pi$ stack in NIN whereas only the acceptor (NI) is self-stacking in NIPh (Fig. 4B). This system is combinatorial in that the same chemistry to connect readily available donor building blocks to the NI acceptor can be used, so a large number of molecules that subsequently assembly are easily generated. As a result the same NI acceptor has also been used with other donors in supramolecular, energy harvesting studies in the Hariharan group that include triphenylamine for CT⁶⁶ and perylenimide for FRET.⁶⁷ The self-stacked donors and acceptors in NIN delocalize photoinduced charge carriers and decrease geminate charge recombination. In contrast, NIPh lacks contiguous pathways along Ph donors for transport of the positive charge carriers produced from CT. These expectations are substantiated by (1) the bathochromic shifting in emission spectra of NIN when varying solvent polarity, whose ground state CT character was higher in NIN (39%) than NIPh (21%), (2) the population of radical ion state found in NIN, when probed with femtosecond transient absorption (fsTA), which is not present in NIPh, and (3) more positive electrochemical reduction potential of NIN in increasing concentrations of NIN, as a result of radical ion delocalization along D–A stacks, while NIPh reduction potential was largely unaffected by concentration. As a consequence, nsTA reveals radical ion pair intermediates surviving 10 000 times longer in their aggregated state than as monomers, demonstrating how photophysical properties were rapidly understood and optimized by adopting combinatorial supramolecular assembly.

A. Molecular structures of active components



B. Assembly driven photoinduced charge-delocalization



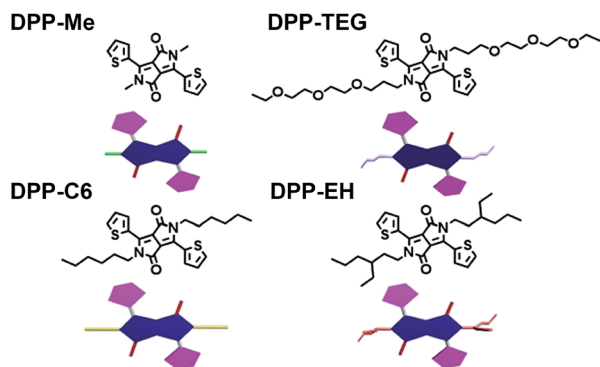
Fig. 4 Charge transfer (CT) in a supramolecular dyad system. (A) Naphthalimide (NI) acceptor with either naphthalene (N) or phenyl (Ph) appended donors. (B) Emergent photoinduced charge separation occurs in NIN superstructures but not NIPh.⁶⁵

2.2 Singlet fission

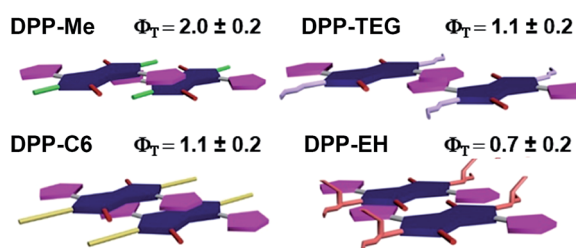
SF is the process by which two electronically coupled chromophores in the ground state (S_0S_0) are photoexcited by a single photon to a singlet state (S_1S_0) and share energy to form a spin-allowed state comprised of two coupled triplets (T_1T_1), each roughly half the energy of the initial singlet state (Fig. 5C).^{46,47} One of the big advantages to SF is that one photon is used to produce two excited electrons, but there are caveats including that the resulting triplet state energy must be roughly half the energy of the initial singlet state, and bound triplet pairs must decouple for the SF process to be complete and the triplets to be harnessed.⁶⁸ SF is an attractive deactivation process because it has the potential to increase the theoretical efficiency limit of solar energy materials to 44% (ref. 46) compared to traditional single band-gap material, which is 33%.⁶⁹ SF has been studied extensively since the 1960's in organic materials, primarily in acenes^{68,70} and more recently in rylenes^{71,72} and diketopyrrolopyrroles (DPPs).^{73,74} Others have shown SF dynamics in various acene derivatives, with⁷⁵ and without^{76,77} linkers to affect coupling, to be highly sensitive to packing, spacing, and orientation. "Ideal" SF chromophore organization could provide a 200% triplet yield. Importantly, optimized geometries would



A. Molecular structures of the components



B. Assembly induced singlet fission



C. Photophysics for singlet fission



Fig. 5 Singlet fission (SF) in self-assembled diketopyrrolopyrrole (DPP). (A) Methyl (Me), *n*-hexyl (C6), triethylene glycol (TEG), and 2-ethylhexyl (EH) substituents appended to the DPP core nitrogen. (B) Varying slip-stack geometries caused by sterics, which affect intermolecular orbital coupling and ultimately SF yields (Φ_T) and lifetimes. (C) SF mechanism, where one photon generates two excitons.⁷³

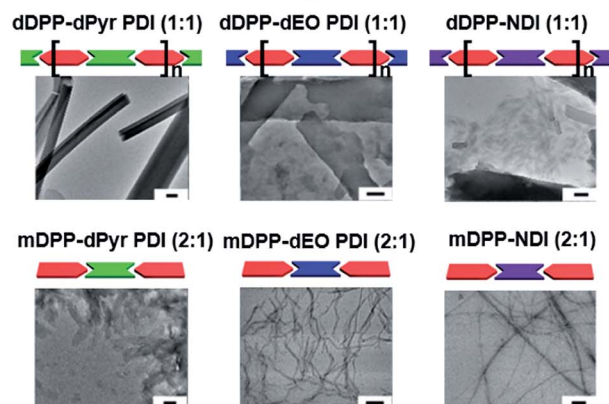
maximize coupled triplet formation, but also promote their decoupling—a necessary event for harvesting these excited states without losing them to recombination. For harvesting decoupled triplets, fullerenes have been used with pentacene, essentially promoting CT after the SF event, to make solar cells.⁷⁸ Control over the heterojunction organization and overall active layer morphology, and stability in ambient conditions, however, are still ongoing challenges whose resolution could lead to higher SF yields as well as greater collection of decoupled triplets.

Mauck *et al.* used a combinatorial approach to study SF kinetics and triplet yields in DPP by installing different side chains off the DPP core nitrogen (Fig. 5A).⁷³ This is

a combinatorial, supramolecular system in that in their work, DPP derivatives with methyl (Me), *n*-hexyl (C6), triethylene glycol (TEG), and 2-ethylhexyl (EH) substituents on the nitrogen of the DPP core are prepared using the same straightforward chemistry. These DPPs assemble into stacks, and crystal structures of these materials show that the side chains alter the DPP stacking torsion angle offset along with transverse and longitudinal displacement with the thiophene substituent of one molecule over the DPP core of its neighbor. This slip-stack geometry is known as *J*-aggregation and is preferable for SF over *H*-aggregation, where molecules are stacked parallel, because of the antisymmetric orbital overlap between coupled neighbors.⁷³ This $\pi \cdots \pi$ stacking geometry is altered by the sterics imposed by side chains off the core, and these relatively subtle offsets in packing geometry play critical roles in orbital overlap, and thus, SF yields and lifetimes (Fig. 5B). Increased sterics of the side chains separates the DPP cores and leads to slower formation (τ_1) of an intermediate state that precedes the formation of (T_1T_1) via SF (τ_2). The Me, C6, and TEG systems demonstrate SF yields over 100%, although τ_2 increases with increasing side chain size of 22.1 ± 0.9 , 336 ± 7 , and 195 ± 8 ps, respectively. The bulkier EH system, however, presents a τ_2 of 1600 ± 500 ps and is the only system with <100% triplet yield. This longer deactivation lifetime is assigned to fluorescence, and based on the 70% triplet yield, τ_2 is calculated to be 1.2 ns. This work demonstrates precisely the importance of control over molecular packing geometry in promoting SF, and because of DPP's structural customizability, this study showed how supramolecular assembly with combinatorial components leads to insight into how structure affects the complex photophysics of SF.

We have also recently developed a supramolecular system to explore how SF yields and lifetimes are affected by subtle changes in stacking geometry.⁷⁹ The active component that undergoes SF is based upon a DPP core that is substituted with diamidopyridine (DAP) H-bonding moieties (Fig. 6A). In addition, orthogonal $\pi \cdots \pi$ stacking between the cores of the aromatic DPP dyes drives organization into hierarchical structures. The appended DAP groups form H-bonds with rylene diimides, which serve as scaffolds for altering relative DPP orientations in the stack. Both DPP and rylene structures are easily modified, providing a lever for altering superstructure geometry in the solid state (Fig. 6B). In our system molecular and long-range geometry were affected in two ways: (1) DPP was monodentate (mDPP) or bidentate (dDPP) depending on the number of DAP groups appended to the DPP core, or (2) core and bay substitution of rylenes were varied to affect their packing geometry, and, as a result, the way they scaffold DPP in the superstructures. From two DPPs and three rylenes, six superstructures with fiber, sheet, and scroll morphologies (Fig. 6C) in the solid state were obtained, and these were all interrogated with fs- and nsTA spectroscopy. Compared to samples composed solely of DPP, some heterosuperstructures show increased decoupled triplet yields and lifetimes. In the case of monodentate mDPP, most decoupled triplet lifetimes from SF were longer (as long as 9.2 μ s) in combinatorial, supramolecular thin films compared to films composed solely of mDPP (1.9 μ s). And in the case of dDPP, most decoupled





triplet yields were higher in mixed films (as high as 28%) compared to films of dDPP (23%). To date, the most common approaches to explore and optimize SF focus solely on dye structure, and orientation of dyes in films is an afterthought. As such, very few groups use secondary components to control their geometry, despite the importance of packing on SF yield. Our work showed that subtle changes in DPP geometry that result from controlled noncovalent binding manifest as changes in SF yields and lifetimes.

FRET occurs when the energy released nonradiatively by an excited chromophore is absorbed by a neighboring molecule

(Fig. 7C). This happens when donor and acceptor are in close proximity, $\sim 10\text{--}100\text{ \AA}$, and the absorbance of the acceptor overlaps with the emission of the donor.⁸⁰ The nonradiative transfer of energy manifests as a decrease in the donor's fluorescence and an increase in the acceptor's. FRET is not as sensitive to electronic coupling as CT or SF and is less affected by orientation changes, but is highly sensitive to chromophore distance and spectral overlap. Therefore a wider range of modifications can be done to donors and acceptors to better control FMOs without as much concern for how the changes in structure affect neighbor orientation with respect to the FRET partner. FRET has many applications including sensitizing triplet oxygen into its excited singlet state, which can be used for photodynamic cancer therapy,⁸¹ as a photocatalyst for synthesis,⁸² and for solar energy harvesting.⁸³

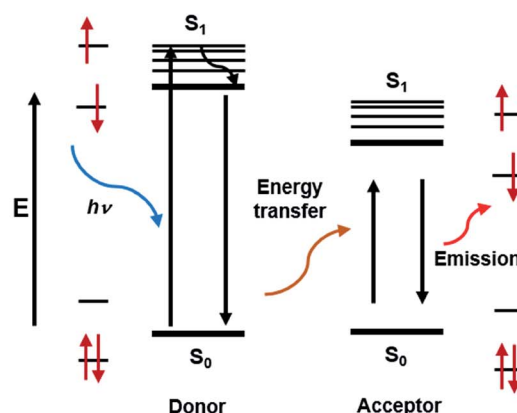
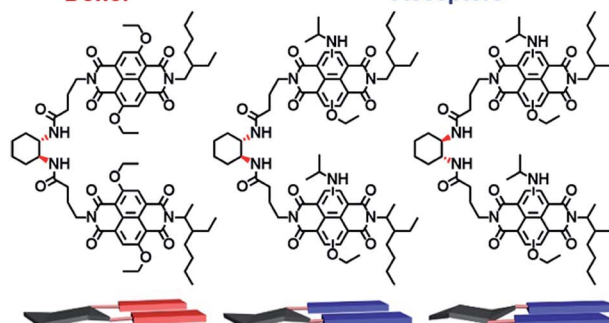


Fig. 7 Förster resonance energy transfer (FRET) in assembling naphthalene dimers. (A) Donors and acceptors synthesized by varying core substitution. (B) Chiral linkers promote either co-assembly or self-sorting structures. (C) FRET mechanism showing energy transfer from donor to acceptor.⁸⁴

Ji *et al.* have recently reported chiral light-harvesting nanotube antennas and studied cooperative assembly and energy transfer amongst its water soluble donor and acceptor components.⁸⁵ In their work, cyanostilbene-appended glutamate (CG) self-assembled into helical nanotubes, as seen in SEM and TEM, whose chirality was controlled by switching between L-CG and D-CG (Fig. 8A). This CG bilayer structure, which was substantiated with XRD, is the basic building block that formed lamellar structures, which then roll into chiral nanohelices and nanotubes (Fig. 8B). When achiral acceptor components thioflavin T (ThT) and/or acridine orange (AO) acceptors were inserted into the L-CG or D-CG to form superstructures, FRET occurs where the CG is the FRET donor. This system is combinatorial because of the variety, and multitude, of acceptors that can be incorporated into the superstructure resulting in 14 possible combinations from five components. Co-assembly was confirmed by emergent signals in circular dichroism (CD) measurements. CG emission overlaps with ThT absorption, making them a suitable FRET pair, and ThT emission overlaps with AO absorption, but CG emission does not overlap with AO absorption. As such, FRET can be seen in CG/ThT dyads but not CG/AO dyads. In CG/ThT/AO triads, ThT absorbs energy from CG, which is then transferred to AO, essentially acting as a bridge, resulting in two sequential FRET (S-FRET) events. In addition to transferring chirality from donor to acceptor, circularly polarized luminescence (CPL)—the circularly polarized emission of light—is also amplified through CG/ThT and triads. All three components in the CG/ThT/AO triad were independently excited and CPL was measured for chirality transfer (ChT) and compared to solutions of the individual components. In the co-assembled superstructures, a CPL signal was seen when only exciting AO, which was attributed to the chirality imparted by the superstructure. AO CPL further increased when directly exciting ThT, and even more so when directly exciting CG. As such, CPL was enhanced for each additional FRET event in the triad system. More generally, this is an elegant example of how biopolymer assembly, like the

this important research area. Combinatorial, supramolecular libraries can have orders of magnitude more components, and it will be then that we have truly tapped into its potential for material discovery. To do so, however, will require concomitant advances in how we study and understand complex photo-physics in hierarchical organic systems.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

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