ISSN1027-5495. Functional Materials, 32, No.3 (2025), p. 323-347
doi:http://dx.doi.org/10.15407/fm32.03.323 © 2025 — STC "Institute for Single Crystals"

Fluorescence properties of cyanine dyes molecular aggregates in nanostructured media: A review

O. V. Sorokin, I. I. Bespalova, S. L. Yefimova

Institute for Scintillation Materials, NAS of Ukraine,
60 Nauky ave., 61072 Kharkiv, Ukraine

Received May 7, 2025

J-aggregates, highly ordered molecular assemblies, continue to attract significant attention in hybrid nanophotonic research owing to their strong absorption, efficient energy transfer, and pronounced fluorescence properties. When combined with nanostructured materials, their spectral properties – such as quantum yield, lifetime, and exciton dynamics – can be substantially modified. This review discusses various aspects of J-aggregates' interactions with different nanostructured materials, focusing on their impact on the aggregates' optical properties, particularly fluorescence. Strategies for enhancing the spectral response of J-aggregates in both liquid and solid media are highlighted.

Keywords: J-aggregate, fluorescence, exciton, nanostructured material, surfactant, silicate shell, nanopore, liquid crystal, Langmuir–Blodgett film, polymer film, plasmon

Флуоресцентні властивості молекулярних агрегатів ціанінових барвників у наноструктурованих середовищах: огляд. *О. В. Сорокін, І. І. Беспалова, С. Л. Єфімова*

J-агрегати, високовпорядковані молекулярні збірки, продовжують привертати значну увагу в гібридних нанофотонних дослідженнях завдяки їхньому сильному поглинанню, ефективному переносу енергії та вираженим флуоресцентним властивостям. У поєднанні з наноструктурованими матеріалами їхні спектральні властивості, такі як квантовий вихід, час життя та динаміка екситонів, можуть бути суттєво змінені. У цьому огляді розглядаються різні аспекти взаємодії J-агрегатів з наноструктурованими матеріалами, зосереджуючись на їхньому впливі на оптичні властивості агрегатів, зокрема флуоресценцію. Виділено стратегії посилення спектральної чутливості J-агрегатів як у рідких, так і в твердих середовищах.

1. Introduction

Currently, considerable attention has been devoted to fundamental studies of the mechanisms behind the formation of optical properties and luminescence in nanodispersed and nanostructured materials of various compositions [1,2]. This interest is driven by the growing demand for advanced materials for efficient photonic and optoelectronic devices, such as next-generation light-emitting diodes, solar cells, and integrated photonic systems operating on subwavelength scales [1,2].

Of particular interest in this context are various semiconductor and organic nanomaterials in which optical excitations exist in the form of delocalized electronic states – excitons [3,4]. Among organic materials, special attention is paid to highly ordered molecular aggregates formed by various planar dyes – so-called J-aggregates [5–10]. J-aggregates are low-dimensional molecular crystals composed of cyanines, porphyrins, merocyanines, perylenes, and other dyes [5–10].

The specific optical properties of J-aggregates are determined by electronic excitations

delocalized along the molecular chains and the formation of molecular (Frenkel) excitons due to translational symmetry and strong dipole-dipole interactions between molecules [5–10]. However, the excitonic properties of J-aggregates often differ from those of typical molecular crystals [11]. This is primarily due to the one- or two-dimensional geometry of J-aggregates, whereas molecular crystals usually exhibit three-dimensional ordering [11]. Another essential feature is the strong influence of the microenvironment on the molecular ordering within J-aggregates, which leads to changes in their optical dynamics [11].

Due to their excitonic nature, J-aggregates exhibit several unique spectral properties, including narrow absorption bands, nearly resonant fluorescence, high oscillator strength, a giant third-order susceptibility, efficient resonant energy migration, and more [5–11]. One of the characteristic features of J-aggregates is a narrow exciton band shifted to the red region of the spectrum relative to the monomer band, which is referred to as the J-band (Fig. 1). The width of the J-band is determined by the coherence (or delocalization) length of the excitons, which is one of the key parameters defining the excitonic properties of J-aggregates [5–11].

High oscillator strengths and, consequently, high extinction coefficients, along with efficient energy transfer, have made J-aggregates key photosensitizers for photographic materials [5–11]. J-aggregates have also found applications in biology and medicine as effective fluorescent probes, including in the infrared range [13–15].

The excitonic properties of J-aggregates have also attracted considerable attention in optoelectronics and photovoltaics. Very narrow exciton bands are advantageous for the development of photodetectors with a narrow spectral response [16,17], but represent a significant drawback in the design of organic solar cells [18]. To overcome this limitation, the use of multilayer composites based on J-aggregates with mutually shifted J-bands has been proposed [19]. This requires studying the interactions between J-aggregates to achieve maximum efficiency in such composite materials.

This review presents the authors' perspective on the influence of the nanostructured microenvironment on the fluorescent properties of J-aggregates, drawing primarily on their own experience.

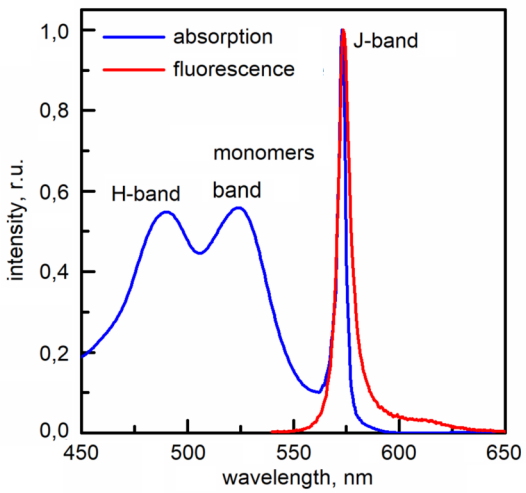

Fig. 1. Absorption (1) and fluorescence (2, λ_{exc} = 530 nm) spectra of pseudoisocyanine iodide (PIC) J-aggregates in aqueous NaCl (0.2 M) solution. Adapted from [12] with permission from AIP Publishing.

2. Some basic properties of J-aggregates

J-aggregates are highly ordered fluorescent assemblies of organic dyes, typically arranged in linear or ring-shaped molecular chains through non-covalent interactions [5–11]. They were first independently observed in the late 1930s by E. Jelley and G. Scheibe, who detected a new red-shifted absorption band in aqueous solutions of 1,1′-diethyl-2,2′-cyanine chloride (pseudoisocyanine, PIC) when its concentration exceeded 5×10^{-3} M [20–24]. These spectral changes were attributed to the formation of dye aggregates, later termed J-aggregates (or Jelley's aggregates) and sometimes referred to as Scheibe aggregates (or Scheibe polymers) [5–11]. Even today, PIC J-aggregates remain widely used as model systems for numerous investigations. Shortly after their discovery, the excitonic nature of the electronic states in these aggregates was proposed [25] and later validated by various experimental approaches, including studies of transition dipole moment orientations [5–11].

Although cyanine dyes are the most commonly employed for constructing J-aggregates [5–11], they are not the only class of molecules capable of this. Other dye families, including porphyrins, phthalocyanines, merocyanines, squaraines, perylenes, oxazines, rhodamines, and bisazomethine compounds, have likewise been utilized to generate J-aggregates [5–11,26–32]. Moreover, the molecular exciton model of J-aggregates has also been extended to systems such as conju-

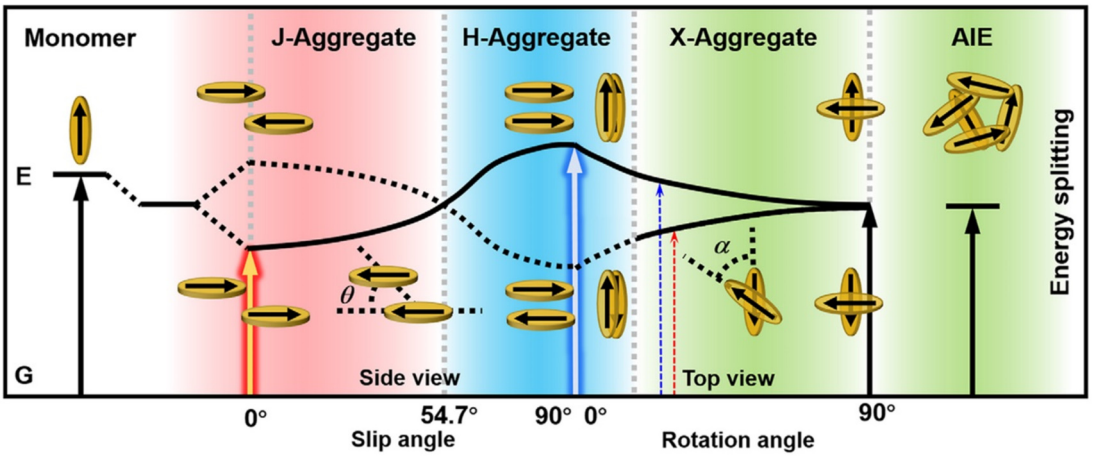

Fig. 2. Excited states energy splitting diagram for molecular aggregates with J-aggregate, H-aggregate, X-aggregate, and AIE (aggregation-induced emission) configurations. Reprinted from [38] with permission from Wiley.

gated polymers [29], organic nanodots [32] and europium-containing complexes [30].

The manifestation of excitonic excitations in the optical dynamics of J-aggregates goes beyond the appearance of the J-band [5–11]. Depending on the arrangement of molecules within the aggregates, another exciton band (the H-band), which is hypsochromically shifted relative to the monomer band, may also emerge [5–11]. Such aggregates are referred to as H-aggregates. The appearance of H- or J-bands can be explained using Kasha's exciton model [33,34], which takes into account Coulombic intermolecular interactions within the framework of Frenkel exciton theory. Although more advanced models have been developed [35–37] Kasha's model remains widely used.

According to Kasha's model, the J-band arises from a "head-to-tail" molecular packing configuration, representing the lowest energy state of the exciton band (Fig.2), while the H-band arises from a "head-to-head" or "sandwich" packing and corresponds to the highest energy state of the exciton band (Fig. 2), which is typically non-fluorescent [5–11,38]. It should be noted that the formation of dimers – the smallest H-aggregates – is a common phenomenon observed in various organic dyes. Some aggregates may simultaneously exhibit both H- and J-bands in their spectra due to the formation of structures referred to as "herringbone" patterns (so-called X-aggregates in Fig. 2) [5–11,38]. In such cases, the relative intensity and spectral position of the exciton bands depend on the molecular arrangement. The fluorescence of "herringbone" aggregates predominantly originates from the J-band [5–11,38].

To describe the J-aggregate structure, several models are usually applied, like ladder, staircase, or brickwork arrangements [5–10]. In solutions, J-aggregates most often adopt rod-like or fibrillar morphologies, typically characterized by lengths much greater than their diameters [5–10,39–48]. Nevertheless, a variety of alternative structures have also been observed, including short cylindrical aggregates [49], two-dimensional sheets and ribbons [50,51], and even spherical assemblies [52]. The internal packing of these morphologies is mostly described using the brickwork model, where planar molecular sheets are envisioned as being rolled into tubular structures [10,48] (Fig. 3), similar to carbon nanotube formation from graphene layers [53]. In this context, the rolling vector **C** specifies which pair of molecules becomes aligned upon rolling, analogous to the way a chiral vector uniquely determines the structure of a particular carbon nanotube [10]. Depending on the resulting arrangement in the cylinders, tubular aggregates can reveal the J-band, or several J-bands, or even the H-band, despite having very similar morphologies [10,41,48,49,51,52,54,55].

In some cases, however, other packing models are invoked, such as those accounting for herringbone-type arrangements [39,41]. When confined to surfaces, J-aggregates may organize into tubular structures or two-dimensional island-like domains, both typically displaying a brickwork molecular arrangement [5–7,40,41,56,57].

Due to their high extinction coefficients and efficient charge transport, J-aggregates have become important as spectral sensitizers for

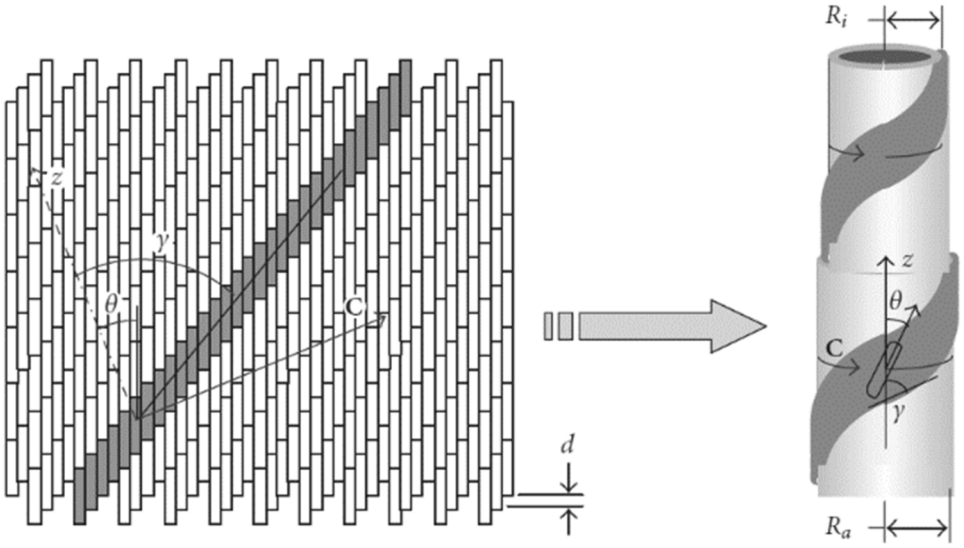

Fig. 3. Structure model of tubular C8S3 J-aggregates: two-cylinder surfaces with different radii Ri and Ra are concentrically arranged to form the double-layer wall. Reprinted from [48] with permission from Hindawi Publishing Corporation.

silver halide microcrystals and have proven to be among the most effective sensitizers for photographic applications [5,58]. This stimulated broad research into their optical and spectral characteristics. A renewed surge of interest emerged in the 1980s, driven by advances in picosecond spectroscopy, which enabled detailed studies of exciton dynamics. Numerous experimental and theoretical works at that time laid the groundwork for the current understanding of J-aggregate photophysics [59–66]. One key result was the explanation of the narrow J-band, attributed to averaging of exciton energies over monomeric fluctuations within the chain, leading to a reduction of the linewidth by approximately $\sqrt{N}$ for an aggregate of N monomers — the so-called "exchange narrowing" (or motional narrowing) effect [11,61]. Another collective effect is exciton superradiance, manifested as cooperative ultrafast spontaneous emission, most evident at low temperatures, where the radiative lifetime of an aggregate shortens in proportion to the number of monomers [11,60].

One more critical phenomenon in J-aggregate photophysics is exciton migration [5–11, 67–71]. Depending on aggregate morphology and experimental conditions, exciton transport has been reported across distances spanning from hundreds to millions of molecules within a single aggregate [67–71]. The importance of this process lies in its potential use of J-aggregates as optical antennas or artificial light-harvesting complexes [48].

Excitonic excitation in J-aggregates is commonly described within the framework of band theory. However, despite the unified approach to describing excitons in J-aggregates and molecular crystals – and the similarities in the exciton characteristics within these molecular structures (such as exciton band width, exciton migration parameters, exciton lifetimes, and extinction coefficients) – there are also significant and nontrivial differences between them [11]. One of the key differences lies in the sensitivity of the J-aggregate structure to the microenvironment (solvation shell), which can induce significant energetic and topological disorder, thereby determining the spectral characteristics of J-aggregates and their exciton dynamics [11]. In addition, for J-aggregates, the exciton–phonon interaction should be taken into account, characterized by $g = \varepsilon_{LR}/2\beta$ (where ε_{LR} is the lattice relaxation energy and 2β is the exciton bandwidth), even though in the majority of studies devoted to the analysis of exciton dynamics in J-aggregates, the coupling constant g has been assumed to be small ($g < 1$) [11,72]. Thus, in the general case, the Hamiltonian of a chain consisting of N molecules in the site representation is written as follows [11]:

$$H = \sum\nolimits_n \left(\bar{\omega} + \delta_n\right) \cdot |n\,n| + \sum\nolimits_{n,m} \left(\bar{\beta} + \beta_{n,m}\right) \cdot |n\,m| + \\ + g \cdot \sum\nolimits_{n,r} q_r \cdot |n\,n|, \quad (1)$$

where: $\bar{\omega}$ – average energy of a monomer molecule in a molecular chain; δ_n – fluctuation of the energy of a molecule at a node (energy

disorder); $\bar{\beta}$. – averaged transfer integral; $\beta_{n,m}$ – fluctuation of the transfer integral (topological disorder); g – exciton-phonon interaction constant; q_r – vibrational coordinate of the r-th phonon mode; $|n$ – nodal states.

It should be noted that the exciton delocalization (or coherence) length N_{del} in a molecular chain is determined by the ratio between the transfer integral ß and the energetic disorder δ_n [11]. Nevertheless, unlike in molecular crystals, it is possible to reliably estimate N_{del} experimentally using two independent parameters, through the ratio of the spectral widths of the absorption bands and the radiative decay times of fluorescence for J-aggregates and monomeric molecules [11]:

$$N_{del} = \frac{3 \cdot (\Delta\upsilon_{FWHM}^{mon})^2}{2 \cdot (\Delta\upsilon_{FWHM}^{J})^2} - 1, \quad (2)$$

$$N_{del} \approx \frac{\pi^2 \cdot \tau_{rad}^{mon}}{8 \cdot \tau_{rad}^{J}}, \quad (3)$$

where: $\Delta\upsilon_{FWHM}^{mon}$ and τ_{rad}^{mon} – the full width at half maximum of the absorption band and the radiation lifetime of the monomers, respectively; $\Delta\upsilon_{FWHM}^{J}$ and τ_{rad}^{J} – the same for J-aggregates.

It should be emphasized that J-aggregates are never entirely free of static disorder, which leads to exciton localization within limited sites of the molecular chain [11,12,65,66]. Most frequently, attention is given to diagonal (energetic) disorder, reflting fluctuations in the site energies of individual monomers along the chain [11,12,65,66]. Nevertheless, in certain cases, off-diagonal (topological) disorder must also be considered, avariations in molecular orientation or intermolecular spacing can significantly affect exciton localization [11,12,65,66,73]. Such disorder alters the low-energy wing of the J-band, shifting it from the conventional Gaussian profile toward a Lorentzian one [11,12,65,73]. It has been demonstrated [69,74] that in the presence of pronounced off-diagonal fluctuations, a heavy-tailed Lévy distribution provides a more accurate description of the J-band low-energy tail, a phenomenon referred to as Lévy-type disorder.

In addition to static effects, localization can also arise from dynamic disorder caused by exciton–phonon interactions [11,12]. It is well established that the interaction between excitons and lattice vibrations gives rise to hybrid quasiparticles known as polarons, which may be described as excitons accompanied – or "dressed" – by local lattice distortions [12,75–77]. The spatial extent of a polaron depends on the strength of exciton–phonon coupling. When the coupling is weak, large-radius polarons are formed; these resemble nearly free excitons and manifest through an enhanced Stokes shift and a broadened emission band [12,75–77]. In contrast, strong coupling can lead to small-radius polarons, where the lattice distortion becomes sufficiently pronounced to trap the exciton within a self-induced potential well [12,75–77]. Such localized states are known as self-trapped excitons [12,75–77].

The concept of exciton self-trapping has been extensively investigated in crystalline materials from both theoretical and experimental perspectives [12,75–77]. For two- and three-dimensional lattices, theory indicates a threshold behavior: when the exciton–phonon coupling constant exceeds a critical value $g > g_{cr} \sim 1$, both free and self-trapped excitons can coexist, separated by an energy barrier (the self-trapping barrier) [12,75–77]. This duality produces two distinct fluorescence signatures: a sharp band near the exciton absorption edge corresponding to free excitons, and a broad, strongly Stokes-shifted band associated with self-trapped states [12,75–77]. In one-dimensional systems, however, the threshold condition usually disappears, and excitons tend to self-trap at any coupling strength [12,75–77]. This barrierless self-trapping is experimentally observed as an increased Stokes shift and broadening of the free-exciton emission band [12,75–77].

3. Influence of nanostructured microenvironments in solutions

Because J-aggregates are stabilized by noncovalent interactions, their environment can strongly influence their aggregation degree, structural organization, and exciton coherence, thereby modulating their optical properties. The presence of salts alters the dielectric constant of water, which in turn affects intermolecular interactions and favors dye aggregation [78]. For example, this phenomenon results in the formation of J-aggregates for the TCC dye [79] and H-aggregates for the methyl meso-substituted dye in the presence of inorganic salts [55,79,80]. Another strategy to promote J-aggregation is pH adjustment of aqueous solutions by adding acids or bases [78,81–85]. In acidic media, protonation of the dye generally shifts the equilibrium toward J-aggregate formation, even when H-aggregates are initially

present [78,82–85]. For example, sulfonate dyes can convert into sulfonic acids under strong acids, such as HCl, whereas weaker acids have little impact on aggregation, despite producing solutions of similar pH [83]. Notably, in specific systems, including porphyrin aggregates, J-aggregate formation under acidic conditions is accompanied by pronounced fluorescence quenching [84].

Moreover, the agglomeration of individual J-aggregates also influences their optical behavior. For instance, well-studied PIC J-aggregates exhibit a fiber-like morphology with an aggregate diameter of approximately 2.3 nm [86]. Still, in aqueous electrolyte solutions, they further assemble into much larger bundles [87–89]. Similarly, various derivatives of the TDC dye form bundles of fiber-like aggregates, which in turn may adopt a tubular structure [41,48,90,91]. For amphi-PIC J-aggregates, agglomeration leads to broadening of the fluorescence band, accompanied by a reduction in fluorescence decay time [42]. This behavior has been attributed to efficient quenching by local traps formed at the contact sites between individual J-aggregates. In the case of C8S3 J-aggregates (a derivative of TDC), significantly more efficient exciton migration is observed in aggregate bundles, with average migration lengths reaching several hundred nanometers, compared to about 140 nm in individual aggregates [68]. This finding indicates highly effective energy transfer between individual aggregates within the agglomerates. For PIC J-aggregates, agglomeration results in enhanced fluorescence properties, even though static disorder increases [89]. This improvement was attributed to efficient inter-aggregate excitonic energy transfer, which boosts exciton migration, as well as to the increased photostability of J-aggregates within the agglomerates [89].

However, the agglomeration process is difficult to control, and using additives that promote J-aggregation seldom results in new spectral features of J-aggregates. Therefore, to achieve J-aggregates with specific spectral properties, employing nanostructured species might be more suitable.

For example, the interaction of J-aggregates with nucleic acids, particularly their incorporation into the minor groove of DNA, is of considerable interest [92–99]. J-aggregates can be employed as selective fluorescence t probes for nucleic acids, while the intrinsic helical structure of DNA provides a versatile scaffold for constructing optically active J-aggregate–based composites [92–99]. Furthermore, such composites hold promise for applications in the design of nonlinear optical devices [6].

In addition, interactions between J-aggregates and polymers can also give rise to helical assemblies in solution, often accompanied by a pronounced circular dichroism (CD) response [100,101]. Such a supramolecular arrangement can emulate natural photosynthetic complexes [101]. In this system, thiacyanine (TC) dye J-aggregates were organized along the helical scaffold of carboxymethyl amylose (CMA), functioning as a light-harvesting antenna for an electron donor–acceptor pair located inside the helical cavity [101]. Both steady-state and time-resolved experiments demonstrated the high energy-transfer efficiency of this system and highlighted its potential as a prototype for artificial photosynthesis [101]. A related approach utilized TC J-aggregates as a photonic antenna to enhance two-step energy transfer within a cyanine triad assembled on hollow microcapsules coated with polyelectrolyte multilayers [102].

Different types of nanoparticles can affect J-aggregate formation [103–108], leading, for instance, to specific molecular arrangements within the aggregates [103]. In certain cases, such as interactions with quantum dots, these complexes can enable efficient energy transfer [103–108].

As another example of nanostructures' influence, surfactants cause a pronounced effect on J-aggregate formation in solution [109–124]. At concentrations below the critical micelle concentration (CMC), they can promote aggregation [109–122] and may even alter aggregate morphology [110,119]. Above the CMC, micelle formation generally leads to J-aggregate disruption through solubilization, as dye molecules are incorporated into micelles in their monomeric form [109–121].

However, in some cases, surfactant micelles have been found to enhance rather than suppress the aggregation of cyanine dyes [111–113,122]. For instance, PIC aggregation persisted even at surfactant concentrations well above the CMC of some anionic surfactants, whereas no such effect was observed with nonionic surfactants [111]. In another study, the addition of a zwitterionic surfactant above the CMC to aqueous solutions containing TDBC J-aggregates was found to enhance their spec-

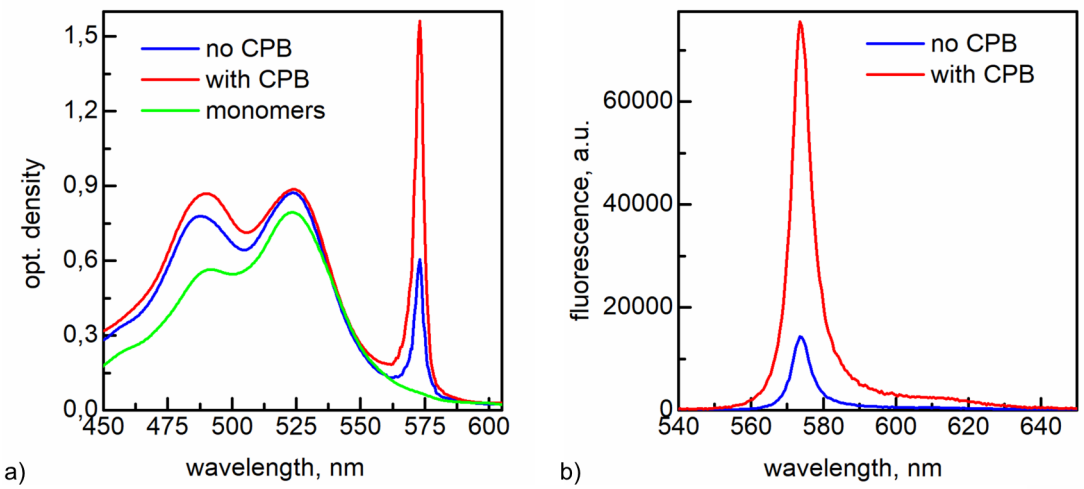

Fig. 4. Absorption (a) and fluorescence (b) spectra of PIC J-aggregates (C = 2.5×10^{-4} M) in aqueous solution with NaCl (C = 0.2 M) in the absence and presence of CPB surfactant. Curve 3 represents the absorption spectrum of PIC monomers in the same solution (C = 1×10^{-6} M). Adapted from [123] with permission from ACS.

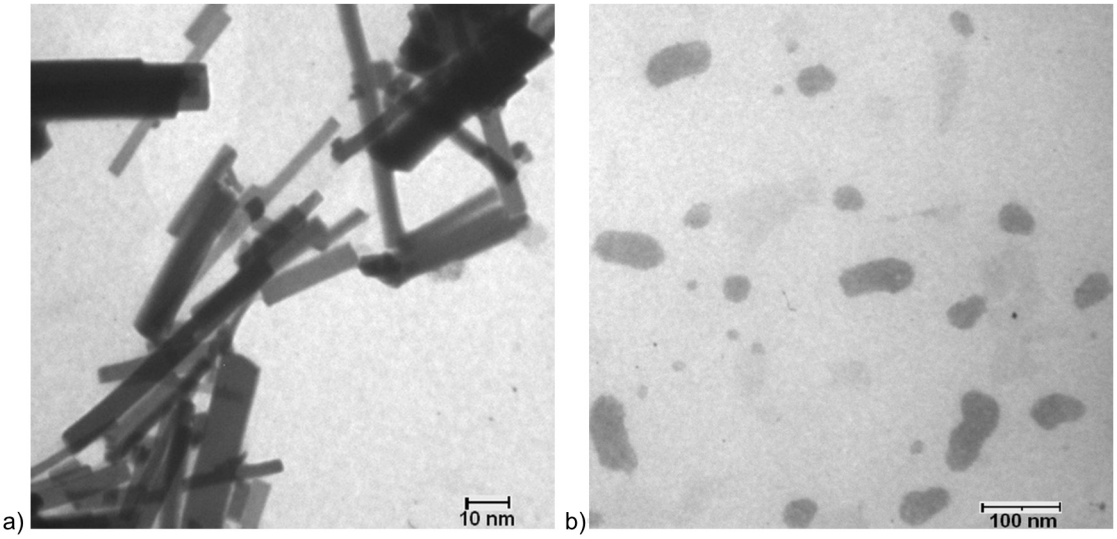

Fig. 5. TEM images of amphi-PIC J-aggregates in the absence (a) and presence (b) of CPB micelles. Figure reprinted from [125] with permission from Elsevier.

tral properties: the J-band became narrower and more intense, and the fluorescence quantum yield increased [112]. In contrast, cationic surfactants led to the disruption of TDBC J-aggregates [112]. Similar behavior has also been reported for porphyrin dyes; for example, porphyrin J-aggregates were shown to form within micelles of the nonionic surfactant Triton X-100 [120,121]. It was proposed that these J-aggregates are localized in the extended hydrophilic shell of the micelles.

For amphi-PIC J-aggregates, interactions with anionic and cationic surfactants also produced markedly different outcomes depending on surfactant type. Micelles of the anionic surfactant sodium dodecyl sulfate (SDS) led to aggregate disruption, whereas micelles of the cationic surfactant cetylpyridinium bromide (CPB) enhanced the J-band, resulting in increased intensity and spectral narrowing [113]. Comparable effects of CPB micelles were also reported for J-aggregates of other cationic cyanine dyes, including L-21, JC-1, and PIC (Fig. 4) [122,123].

For all of these aggregates, a narrowing and intensification of the J-band was observed, accompanied by a pronounced increase in fluorescence quantum yield – up to fifteenfold [122,123]. This effect was attributed to the formation of a molecular shell around the

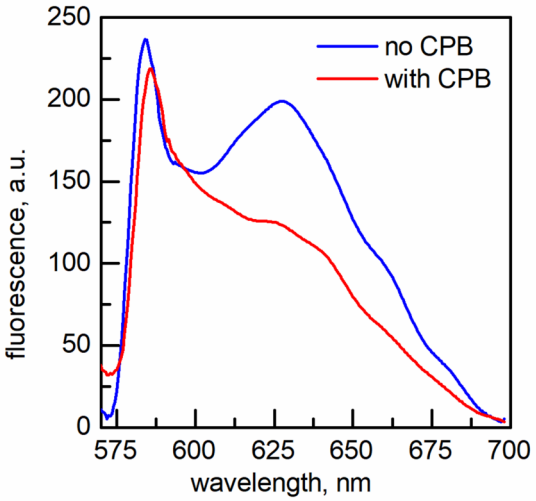

Fig. 6. Fluorescence spectra of amphi-PIC J-aggregates at T = 80 K (λ_{exc} = 532 nm) in DMF: water (90%) solutions without and with CPB. The figure is adapted from [127] with permission from Taylor & Francis.

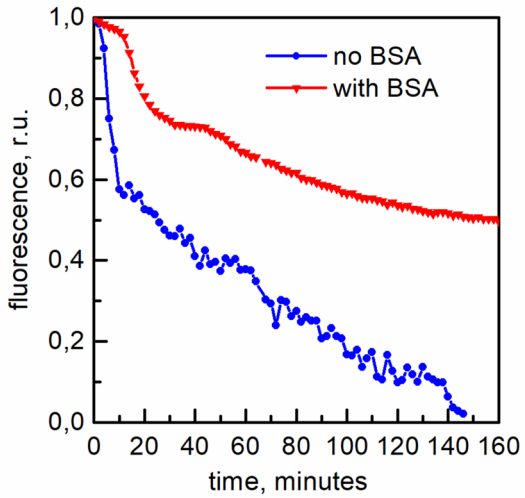

Fig. 7. Time evolution of the fluorescence intensity at the band maximum (λ_{reg} = 595 nm) for amphi-PIC J-aggregates under continuous illumination, recorded in the absence (1) and presence (2) of BSA. For clarity, the curves are normalized to their initial intensity. The figure is adapted from [129] with permission from Elsevier.

J-aggregates, which improves their structural organization and thereby reduces static disorder [122,123]. The formation of such a CPB shell surrounding amphi-PIC J-aggregates was directly confirmed by TEM (Fig. 5) [125].

On this basis, it was proposed that the spectral modifications observed for amphi-PIC, L-21, JC-1, and PIC J-aggregates in the presence of CPB surfactant are associated with the suppression of exciton self-trapping [73,122,123,125–127]. The study [128] demonstrated that the strength of the electron–phonon interaction depends on the degree of localization of the electronic excitation: more localized excitations exhibit stronger electron–phonon coupling. The localization of electronic excitations in J-aggregates – specifically, the exciton delocalization length – is strongly influenced by the degree of static disorder within the aggregates [12,73]. Consequently, the increase in exciton delocalization observed for amphi-PIC, L-21, JC-1, and PIC J-aggregates in the presence of CPB surfactant [122,123] leads to a reduction in exciton–phonon coupling and a suppression of exciton self-trapping [12]. This effect has been experimentally confirmed for all studied J-aggregates within the "J-aggregate–CPB" complex [125–127], and for amphi-PIC J-aggregates, the suppression of exciton self-trapping has been directly visualized (Fig. 6) [127]. It is evident that the broad red-shifted band, associated with self-trapped exciton emission, exhibits reduced intensity in the presence of CPB (Fig. 6).

Interestingly, serum albumin molecules can also form a molecular shell around amphi-PIC J-aggregates, thereby enhancing their optical properties [129]. Similar to surfactants, when natural blood proteins such as serum albumin interact with J-aggregates, they frequently induce disaggregation, accompanied by the binding of individual cyanine dye molecules to the albumin [130–132]. In contrast to the usual disaggregation behavior, the addition of bovine serum albumin (BSA) at concentrations only slightly higher than that of the amphi-PIC dye leads to notable improvements in the spectroscopic features of the J-aggregates [129]. These include a narrower J-band, implying a greater exciton coherence length, as well as enhanced fluorescence quantum yield, extended lifetime, and increased photostability (Fig. 7) and stability [129].

Measurements indicate that in BSA-containing solutions the average size of the aggregates is significantly smaller compared to pure J-aggregates [129]. The formation of BSA–amphi-PIC J-aggregate complexes has been proposed [129], with the interaction assumed to suppress agglomeration, a process typically occurring in solution [87–89]. Such complexation is expected to take place when amphi-PIC J-aggregates enter the bloodstream [133]. Consequently, J-aggregate–protein complexes with superior optical performance may hold promise as fluorescent probes for biological applications.

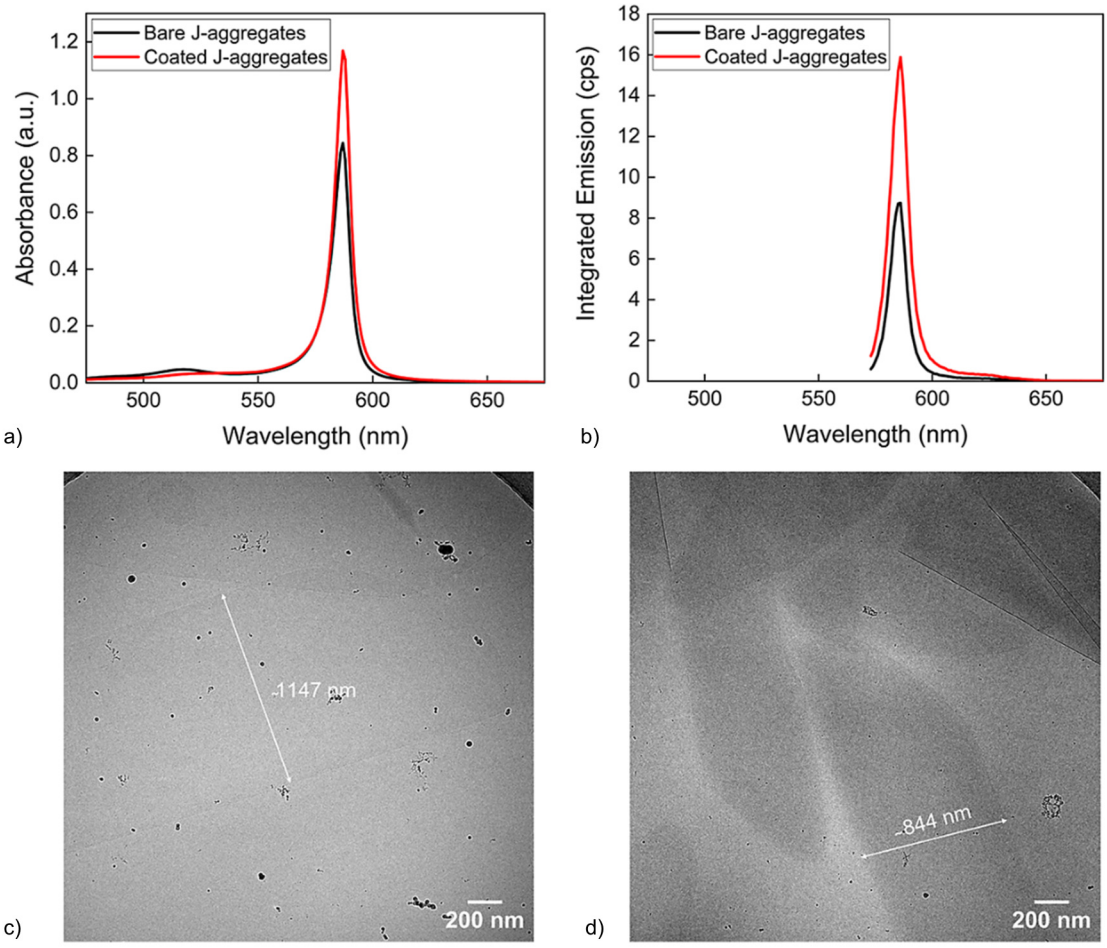

Fig. 8. Characterization of silica-encapsulated vs bare TDBC J-aggregates. (a) Steady-state absorption and (b) emission spectra for bare (black) and silica-encapsulated (red) J-aggregates. (c and d) Cryo-TEM images of bare and silica-encapsulated J-aggregates, respectively, further confirming the smaller size distribution for silica-encapsulated J-aggregate sheets. Scale bar: 200 nm. The figure is reprinted from [139] with permission from ACS.

Although the formation of molecular shells around J-aggregates using surfactants or proteins offers certain advantages, the long-term stability of such complexes remains questionable. To address this limitation, the encapsulation of J-aggregates within ultrathin silica shells (only a few nanometers thick) has been proposed, initially for porphyrin aggregates [134,135] and later extended to cyanine-based systems [45,136–139]. This strategy is effective for both tubular [45,134–138] and two-dimensional "leaf-like" [139] J-aggregates and leads to substantial improvements in their spectral properties (Fig. 8), while also enabling controlled manipulation through interactions with plasmonic nanoparticles [135,137]. For example, silica-encapsulated TDBC J-aggregates exhibit an exceptionally high fluorescence quantum yield of ~98% along with a short emissive lifetime of 234 ps and high robustness [139].

4. J-aggregates in porous and highly ordered systems

Another practically important example of a nanostructured environment is represented by various nanoporous structures, within which J-aggregate formation has been reported [140–159]. Aggregation of TDBC in a nanoporous SiO_2 sol–gel matrix was achieved in [140]. In this case, the dye was incorporated into the matrix during synthesis, which prevented sufficient thermal treatment of the matrix; consequently, its mechanical properties, such as strength, remained poor [140]. It should also be noted that J-aggregate formation required sample aging for three months at 60 °C [140]. Even under these conditions, the J-band remained very broad and its maximum was considerably blue-shifted compared to that observed in aqueous solution [140]. Interestingly, exposure of

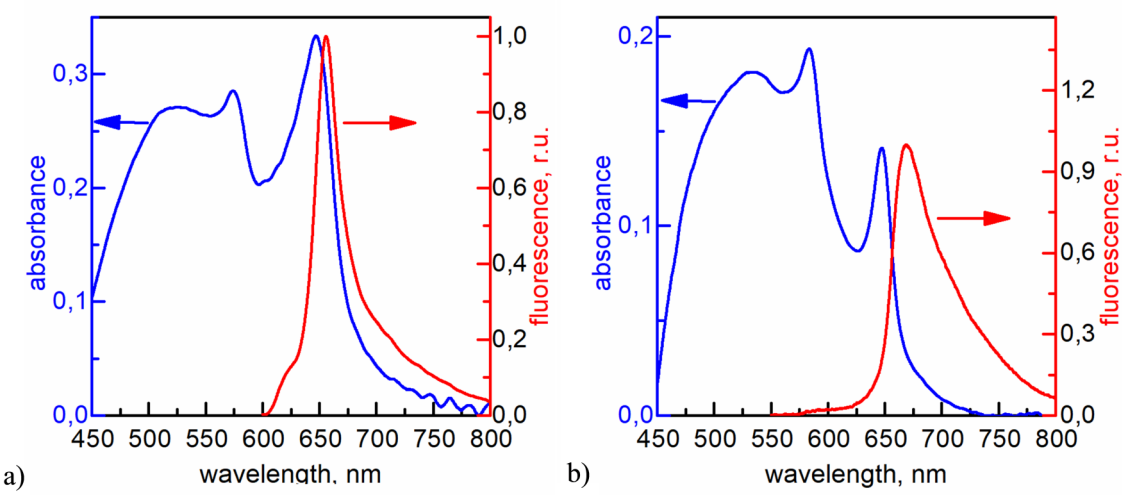

Fig. 9. Absorption (curves 1) and fluorescence (curves 2, λ_{exc} = 530 nm) spectra of deposited pairs of J-aggregates: a) first PIC and second TCC J-aggregates on negatively charged TiO_2 film, b) first TDBC and second TCC J-aggregates on positively charged TiO_2 film. The fluorescence curves are normalized for clarity. The figure is adapted from [151] with permission from Elsevier.

the samples to an ammonia atmosphere led to narrowing and red-shifting of the J-band [140], an effect attributed to either an increase in matrix polarity or an enlargement of pore size.

J-aggregates of the merocyanine dye Mc2, exhibiting either a single J-band or both J- and H-bands, were obtained in thin nanoporous films of TiO_2, Al_2O_3, and ZrO_2 [141]. In the case of Al_2O_3 and ZrO_2 films, successful aggregation required pre-saturation with salt solutions or concentrated hydroxide solutions. For TiO_2 films, both types of J-aggregates exhibited electron injection into TiO_2 nanoparticles [141]. Thin SiO_2 sol–gel films prepared by spin-coating were successfully loaded with J-aggregates of PIC and its derivatives (including amphi-PIC) [142,143]. Such films demonstrated relatively high third-order nonlinear susceptibility (~5×10–7 esu) and were suggested as promising candidates for nonlinear optical devices [142,143].

Broadening of the J-band, indicative of increased static disorder, is often observed during J-aggregate formation on or within nanoporous matrices [140–151,153]. Nevertheless, the manifestation of key functional properties – such as enhanced stability and applicability in advanced optical and optoelectronic technologies – underscores the considerable practical significance of these systems [160–168]. For example, in [151] we reported the fabrication of TiO_2 matrices composed of nanoparticles with different surface charges. J-aggregates of the cationic dye PIC and the anionic dye TDBC were formed on oppositely charged matrices, in both cases exhibiting pronounced static disorder [151]. Subsequently, additional J-aggregates of another dye with a red-shifted excitonic band were deposited onto these layers. As a result [151], highly efficient energy transfer from donor to acceptor aggregates was achieved in both systems (Fig. 9), demonstrating their potential for photovoltaic and optoelectronic applications based on J-aggregates with extended spectral sensitivity [169]. Indeed, although the absorption spectra of both J-aggregate pairs (PIC–TCC and TDBC–TCC, Fig. 9) display J-bands corresponding to both donor and acceptor aggregates, only the band of the acceptor TCC J-aggregates appears in the fluorescence spectra. The fluorescence excitation spectra further confirm this result, showing the absence of donor J-aggregate excitation peaks due to efficient energy transfer [169].

Promising opportunities for assembling J-aggregates from unconventional molecules are offered by materials with one-dimensional pores [154–157]. For example, in [154] the formation of J-aggregates of pyronine dye was observed within zeolite nanochannels at high loading, whereas at low concentrations the dye remained in its monomeric form. Similarly, in NaX–NaY zeolites, the proton-transfer dye HBN-4NP was shown to form monomers, H-aggregates, or J-aggregates, with the resulting structures exhibiting a wide range of fluorescence properties, particularly tunable lifetimes spanning from picoseconds to several nanoseconds [155]. Classical J-aggregating dyes such as PIC can also be incorporated into alumino-

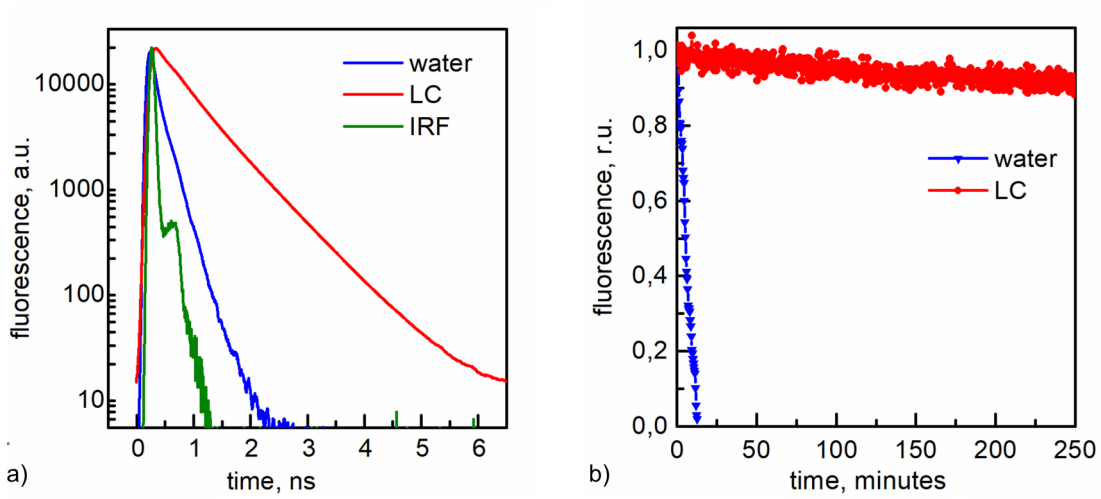

Fig. 10. a) Fluorescence decays (λ_{reg} = 590 nm) for TDBC J-aggregates in water and LC; b) time evolution of fluorescence intensity at the emission maximum (λ = 590 nm) for TDBC J-aggregates in water (1) and in the LC matrix (2) under continuous illumination. The curves are normalized to their initial values for clarity. The figure is adapted from [173] with permission from Optica.

phosphate zeolitic structures, enabling efficient one-dimensional energy transfer from monomers – typically non-fluorescent in solution – to J-aggregates [157]. Single-walled carbon nanotubes have likewise been demonstrated as effective hosts for J-aggregate formation with various dyes, including α-sexithiophene, ß-carotene, methylene violet B, and others [156]. These hybrid complexes display exceptionally strong Raman scattering, making them attractive for Raman imaging with robust detection through multispectral analysis [156].

Nanoporous materials offer confined environments that promote the formation of J-aggregates and can influence their optical properties. A comparable effect may also arise when J-aggregates are organized within well-ordered nanostructured systems such as liquid crystals (LCs). Although LCs are not typically recognized as favorable media for J-aggregate formation, several studies have demonstrated this possibility [170–174]. Interest in dispersions of J-aggregates in liquid crystals (LCs) has been stimulated by advances in luminescent liquid crystals (LLCs) – LCs doped with luminescent species – owing to their strong potential for optoelectronic applications, particularly where highly anisotropic luminescence is desired [175–178]. It is worth noting that J-aggregates themselves can form liquid-crystalline phases [179–183], enabling the creation of LLCs with pronounced anisotropy. However, many J-aggregating dyes, such as cyanines, suffer from poor photostability, largely due to interactions with oxygen [5–9,184]. As a result, liquid-crystalline phases of these dyes are generally unsuitable for practical applications. Notably, Ref. [171] demonstrated the formation of perylene J-aggregates within a liquid-crystal matrix. Owing to the matrix's low oxygen permeability and solubility, the photostability of the J-aggregates was markedly enhanced, enabling stimulated emission (laser generation) [171]. These findings suggest that dispersions of J-aggregates in liquid-crystal matrices may offer a promising route for the design of luminescent liquid crystals.

A stable dispersion of TDBC and PIC J-aggregates was successfully achieved in a 5CB liquid-crystal matrix [173,174]. Both dyes exhibit a limited concentration window for J-aggregate formation in liquid crystals, accompanied by pronounced J-band broadening, with TDBC J-aggregates showing better performance. Compared to aqueous solutions, the exciton delocalization lengths in the LC environment were shorter for both J-aggregates, indicating stronger static disorder [173,174]. Nevertheless, both the fluorescence quantum yield and lifetime (Fig. 10a) increased, pointing to suppressed nonradiative relaxation and an unusually long radiative lifetime [173].

A remarkable enhancement in photostability was also observed (Fig. 10b), although its underlying mechanism remains unclear [173,174]. Incorporation of TDBC J-aggregates was further shown to alter the electro-optical response of the LC host without significantly disturbing its molecular order; in particular, the Fredericks transition became sharper rel-

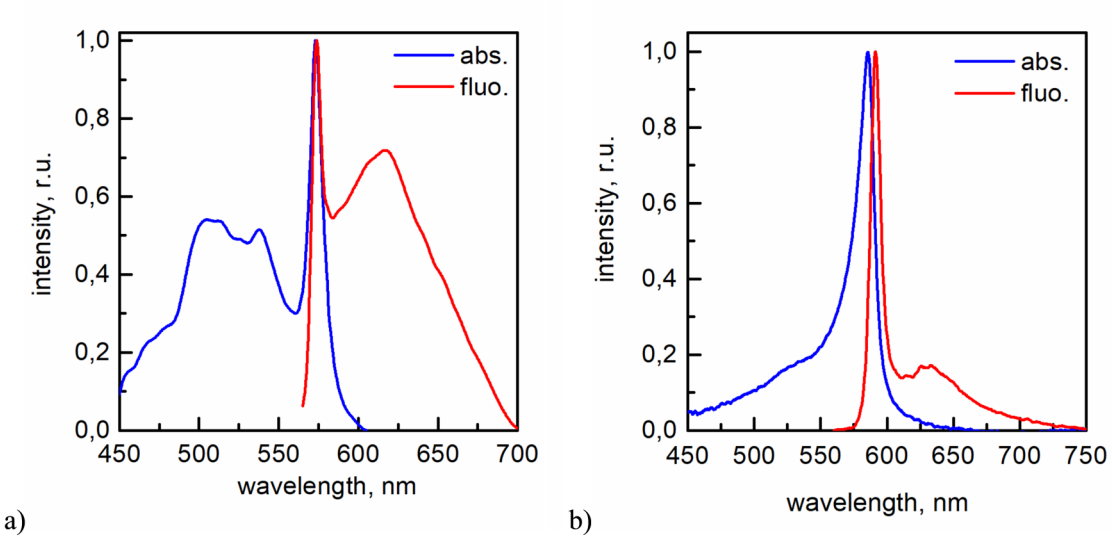

Fig. 11. Absorption and fluorescence (λ_{exc} = 530 nm) spectra of PIC (a) and TDBC (b) J-aggregates formed in LbL films at T = 80 K. Spectra normalized for clarity. The figures are adapted from [56,57] with permission from ACS.

ative to the pure LC matrix [173,174]. These findings highlight the potential of such hybrid systems for the development of advanced luminescent liquid-crystal materials and motivate further in-depth investigation.

5. J-aggregates in thin films

To obtain highly ordered thin films of J-aggregates, the Langmuir–Blodgett (LB) monolayer deposition method on hydrophobic substrates is often employed [185]. This approach makes it possible to prepare thin-film solid samples of J-aggregates with excellent spectral characteristics [5–9,186–202], achieved primarily through the very dense packing of the J-aggregate–forming molecules on the substrate surface. As a result, J-aggregates in LB films adopt a two-dimensional brickwork arrangement, as confirmed by high-resolution microscopic studies [190].

An advantage of LB films is the ability to form J-aggregates even from dyes that typically do not assemble into ordered structures due to steric hindrance, such as DiO [200] and DiI [201]. On the other hand, the photostability of J-aggregates in such films may be insufficient; however, as recently shown, it can be improved by constructing multilayer films [202]. Cyanine dye J-aggregates formed in LB films have been extensively employed to investigate exciton migration and energy transfer processes [188–200].

In particular, this approach enabled the preparation of mixed J-aggregates with excitonic properties distinct from those of the individual aggregates forming them [191–197]. Furthermore, studies [188,189] demonstrated that the energy transfer rate from J-aggregates to another dye acting as an exciton trap decreases by an order of magnitude when the trap is introduced into a separate monolayer deposited on top of the J-aggregate film, compared with the case when the trap is incorporated directly into the J-aggregate layer.

Another promising strategy to enhance the stability of J-aggregates is to form them in thin polymer films [9]. Two primary methods are employed to fabricate polymer films containing J-aggregates: spin-coating [9,40,57,203–205] and layer-by-layer (LbL) assembly [9,56,57,147,206–213]. In both cases, the optical properties of J-aggregates are influenced by the surrounding microenvironment; for instance, their fluorescence quantum yield may be markedly reduced [9,56,57,205,210,212,214,215]. A detailed review of how embedding J-aggregates into polymer films affects their optical properties can be found in [9]. Here, we will address only selected aspects of this interaction.

Formation of J-aggregates in LbL films can lead to structural modifications and, consequently, to changes in their spectral properties compared with spin-coated polymer films. For instance, PIC and TDBC J-aggregates formed in LbL films [56,57] exhibited an island-like morphology, which is markedly different from the fibrillar structures observed for these J-aggregates in spin-coated films [40,57,216–219]. As a result, corresponding J-bands in LbL films

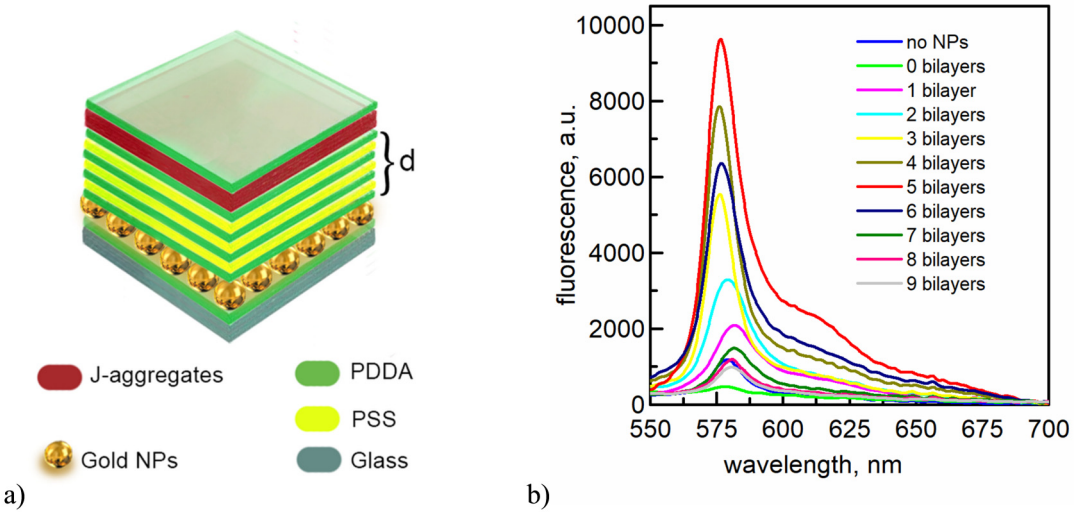

Fig. 12. a) Schematic representation of a layered polymer film incorporating J-aggregates and gold nanoparticle layers, separated by a polymer spacer of thickness *d*; b) fluorescence spectra of PIC J-aggregates in LbL films as a function of the polymer spacer thickness between Au NPs and the J-aggregates. The figures are adapted from [210,212] with permission from ACS.

appeared broader, indicating enhanced static disorder and stronger exciton–phonon coupling [56,57]. At low temperatures, this effect gave rise to a broad red-shifted fluorescense band (Fig.11) originating from self-trapped excitons, which accounts for their reduced fluorescence quantum yield and substantially shorter fluorescence decay times [56,57].

There is an approach to enhance the fluorescence properties of J-aggregates in layered thin films, which involves exciton–plasmon coupling through their interaction with noble metal nanostructures [9,210,212,213,220]. When light couples to the collective oscillations of free electrons in metals, surface plasmon polariton (SPP) resonances arise in the nanostructures [221–226]. The resulting SPP field is confined within the skin-depth region near the nanostructure and is significantly stronger than the incident light field [221–226]. Consequently, SPPs can substantially modify the spectral characteristics of a quantum emitter (QE) located in close proximity to the metal nanostructure [221–226]. In the weak coupling regime, coherent energy exchange between the SPP and the QE is suppressed by the dephasing of individual oscillators [226]. Under these conditions, exciton–plasmon interaction is typically manifested as Purcell-enhanced spontaneous emission [226].

In the weak exciton–plasmon coupling regime, enhancement of J-aggregate fluorescence quantum yield has been demonstrated by positioning the aggregates at an optimal distance from metal nanoparticles [210,212,213,220]. For example, in layered polymer films containing pseudoisocyanine J-aggregates, an eightfold fluorescence enhancement was observed when the distance between the aggregates and Au nanoparticles (NPs) was 16 nm (Fig. 12).

It was found that [212], under plasmon-enhanced fluorescence conditions, exciton self-trapping in PIC J-aggregates is suppressed (Fig. 13a). This effect is attributed to exciton–plasmon coupling, which is assumed to cause a twofold increase in the exciton coherence length, thereby reducing the exciton–phonon coupling constant by half [212]. The weakened exciton–phonon interaction consequently suppresses self-trapping. Similar to plasmon-induced fluorescence enhancement, the suppression of exciton self-trapping not only increases J-aggregate fluorescence but also prolongs the fluorescence lifetime (Fig. 13b) by reducing the non-radiative decay rate [212]. This effect opens new possibilities for controlling the optical properties of J-aggregates in solid films through exciton–plasmon interactions.

Concluding remarks

Highly ordered molecular assemblies known as J-aggregates remain at the forefront of research on hybrid nanophotonic systems due to their remarkable absorption strength, efficient energy transfer, and pronounced nonlinear optical response. Their integration with nanostructured media provides a powerful platform

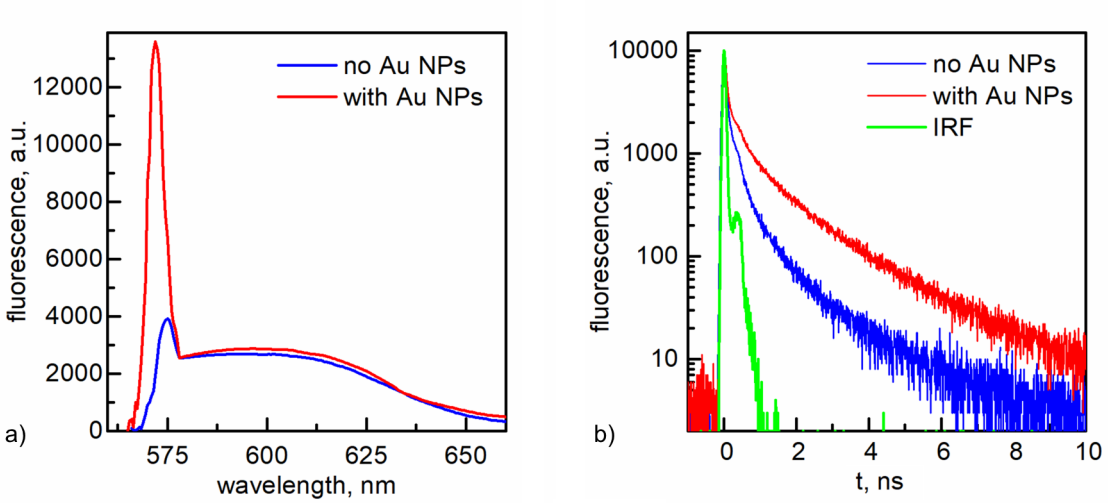

Fig. 13. Fluorescence spectra (a, λ_{exc} = 530 nm) and decay curves (b, λ_{reg} = 585 nm) of PIC J-aggregates in LbL films without and with Au NPs positioned at the optimal distance from the J-aggregates, measured at T = 80 K. The figures are adapted from [212] with permission from ACS.

for tailoring optical functionalities. Depending on the nature of the interaction, nanostructures can profoundly modify the spectral characteristics of J-aggregates, including emission efficiency and exciton dynamics.

At the same time, such hybrid systems enable unique opportunities, including plasmon-enhanced fluorescence and efficient resonance energy transfer. These effects open pathways for advanced applications in nanophotonics, optoelectronics, and light-harvesting technologies. Overall, J-aggregate–nanostructure composites represent a versatile and promising direction, ensuring that their study will remain a focus of both fundamental exploration and applied development.

Acknowlegements

The authors gratefully acknowledge the Ukrainian Army for making it possible to prepare this work. O.S. sincerely thanks Dr. Franziska Fennel (University of Rostock) for her invaluable assistance.

References

1. P.N. Prasad, Nanophotonics, John Wiley & Sons, Inc, Hoboken, 2004. https://doi.org/10.1002/0471670251.
2. L. Novotny, B. Hecht, Principles of Nano-Optics, Cambridge University Press, Cambridge, 2006. https://doi.org/10.1017/CBO9780511813535.
3. J. Singh, R.T. Williams, eds., Excitonic and Photonic Processes in Materials, Springer Singapore, Singapore, 2015. https://doi.org/10.1007/978-981-287-131-2.
4. S. Datta, X. Marie, Excitons and excitonic materials, MRS Bull 49 (2024) 852–861. https://doi.org/10.1557/s43577-024-00766-x.
5. T. Kobayashi, ed., J-Aggregates, World Scientific, Singapore, 1996. https://doi.org/10.1142/3168.
6. T. Kobayashi, ed., J-Aggregates, Volume 2, World Scientific, Singapore, 2012. https://doi.org/10.1142/8226.
7. F. Würthner, T.E. Kaiser, C.R. Saha-Möller, J-Aggregates: From Serendipitous Discovery to Supramolecular Engineering of Functional Dye Materials, Angewandte Chemie International Edition 50 (2011) 3376–3410. https://doi.org/10.1002/anie.201002307.
8. J.L. Bricks, Y.L. Slominskii, I.D. Panas, A.P. Demchenko, Fluorescent J-aggregates of cyanine dyes: basic research and applications review, Methods Appl Fluoresc 6 (2017) 012001. https://doi.org/10.1088/2050-6120/aa8d0d.
9. A. V. Sorokin, S.L. Yefimova, Y. V. Malyukin, Polymer-Bound Supramolecular J-Aggregates: Optical Properties and Applications, in: Encyclopedia of Polymer Science and Technology, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2018: pp. 1–33. https://doi.org/10.1002/0471440264.pst664.
10. T.L.C. Jansen, L.M. Günther, J. Knoester, J. Köhler, Electronically excited states in cylindrical molecular aggregates: Exciton delocalization, dynamics, and optical response, Chemical Physics Reviews 5 (2024) 041305. https://doi.org/10.1063/5.0225327.
11. J. Knoester, V.M. Agranovich, Frenkel and Charge-Transfer Excitons in Organic Solids, in: V.M. Agranovich, G.F. Bassani (Eds.), Thin Films and Nanostructures: Electronic Excita-

tions in Organic Based Nanostructures, Volume 31, 2003: pp. 1–96. https://doi.org/10.1016/S1079-4050(03)31001-4.
12. Y.V. Malyukin, A.V. Sorokin, V.P. Semynozhenko, Features of exciton dynamics in molecular nanoclusters (J-aggregates): Exciton self-trapping (Review Article), Low Temperature Physics 42 (2016) 429–440. https://doi.org/10.1063/1.4955493.
13. A.P. Demchenko, ed., Advanced Fluorescence Reporters in Chemistry and Biology II, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010. https://doi.org/10.1007/978-3-642-04701-5.
14. S. Xu, H.-W. Liu, S.-Y. Huan, L. Yuan, X.-B. Zhang, Recent progress in utilizing near-infrared J-aggregates for imaging and cancer therapy, Mater Chem Front 5 (2021) 1076–1089. https://doi.org/10.1039/D0QM00557F.
15. Z. Li, P.-Z. Liang, L. Xu, X.-X. Zhang, K. Li, Q. Wu, X.-F. Lou, T.-B. Ren, L. Yuan, X.-B. Zhang, In situ orderly self-assembly strategy affording NIR-II-J-aggregates for in vivo imaging and surgical navigation, Nat Commun 14 (2023) 1843. https://doi.org/10.1038/s41467-023-37586-7.
16. A. Liess, A. Arjona-Esteban, A. Kudzus, J. Albert, A. Krause, A. Lv, M. Stolte, K. Meerholz, F. Würthner, Ultranarrow Bandwidth Organic Photodiodes by Exchange Narrowing in Merocyanine H- and J-Aggregate Excitonic Systems, Adv Funct Mater 29 (2019) 1805058. https://doi.org/10.1002/adfm.201805058.
17. S.B. Anantharaman, K. Strassel, M. Diethelm, A. Gubicza, E. Hack, R. Hany, F.A. Nüesch, J. Heier, Exploiting supramolecular assemblies for filterless ultra-narrowband organic photodetectors with inkjet fabrication capability, J Mater Chem C Mater 7 (2019) 14639–14650. https://doi.org/10.1039/C9TC04773E.
18. Q. Zhao, H. Lai, H. Chen, H. Li, F. He, H- and J-aggregation inspiring efficient solar conversion, J Mater Chem A Mater 9 (2021) 1119–1126. https://doi.org/10.1039/D0TA11146E.
19. J.H. Kim, T. Schembri, D. Bialas, M. Stolte, F. Würthner, Slip-Stacked J-Aggregate Materials for Organic Solar Cells and Photodetectors, Advanced Materials 34 (2022). https://doi.org/10.1002/adma.202104678.
20. E.E. Jelley, Spectral Absorption and Fluorescence of Dyes in the Molecular State, Nature 138 (1936) 1009–1010. https://doi.org/10.1038/1381009a0.
21. E.E. Jelley, Molecular, Nematic and Crystal States of I:I'-Diethyl-ψ-Cyanine Chloride, Nature 139 (1937) 631–632. https://doi.org/10.1038/139631b0.
22. G. Scheibe, L. Kandler, H. Ecker, Polymerisation und polymere Adsorption als Ursache neuartiger Absorptionsbanden von organischen Farbstoffen, Naturwissenschaften 25 (1937) 75–75. https://doi.org/10.1007/BF01493278.
23. G. Scheibe, Reversible Polymerisation als Ursache neuartiger Absorptionsbanden von Farbstoffen, Kolloid-Zeitschrift 82 (1938) 1–14. https://doi.org/10.1007/BF01509409.
24. G. Scheibe, Über die Veränderlichkeit der Absorptionsspektren in Lösungen und die Nebenvalenzen als ihre Ursache, Angewandte Chemie 50 (1937) 212–219. https://doi.org/10.1002/ange.19370501103.
25. J. Franck, E. Teller, Migration and Photochemical Action of Excitation Energy in Crystals, J Chem Phys 6 (1938) 861–872. https://doi.org/10.1063/1.1750182.
26. U. Giovanella, G. Leone, G. Ricci, T. Virgili, I.S. Lopez, S.K. Rajendran, C. Botta, Oxazine-1 J-aggregates in polymer nanohybrids, Physical Chemistry Chemical Physics 14 (2012) 13646. https://doi.org/10.1039/c2cp42361h.
27. S. Matsumoto, T. Kobayashi, T. Aoyama, T. Wada, J-Aggregates in vapor deposited films of a bisazomethine dye, Chemical Communications (2003) 1910. https://doi.org/10.1039/b304028c.
28. S. Kim, M. Fujitsuka, N. Tohnai, T. Tachikawa, I. Hisaki, M. Miyata, T. Majima, The unprecedented J-aggregate formation of rhodamine moieties induced by 9-phenylanthracenyl substitution, Chem. Commun. 51 (2015) 11580–11583. https://doi.org/10.1039/C5CC03969J.
29. F.C. Spano, C. Silva, H- and J-Aggregate Behavior in Polymeric Semiconductors, Annu Rev Phys Chem 65 (2014) 477–500. https://doi.org/10.1146/annurev-physchem-040513-103639.
30. Y. Sun, H. Jiu, D. Zhang, J. Gao, B. Guo, Q. Zhang, Preparation and optical properties of Eu(III) complexes J-aggregate formed on the surface of silver nanoparticles, Chem Phys Lett 410 (2005) 204–208. https://doi.org/10.1016/j.cplett.2005.05.064.
31. M. Hecht, F. Würthner, Supramolecularly Engineered J-Aggregates Based on Perylene Bisimide Dyes, Acc Chem Res 54 (2021) 642–653. https://doi.org/10.1021/acs.accounts.0c00590.
32. H. Piwoński, S. Nozue, H. Fujita, T. Michinobu, S. Habuchi, Organic J-Aggregate Nanodots with Enhanced Light Absorption and Near-Unity Fluorescence Quantum Yield, Nano Lett 21 (2021) 2840–2847. https://doi.org/10.1021/acs.nanolett.0c04928.
33. M. Kasha, Molecular Excitons in Small Aggregates, Spectroscopy of the Excited State (1976)

337–363. https://doi.org/10.1007/978-1-4684-2793-6_12.
34. M. Kasha, H.R. Rawls, M. Ashraf El-Bayoumi, The exciton model in molecular spectroscopy, Pure Appl. Chem. 11 (1965) 371–392. https://doi.org/10.1351/pac196511030371.
35. A.P. Deshmukh, N. Geue, N.C. Bradbury, T.L. Atallah, C. Chuang, M. Pengshung, J. Cao, E.M. Sletten, D. Neuhauser, J.R. Caram, Bridging the gap between H- and J-aggregates: Classification and supramolecular tunability for excitonic band structures in two-dimensional molecular aggregates, Chemical Physics Reviews 3 (2022) 021401. https://doi.org/10.1063/5.0094451.
36. N.J. Hestand, F.C. Spano, Molecular Aggregate Photophysics beyond the Kasha Model: Novel Design Principles for Organic Materials, Acc Chem Res 50 (2017) 341–350. https://doi.org/10.1021/acs.accounts.6b00576.
37. N.J. Hestand, F.C. Spano, Expanded Theory of H- and J-Molecular Aggregates: The Effects of Vibronic Coupling and Intermolecular Charge Transfer, Chem Rev 118 (2018) 7069–7163. https://doi.org/10.1021/acs.chemrev.7b00581.
38. S. Ma, S. Du, G. Pan, S. Dai, B. Xu, W. Tian, Organic molecular aggregates: From aggregation structure to emission property, Aggregate 2 (2021). https://doi.org/10.1002/agt2.96.
39. H. von Berlepsch, C. Böttcher, L. Dähne, Structure of J-aggregates of pseudoisocyanine dye in aqueous solution, J. Phys. Chem. B 104 (2000) 8792–8799. https://doi.org/10.1021/jp000085q.
40. D.A. Higgins, P.F. Barbara, Excitonic transitions in J-aggregates probed by near-field scanning optical microscopy, J Phys Chem 99 (1995) 3–7. https://doi.org/10.1021/j100001a002.
41. H. v. Berlepsch, C. Böttcher, Supramolecular Structure of TTBC J-Aggregates in Solution and on Surface, Langmuir 29 (2013) 4948–4958. https://doi.org/10.1021/la400417d.
42. Yu.V. Malyukin, A.V. Sorokin, S.L. Yefimova, A.N. Lebedenko, Photo-induced reorganization of molecular packing of amphi-PIC J-aggregates (single J-aggregate spectroscopy), J Lumin 112 (2005) 429–433. https://doi.org/10.1016/j.jlumin.2004.09.082.
43. T.E. Kaiser, V. Stepanenko, F. Würthner, Fluorescent J-Aggregates of Core-Substituted Perylene Bisimides: Studies on Structure−Property Relationship, Nucleation−Elongation Mechanism, and Sergeants-and-Soldiers Principle, J Am Chem Soc 131 (2009) 6719–6732. https://doi.org/10.1021/ja900684h.
44. F. Würthner, C.R. Saha-Möller, B. Fimmel, S. Ogi, P. Leowanawat, D. Schmidt, Perylene Bisimide Dye Assemblies as Archetype Functional Supramolecular Materials, Chem Rev 116 (2016) 962–1052. https://doi.org/10.1021/acs.chemrev.5b00188.
45. K. Herman, H. Kirmse, A. Eljarrat, C.T. Koch, S. Kirstein, J.P. Rabe, Individual tubular J-aggregates stabilized and stiffened by silica encapsulation, Colloid Polym Sci 298 (2020) 937–950. https://doi.org/10.1007/s00396-020-04661-0.
46. C. Shen, D. Bialas, M. Hecht, V. Stepanenko, K. Sugiyasu, F. Würthner, Polymorphism in Squaraine Dye Aggregates by Self-Assembly Pathway Differentiation: Panchromatic Tubular Dye Nanorods versus J-Aggregate Nanosheets, Angewandte Chemie International Edition 60 (2021) 11949–11958. https://doi.org/10.1002/anie.202102183.
47. Z. Chen, Y. Liu, W. Wagner, V. Stepanenko, X. Ren, S. Ogi, F. Würthner, Near-IR Absorbing J-Aggregate of an Amphiphilic BF_2 -Azadipyrromethene Dye by Kinetic Cooperative Self-Assembly, Angewandte Chemie International Edition 56 (2017) 5729–5733. https://doi.org/10.1002/anie.201701788.
48. S. Kirstein, S. Daehne, J-aggregates of amphiphilic cyanine dyes: Self-organization of artificial light harvesting complexes, International Journal of Photoenergy 2006 (2006) 1–21. https://doi.org/10.1155/IJP/2006/20363.
49. E. Lang, A. Sorokin, M. Drechsler, Y. V. Malyukin, J. Köhler, Optical Spectroscopy on Individual amphi-PIC J-Aggregates, Nano Lett 5 (2005) 2635–2640. https://doi.org/10.1021/nl051132z.
50. A.P. Deshmukh, A.D. Bailey, L.S. Forte, X. Shen, N. Geue, E.M. Sletten, J.R. Caram, Thermodynamic Control over Molecular Aggregate Assembly Enables Tunable Excitonic Properties across the Visible and Near-Infrared, J Phys Chem Lett 11 (2020) 8026–8033. https://doi.org/10.1021/acs.jpclett.0c02204.
51. S. Rhodes, W. Liang, X. Wang, N.R. Reddy, J. Fang, Transition from H-Aggregate Nanotubes to J-Aggregate Nanoribbons, The Journal of Physical Chemistry C 124 (2020) 11722–11729. https://doi.org/10.1021/acs.jpcc.0c02908.
52. A. V. Sorokin, I.Yu. Ropakova, R.S. Grynyov, M.M. Vilkisky, V.M. Liakh, I.A. Borovoy, S.L. Yefimova, Y. V. Malyukin, Strong difference between optical properties and morphologies for J-Aggregates of similar cyanine dyes, Dyes and Pigments 152 (2018) 49–53. https://doi.org/10.1016/j.dyepig.2018.01.032.
53. P.M. Ajayan, Nanotubes from Carbon, Chem Rev 99 (1999) 1787–1800. https://doi.org/10.1021/cr970102g.

54. H. Yao, K. Domoto, T. Isohashi, K. Kimura, In Situ Detection of Birefringent Mesoscopic H and J Aggregates of Thiacarbocyanine Dye in Solution, Langmuir 21 (2005) 1067–1073. https://doi.org/10.1021/la0479004.
55. H. Yao, T. Isohashi, K. Kimura, Electrolyte-induced mesoscopic aggregation of thiacarbocyanine dye in aqueous solution: Counterion size specificity, Journal of Physical Chemistry B 111 (2007) 7176–7183. https://doi.org/10.1021/jp070520h.
56. A.V. Sorokin, N.V. Pereverzev, I.I. Grankina, S.L. Yefimova, Y.V. Malyukin, Evidence of Exciton Self-Trapping in Pseudoisocyanine J-Aggregates Formed in Layered Polymer Films, Journal of Physical Chemistry C 119 (2015) 27865–27873. https://doi.org/10.1021/acs.jpcc.5b09940.
57. A. V. Sorokin, I.Yu. Ropakova, S. Wolter, R. Lange, I. Barke, S. Speller, S.L. Yefimova, Y. V. Malyukin, S. Lochbrunner, Exciton Dynamics and Self-Trapping of Carbocyanine J-Aggregates in Polymer Films, The Journal of Physical Chemistry C 123 (2019) 9428–9444. https://doi.org/10.1021/acs.jpcc.8b09338.
58. T.H. James, The theory of the photographic process., New York: Macmillan, 1977.
59. F.C. Spano, S. Mukamel, Nonlinear susceptibilities of molecular aggregates: Enhancement of $\chi 3$ by size, Phys Rev A 40 (1989) 5783–5801. https://doi.org/10.1103/PhysRevA.40.5783.
60. F.C. Spano, S. Mukamel, Superradiance in molecular aggregates, J Chem Phys 91 (1989) 683–700. https://doi.org/10.1063/1.457174.
61. E.W. Knapp, P.O.J. Scherer, S.F. Fischer, On the lineshapes of vibronically resolved molecular aggregate spectra. application to pseudoisocyanin (PIC), Chem Phys Lett 111 (1984) 481–486. https://doi.org/10.1016/0009-2614(84)85544-X.
62. P.O.J. Scherer, S.F. Fischer, On the theory of vibronic structure of linear aggregates. Application to pseudoisocyanin (PIC), Chem Phys 86 (1984) 269–283. https://doi.org/10.1016/0301-0104(84)80015-4.
63. V. Sundström, T. Gillbro, R.A. Gadonas, A. Piskarskas, Annihilation of singlet excitons in J aggregates of pseudoisocyanine (PIC) studied by pico- and subpicosecond spectroscopy, J Chem Phys 89 (1988) 2754–2762. https://doi.org/10.1063/1.455027.
64. S. De Boer, D.A. Wiersma, Dephasing-induced damping of superradiant emission in J-aggregates, Chem Phys Lett 165 (1990) 45–53. https://doi.org/10.1016/0009-2614(90)87010-O.
65. H. Fidder, J. Knoester, D.A. Wiersma, Optical properties of disordered molecular aggregates: A numerical study, J Chem Phys 95 (1991) 7880–7890. https://doi.org/10.1063/1.461317.
66. H. Fidder, J. Terpstra, D.A. Wiersma, Dynamics of Frenkel excitons in disordered molecular aggregates, J Chem Phys 94 (1991) 6895–6907. https://doi.org/10.1063/1.460220.
67. A.V. Sorokin, I.I. Filimonova, R.S. Grynyov, G.Y. Guralchuk, S.L. Yefimova, Y.V. Malyukin, Control of exciton migration efficiency in disordered J-aggregates, Journal of Physical Chemistry C 114 (2010) 1299–1305. https://doi.org/10.1021/jp906665j.
68. K.A. Clark, E.L. Krueger, D.A. Vanden Bout, Direct Measurement of Energy Migration in Supramolecular, Journal of Physical Chemistry Letters 5 (2014) 2274–2282. https://doi.org/10.1021/jz500634f.
69. A. Merdasa, Á.J. Jiménez, R. Camacho, M. Meyer, F. Würthner, I.G. Scheblykin, Single Lévy States–Disorder Induced Energy Funnels in Molecular Aggregates, Nano Lett 14 (2014) 6774–6781. https://doi.org/10.1021/nl5021188.
70. J.R. Caram, S. Doria, D.M. Eisele, F.S. Freyria, T.S. Sinclair, P. Rebentrost, S. Lloyd, M.G. Bawendi, Room-Temperature Micron-Scale Exciton Migration in a Stabilized Emissive Molecular Aggregate, Nano Lett 16 (2016) 6808–6815. https://doi.org/10.1021/acs.nanolett.6b02529.
71. T. Brixner, R. Hildner, J. Köhler, C. Lambert, F. Würthner, Exciton Transport in Molecular Aggregates - From Natural Antennas to Synthetic Chromophore Systems, Adv Energy Mater 7 (2017) 1700236. https://doi.org/10.1002/aenm.201700236.
72. D. Embriaco, D.B. Balagurov, G.C. La Rocca, V.M. Agranovich, Topical questions in the photophysics of J aggregates, Physica Status Solidi C: Conferences 1 (2004) 1429–1438. https://doi.org/10.1002/pssc.200304081.
73. S.L. Yefimova, A. V. Sorokin, I.K. Katrunov, Yu. V. Malyukin, Excitation localization effects in nanoscale molecular clusters (J-aggregates), Low Temperature Physics 37 (2011) 157–162. https://doi.org/10.1063/1.3556666.
74. A. Eisfeld, S.M. Vlaming, V.A. Malyshev, J. Knoester, Excitons in Molecular Aggregates with Lévy-Type Disorder: Anomalous Localization and Exchange Broadening of Optical Spectra, Phys Rev Lett 105 (2010) 137402. https://doi.org/10.1103/PhysRevLett.105.137402.
75. Jai. Singh, Excitation Energy Transfer Processes in Condensed Matter, Springer US, Boston, MA, 1994. https://doi.org/10.1007/978-1-4899-0996-1.

76. K.S. Song, R.T. Williams, Self-Trapped Excitons, 2nd Ed., Springer Berlin Heidelberg, 1996. https://doi.org/10.1007/978-3-642-85236-7.
77. Y. Toyozawa, Optical Processes in Solids, Cambridge University Press, Cambridge, 2003. https://doi.org/10.1017/CBO9780511615085.
78. A.H. Herz, Aggregation of sensitizing dyes in solution and their adsorption onto silver halides, Adv Colloid Interface Sci 8 (1977) 237–298. https://doi.org/10.1016/0001-8686(77)80011-0.
79. D. Takahashi, H. Oda, T. Izumi, R. Hirohashi, Substituent effects on aggregation phenomena in aqueous solution of thiacarbocyanine dyes, Dyes and Pigments 66 (2005) 1–6. https://doi.org/10.1016/j.dyepig.2004.08.008.
80. J. Xiang, X. Yang, C. Chen, Y. Tang, W. Yan, G. Xu, Effects of NaCl on the J-aggregation of two thiacarbocyanine dyes in aqueous solutions, J Colloid Interface Sci 258 (2003) 198–205. https://doi.org/10.1016/S0021-9797(02)00187-X.
81. I.A. Struganova, H. Lim, S.A. Morgan, The influence of inorganic salts and bases on the formation of the J-band in the absorption and fluorescence spectra of the diluted aqueous solutions of TDBC, Journal of Physical Chemistry B 106 (2002) 11047–11050. https://doi.org/10.1021/jp013511w.
82. S.R. Clowes, D.M. Răsădean, T.-M. Gianga, T. Jávorfi, R. Hussain, G. Siligardi, G.D. Pantoș, Mueller Matrix Polarimetry on Cyanine Dye J-Aggregates, Molecules 28 (2023) 1523. https://doi.org/10.3390/molecules28041523.
83. C. Sun, S. Zhou, P. Chen, Effects of different H^+ sources on formation of J aggregation of cyanine dye, The Imaging Science Journal 54 (2006) 142–146. https://doi.org/10.1179/174313106X106296.
84. Y. Egawa, R. Hayashida, J. Anzai, pH-Induced Interconversion between J-Aggregates and H-Aggregates of 5,10,15,20-Tetrakis(4-sulfonatophenyl)porphyrin in Polyelectrolyte Multilayer Films, Langmuir 23 (2007) 13146–13150. https://doi.org/10.1021/la701957b.
85. L. Ding, J. Yang, M. Dai, S. Li, K. Yin, J. Li, Effect of environmental factors on the aggregation behavior of astaxanthin in water, Spectrochim Acta A Mol Biomol Spectrosc 280 (2022) 121506. https://doi.org/10.1016/j.saa.2022.121506.
86. H. von Berlepsch, C. Böttcher, L. Dähne, Structure of J-aggregates of pseudoisocyanine dye in aqueous solution, J. Phys. Chem. B 104 (2000) 8792–8799. https://doi.org/10.1021/jp000085q.
87. H. von Berlepsch, C. Böttcher, Network Superstructure of Pseudoisocyanine J -Aggregates in Aqueous Sodium Chloride Solution Revealed by Cryo-Transmission Electron Microscopy, J Phys Chem B 106 (2002) 3146–3150. https://doi.org/10.1021/jp0143701.
88. A.N. Lebedenko, G.Ya. Guralchuk, A.V. Sorokin, S.L. Yeflmova, Y.V. Malyukin, Pseudoisocyanine J-aggregate to optical waveguiding crystallite transition: Microscopic and microspectroscopic exploration, Journal of Physical Chemistry B 110 (2006) 17772–17775. https://doi.org/10.1021/jp061965t.
89. A.V. Sorokin, I.Yu. Ropakova, S.L. Yefimova, Yu.V. Malyukin, Influence of pseudoisocyanine J-aggregate agglomeration on the optical properties, Functional Materials 25 (2018) 088–092. https://doi.org/10.15407/fm25.01.088.
90. H. von Berlepsch, C. Böttcher, A. Ouart, C. Burger, S. Daehne, S. Kirstein, S. Dähne, S. Kirstein, Supramolecular structures of J-aggregates of carbocyanine dyes in solution, J Phys Chem B 104 (2000) 5255–5262. https://doi.org/10.1021/jp000220z.
91. A. V. Sorokin, I.Yu. Ropakova, R.S. Grynyov, M.M. Vilkisky, V.M. Liakh, I.A. Borovoy, S.L. Yefimova, Y. V. Malyukin, Strong difference between optical properties and morphologies for J-Aggregates of similar cyanine dyes, Dyes and Pigments 152 (2018) 49–53. https://doi.org/10.1016/j.dyepig.2018.01.032.
92. G.Ya. Guralchuk, A. V. Sorokin, I.K. Katrunov, S.L. Yefimova, A.N. Lebedenko, Yu. V. Malyukin, S.M. Yarmoluk, Specificity of Cyanine Dye L-21 Aggregation in Solutions with Nucleic Acids, J Fluoresc 17 (2007) 370–376. https://doi.org/10.1007/s10895-007-0201-5.
93. M.Yu. Losytskyy, V.M. Yashchuk, Fluorescent J-Aggregates and Their Biological Applications, in: A.P. Demchenko (Ed.), Advanced Fluorescence Reporters in Chemistry and Biology II: Molecular Constructions, Polymers and Nanoparticles, Springer-Verlag Berlin Heidelberg, 2010: pp. 135–157. https://doi.org/10.1007/978-3-642-04701-5_4.
94. M.Y. Losytskyy, V.M. Yashchuk, S.S. Lukashov, S.M. Yarmoluk, Davydov Splitting in Spectra of Cyanine Dye J-Aggregates, Formed on the Polynucleotides, J Fluoresc 12 (2002) 109–112. https://doi.org/10.1023/A:1015379723901.
95. J.O. Smith, D.A. Olson, B.A. Armitage, Molecular Recognition of PNA-Containing Hybrids: Spontaneous Assembly of Helical Cyanine Dye Aggregates on PNA Templates, J Am Chem Soc 121 (1999) 2686–2695. https://doi.org/10.1021/ja9837553.
96. M. Wang, G.L. Silva, B.A. Armitage, DNA-Templated Formation of a Helical Cyanine Dye J-Ag-

gregate, J Am Chem Soc 122 (2000) 9977–9986. https://doi.org/10.1021/ja002184n.
97. R.A. Garoff, E.A. Litzinger, R.E. Connor, I. Fishman, B.A. Armitage, Helical Aggregation of Cyanine Dyes on DNA Templates: Effect of Dye Structure on Formation of Homo- and Heteroaggregates, Langmuir 18 (2002) 6330–6337. https://doi.org/10.1021/la025742f.
98. B.A. Armitage, Cyanine Dye–DNA Interactions: Intercalation, Groove Binding, and Aggregation, in: Top Curr Chem, 2005: pp. 55–76. https://doi.org/10.1007/b100442.
99. T.Y. Ogul'chansky, M.Y. Losytskyy, V.B. Kovalska, S.S. Lukashov, V.M. Yashchuk, S.M. Yarmoluk, Interaction of cyanine dyes with nucleic acids. XVIII. Formation of the carbocyanine dye J-aggregates in nucleic acid grooves, Spectrochim Acta A Mol Biomol Spectrosc 57 (2001) 2705–2715. https://doi.org/10.1016/S1386-1425(01)00537-6.
100. A.S.R. Koti, N. Periasamy, Self-assembly of template-directed J-aggregates of porphyrin, Chemistry of Materials 15 (2003) 369–371. https://doi.org/10.1021/cm025664h.
101. O.K. Kim, J. Melinger, S.J. Chung, M. Pepitone, Supramolecular device for artificial photosynthetic mimics as helix-mediated antenna/reaction center ensemble, Org Lett 10 (2008) 1625–1628. https://doi.org/10.1021/ol800320f.
102. Z. Dai, L. Dähne, E. Donath, H. Möhwald, Mimicking photosynthetic two-step energy transfer in cyanine triads assembled into capsules, Langmuir 18 (2002) 4553–4555. https://doi.org/10.1021/la0255222.
103. S.L. Yefimova, G. V. Grygorova, V.K. Klochkov, I.A. Borovoy, A. V. Sorokin, Y. V. Malyukin, Molecular Arrangement in Cyanine Dye J-Aggregates Formed on CeO 2 Nanoparticles, The Journal of Physical Chemistry C 122 (2018) 20996–21003. https://doi.org/10.1021/acs.jpcc.8b06590.
104. O.P. Dimitriev, I.A. Mazarchuk, V.Y. Morozovska, L.I. Trischuk, Antenna size effect: The influence on energy transfer in the CdTe-pseudoisocyanine nanocomposite system, Chem Phys Lett 554 (2012) 168–171. https://doi.org/10.1016/j.cplett.2012.10.044.
105. V.Yu. Petrenko, Yu.L. Slominskii, G.L. Smirnova, I.A. Mazarchuk, O.P. Dimitriev, Influence of CdTe Nanoparticles on the Formation of J-Aggregates of Thiamonomethinecyanine Dyes, Ukrainian Journal of Physics 58 (2013) 480–489. https://doi.org/10.15407/ujpe58.05.0480.
106. F.S. Freyria, J.M. Cordero, J.R. Caram, S. Doria, A. Dodin, Y. Chen, A.P. Willard, M.G. Bawendi, Near-Infrared Quantum Dot Emission Enhanced by Stabilized Self-Assembled J-Aggregate Antennas, Nano Lett 17 (2017) 7665–7674. https://doi.org/10.1021/acs.nanolett.7b03735.
107. J.E. Halpert, J.R. Tischler, G. Nair, B.J. Walker, W. Liu, V. Bulović, M.G. Bawendi, Electrostatic formation of quantum dot/J-aggregate FRET pairs in solution, Journal of Physical Chemistry C 113 (2009) 9986–9992. https://doi.org/10.1021/jp8099169.
108. Y. Qiao, F. Polzer, H. Kirmse, E. Steeg, S. Kühn, S. Friede, S. Kirstein, J.P. Rabe, Nanotubular J-Aggregates and Quantum Dots Coupled for Efficient Resonance Excitation Energy Transfer, ACS Nano 9 (2015) 1552–1560. https://doi.org/10.1021/nn506095g.
109. R.V. Pereira, M.H. Gehlen, Fluorescence of acridinic dyes in anionic surfactant solution, Spectrochim Acta A Mol Biomol Spectrosc 61 (2005) 2926–2932. https://doi.org/10.1016/j.saa.2004.11.009.
110. S. Kirstein, S. Daehne, J-aggregates of amphiphilic cyanine dyes: Self-organization of artificial light harvesting complexes, International Journal of Photoenergy 2006 (2006) 1–21. https://doi.org/10.1155/IJP/2006/20363.
111. N.O. Mchedlov-Petrossyan, S.A. Shapovalov, V.L. Koval, T.A. Shakhverdov, Y.A. Bochkaryov, The surfactant-induced formation of J- and H-aggregates in aqueous pseudoisocyanine solutions, Dyes and Pigments 19 (1992) 33–40. https://doi.org/10.1016/0143-7208(92)87009-P.
112. U. De Rossi, S. Daehne, M. Lindrum, Increased Coupling Size in J-Aggregates through N-n-Alkyl Betaine Surfactants, Langmuir 12 (1996) 1159–1165.
113. Yu.V. Malyukin, S.L. Efimova, K. Kemnitz, Spectroscopy of intermolecular interaction in the system: Dye–sodium dodecylsulphate micelles, J Lumin 94–95 (2001) 239–242. https://doi.org/10.1016/S0022-2313(01)00286-1.
114. P.W. Bohn, Aspects of structure and energy transport in artificial molecular assemblies, Annu Rev Phys Chem 44 (1993) 37–60. https://doi.org/10.1146/annurev.pc.44.100193.000345
115. A.K. Chibisov, V.I. Prokhorenko, H. Görner, Effects of surfactants on the aggregation behaviour of thiacarbocyanine dyes, Chem Phys 250 (1999) 47–60. https://doi.org/10.1016/S0301-0104(99)00245-1.
116. N.C. Maiti, S. Mazumdar, N. Periasamy, J- and H-Aggregates of Porphyrins with Surfactants: Fluorescence, Stopped Flow and Electron Microscopy Studies, Journal of Porphyrins and

Phthalocyanines (JPP) 02 (1998) 369–376. https://doi.org/10.1002/(SICI)1099-1409(19980 7/10)2:4/5<369::AID-JPP92>3.0.CO;2-3.
117. A.K. Chibisov, G. V. Zakharova, H. Görner, Photoprocesses of thiamonomethinecyanine monomers and dimers, Physical Chemistry Chemical Physics 3 (2001) 44–49. https://doi.org/10.1039/b005683i.
118. X. Li, Y. Xie, Z. Chen, G. Zou, The interaction of 2-hydroquinone-5,10,15,20-tetra(p-hydroxyphenyl)porphyrin with surfactants: solubilization and J-aggregates, Spectrochim Acta A Mol Biomol Spectrosc 61 (2005) 2468–2473. https://doi.org/10.1016/j.saa.2004.09.011.
119. H. von Berlepsch, S. Kirstein, R. Hania, A. Pugžlys, C. Böttcher, Modification of the Nanoscale Structure of the J-Aggregate of a Sulfonate-Substituted Amphiphilic Carbocyanine Dye through Incorporation of Surface-Active Additives, J Phys Chem B 111 (2007) 1701–1711. https://doi.org/10.1021/jp065826n.
120. X. Li, Z. Zheng, M. Han, Z. Chen, G. Zou, Tuning J-Aggregates of Tetra(p -hydroxyphenyl)porphyrin by the Headgroups of Ionic Surfactants in Acidic Nonionic Micellar Solution, J Phys Chem B 111 (2007) 4342–4348. https://doi.org/10.1021/jp067148a.
121. X. Li, D. Li, W. Zeng, G. Zou, Z. Chen, Exciton Coupling of Tetra(p -hydroxyphenyl)porphyrin Controlled by Substituents of Counterions in Triton X-100 Micellar Solution, J Phys Chem B 111 (2007) 1502–1506. https://doi.org/10.1021/jp0669815.
122. G.Ya. Guralchuk, I.K. Katrunov, R.S. Grynyov, A.V. Sorokin, S.L. Yefimova, Yu.V. Malyukin, S.M. Yarmoluk, Strong enhancement of cyanine dye aggregation by a cationic surfactant, Functional Materials 14 (2007) 228–232.
123. G.Ya. Guralchuk, I.K. Katrunov, R.S. Grynyov, A. V. Sorokin, S.L. Yefimova, I.A. Borovoy, Y. V. Malyukin, Anomalous Surfactant-Induced Enhancement of Luminescence Quantum Yield of Cyanine Dye J-Aggregates, The Journal of Physical Chemistry C 112 (2008) 14762–14768. https://doi.org/10.1021/jp802933n.
124. S. Yefimova, A. Lebed, A. Sorokin, G. Guralchuk, I. Borovoy, Y. Malyukin, J-type aggregation of squaraine dye Sq-2Me in surfactant solutions, J Mol Liq 165 (2012) 113–118. https://doi.org/10.1016/j.molliq.2011.10.016.
125. Yu.V. Malyukin, B.A. Gnap, A.V. Sorokin, S.L. Yefimova, Control of electron–lattice interaction in organic nanoclusters, Opt Mater (Amst) 34 (2012) 2008–2011. https://doi.org/10.1016/j.optmat.2012.01.029.
126. I.K. Katrunov, S.L. Yefimova, A.V. Sorokin, Y.V. Malyukin, Control of polaron formation in J-aggregates, Functional Materials 17 (2010) 52–58.
127. I.K. Katrunov, A. V. Sorokin, S.L. Yefimova, Yu. V. Malyukin, Manifestation of Exciton-Lattice Interaction in J-Aggregates, Molecular Crystals and Liquid Crystals 535 (2011) 57–63. https://doi.org/10.1080/15421406.2011.537904.
128. R. Atta-Fynn, P. Biswas, D.A. Drabold, Electron–phonon coupling is large for localized states, Phys Rev B 69 (2004) 245204. https://doi.org/10.1103/PhysRevB.69.245204.
129. I.I. Grankina, I.A. Borovoy, S.I. Petrushenko, S.S. Hrankina, V.P. Semynozhenko, S.L. Yefimova, A. V. Sorokin, Fluorescent properties of amphi-PIC J-aggregates in the complexes with bovine serum albumin, J Mol Liq 368 (2022) 120755. https://doi.org/10.1016/j.molliq.2022.120755.
130. S. Xu, H.-W. Liu, S.-Y. Huan, L. Yuan, X.-B. Zhang, Recent progress in utilizing near-infrared J-aggregates for imaging and cancer therapy, Mater Chem Front 5 (2021) 1076–1089. https://doi.org/10.1039/D0QM00557F.
131. P.R. Patlolla, N. Desai, S. Gupta, B. Datta, Interaction of a dimeric carbocyanine dye aggregate with bovine serum albumin in non-aggregated and aggregated forms, Spectrochim Acta A Mol Biomol Spectrosc 209 (2019) 256–263. https://doi.org/10.1016/j.saa.2018.10.048.
132. Y. Zhang, H. Du, Y. Tang, G. Xu, W. Yan, Spectroscopic investigation on the interaction of J-aggregate with human serum albumin, Biophys Chem 128 (2007) 197–203. https://doi.org/10.1016/j.bpc.2007.04.002.
133. A. Sorokin, V. Prokopiuk, I. Grankina, I. Borovoy, A. Tkachenko, S. Yefimova, Amphi-PIC J-Aggregate - Protein Complexes: Stability in Blood and Toxicity to Cell Cultures, in: 2022 IEEE 12th International Conference Nanomaterials: Applications & Properties (NAP), IEEE, 2022: pp. 1–5. https://doi.org/10.1109/NAP55339.2022.9934581.
134. P.J. Meadows, E. Dujardin, S.R. Hall, S. Mann, Template-directed synthesis of silica-coated J-aggregate nanotapes, Chemical Communications (2005) 3688. https://doi.org/10.1039/b502436f.
135. K.L. Gurunatha, E. Dujardin, Tuning the Optical Coupling between Molecular Dyes and Metal Nanoparticles by the Templated Silica Mineralization of J-Aggregates, The Journal of Physical Chemistry C 117 (2013) 3489–3496. https://doi.org/10.1021/jp311911f.

136. Y. Qiao, F. Polzer, H. Kirmse, S. Kirstein, J.P. Rabe, Nanohybrids from nanotubular J-aggregates and transparent silica nanoshells, Chemical Communications 51 (2015) 11980–11982. https://doi.org/10.1039/C5CC00901D.
137. C.M. Walters, C. Pao, B.P. Gagnon, C.R. Zamecnik, G.C. Walker, Bright Surface-Enhanced Raman Scattering with Fluorescence Quenching from Silica Encapsulated J-Aggregate Coated Gold Nanoparticles, Advanced Materials 30 (2017) 1705381. https://doi.org/10.1002/adma.201705381.
138. K. Ng, M. Webster, W.P. Carbery, N. Visaveliya, P. Gaikwad, S.J. Jang, I. Kretzschmar, D.M. Eisele, Frenkel excitons in heat-stressed supramolecular nanocomposites enabled by tunable cage-like scaffolding, Nat Chem 12 (2020) 1157–1164. https://doi.org/10.1038/s41557-020-00563-4.
139. D.H. Thanippuli Arachchi, U. Barotov, C.F. Perkinson, T. Šverko, A.E.K. Kaplan, M.G. Bawendi, Bright and Fast Emission from Robust Supramolecular J-Aggregate Nanostructures through Silica-Encapsulation, ACS Nano 18 (2024) 20422–20434. https://doi.org/10.1021/acsnano.4c04732.
140. U. De Rossi, S. Daehne, R. Reisfeld, Photophysical properties of cyanine dyes in sol-gel matrices, Chem Phys Lett 251 (1996) 259–267. https://doi.org/10.1016/0009-2614(96)00117-0.
141. F. Nüesch, J.E. Moser, V. Shklover, M. Grätzel, Merocyanine aggregation in mesoporous networks, J Am Chem Soc 118 (1996) 5420–5431. https://doi.org/10.1021/ja953042+.
142. T. Watanabe, H.S. Zhou, I. Honma, K. Asai, K. Ishigure, Synthesis and nonlinear optical susceptibility of cyanine dye J-aggregate doped silica film (I), J Solgel Sci Technol 19 (2000) 257–261. https://doi.org/10.1023/A:1008752708964.
143. H.S. Zhou, T. Watanabe, A. Mito, K. Asai, K. Ishigure, I. Honma, Synthesis and Nonlinear Optical Susceptibility of Cyanine Dye J-Aggregates Doped Silica Film (II), J Solgel Sci Technol 19 (2000) 803–806. https://doi.org/10.1023/A:1008720402488.
144. N. Kato, K. Yamamoto, Y. Uesu, Aqueous dispersions of J-aggregates and J-aggregate-doped silica bulk gels, Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers 46 (2007) 5318–5320. https://doi.org/10.1143/JJAP.46.5318.
145. J. Bujdák, N. Iyi, J. Hrobáriková, T. Fujita, Aggregation and Decomposition of a Pseudoisocyanine Dye in Dispersions of Layered Silicates, J. Colloid Interface Sci. 247 (2002) 494–503. https://doi.org/10.1006/jcis.2001.8140.
146. J. Bujdák, N. Iyi, Spectral properties and structure of the J-aggregates of pseudoisocyanine dye in layered silicate films, J Colloid Interface Sci 326 (2008) 426–432. https://doi.org/10.1016/j.jcis.2008.06.036.
147. J. Bujdák, Layer-by-Layer Assemblies Composed of Polycationic Electrolyte, Organic Dyes, and Layered Silicates, The Journal of Physical Chemistry C 118 (2014) 7152–7162. https://doi.org/10.1021/jp411155x.
148. H.S. Zhou, T. Watanabe, A. Mito, I. Honma, K. Asai, K. Ishigure, M. Furuki, High nonlinear optical coefficient ($\chi 3 = 10\text{-}7$ esu) of cyanine dye J aggregates doped silica film synthesized by a simple sol-gel method, Mater Sci Eng B Solid State Mater Adv Technol 95 (2002) 180–186. https://doi.org/10.1016/S0921-5107(02)00232-5.
149. A.V. Sorokin, A.V. Voloshko, I.I. Fylymonova, I.I. Bespalova, S.L. Yefimova, Features of J-aggregates formation in pores of nanostructured anodic aluminum oxide, Functional Materials 21 (2014) 42–46.
150. I.Yu. Ropakova, P.V. Pisklova, I.I. Bespalova, I.A. Borovoy, O.G. Viagin, P.V. Mateychenko, S.L. Yefimova, A.V. Sorokin, Optical spectroscopy of cyanine dyes J-aggregates in porous TiO2 matrices, Functional Materials 29 (2022) 494–501. https://doi.org/10.15407/fm29.04.494.
151. P. Pisklova, I. Ropakova, I. Bespalova, S. Kryvonogov, O. Viagin, S. Yefimova, A. Sorokin, Features of cyanine dyes aggregation on differently charged TiO2 matrices, Chemical Physics Impact 6 (2023) 100176. https://doi.org/10.1016/j.chphi.2023.100176.
152. Q. Liu, J. Zhu, T. Sun, H. Zhou, Q. Shao, G. Li, X. Liu, Y. Yin, Porphyrin nanotubes composed of highly ordered molecular arrays prepared by anodic aluminum template method, RSC Adv 3 (2013) 2765. https://doi.org/10.1039/c2ra21364h.
153. W. Xu, H. Guo, D.L. Akins, Aggregation and exciton emission of a cyanine dye encapsulated within mesoporous MCM-41, Journal of Physical Chemistry B 105 (2001) 7686–7689. https://doi.org/10.1021/jp004154c.
154. M. Busby, C. Blum, M. Tibben, S. Fibikar, G. Calzaferri, V. Subramaniam, L. De Cola, Time, space, and spectrally resolved studies on J-aggregate interactions in zeolite L nanochannels, J Am Chem Soc 130 (2008) 10970–10976. https://doi.org/10.1021/ja801178p.

155. N. Alarcos, J.A. Organero, F. Sánchez, A. Douhal, Exploring the Photobehavior of Nanocaged Monomers and H- and J-Aggregates of a Proton-Transfer Dye within NaX and NaY Zeolites, The Journal of Physical Chemistry C 118 (2014) 8217–8226. https://doi.org/10.1021/jp412544y.
156. E. Gaufrès, N.Y.-W. Tang, F. Lapointe, J. Cabana, M.-A. Nadon, N. Cottenye, F. Raymond, T. Szkopek, R. Martel, Giant Raman scattering from J-aggregated dyes inside carbon nanotubes for multispectral imaging, Nat Photonics 8 (2014) 72–78. https://doi.org/10.1038/nphoton.2013.309.
157. R. Sola-Llano, Y. Fujita, L. Gómez-Hortigüela, A. Alfayate, H. Uji-i, E. Fron, S. Toyouchi, J. Pérez-Pariente, I. López-Arbeloa, V. Martínez-Martínez, One-Directional Antenna Systems: Energy Transfer from Monomers to J-Aggregates within 1D Nanoporous Aluminophosphates, ACS Photonics 5 (2018) 151–157. https://doi.org/10.1021/acsphotonics.7b00553.
158. N. Sikdar, D. Dutta, R. Haldar, T. Ray, A. Hazra, A.J. Bhattacharyya, T.K. Maji, Coordination-Driven Fluorescent J-Aggregates in a Perylenetetracarboxylate-Based MOF: Permanent Porosity and Proton Conductivity, The Journal of Physical Chemistry C 120 (2016) 13622–13629. https://doi.org/10.1021/acs.jpcc.6b04347.
159. M. Rödl, V. Kiefer, S. Olthof, K. Meerholz, G. Jung, H.A. Schwartz, Confinement-Driven Aggregate Formation of Photoacids within Porous Metal–Organic Frameworks, ACS Omega 10 (2025) 4711–4721. https://doi.org/10.1021/acsomega.4c09621.
160. M.S.A. Abdel-Mottaleb, M.M.S. Abdel-Mottaleb, H.S. Hafez, M. Saif, J-Aggregates of Amphiphilic Cyanine Dyes for Dye-Sensitized Solar Cells: A Combination between Computational Chemistry and Experimental Device Physics, International Journal of Photoenergy 2014 (2014) 1–6. https://doi.org/10.1155/2014/579476.
161. R. Hany, B. Fan, F.A. de Castro, J. Heier, W. Kylberg, F. Nüesch, Strategies to improve cyanine dye multi layer organic solar cells, Progress in Photovoltaics: Research and Applications 19 (2011) 851–857. https://doi.org/10.1002/pip.1049.
162. D. Saccone, S. Galliano, N. Barbero, P. Quagliotto, G. Viscardi, C. Barolo, Polymethine Dyes in Hybrid Photovoltaics: Structure-Properties Relationships, European J Org Chem 2016 (2016) 2244–2259. https://doi.org/10.1002/ejoc.201501598.
163. K. Sayama, S. Tsukagoshi, K. Hara, Y. Ohga, A. Shinpou, Y. Abe, S. Suga, H. Arakawa, Photoelectrochemical Properties of J Aggregates of Benzothiazole Merocyanine Dyes on a Nanostructured TiO 2 Film, J Phys Chem B 106 (2002) 1363–1371. https://doi.org/10.1021/jp0129380.
164. G. Chen, H. Sasabe, W. Lu, X.-F. Wang, J. Kido, Z. Hong, Y. Yang, J-aggregation of a squaraine dye and its application in organic photovoltaic cells, J Mater Chem C Mater 1 (2013) 6547. https://doi.org/10.1039/c3tc31243g.
165. P.K.D. Duleepa Pitigala, M.M. Henary, E.A. Owens, A.G. UnilPerera, K. Tennakone, Excitonic photovoltaic effect in a cyanine dye molecular assembly electronically coupled to n- and p-type semiconductors, J Photochem Photobiol A Chem 325 (2016) 39–44. https://doi.org/10.1016/j.jphotochem.2015.11.018.
166. J. Xiang, C. Chen, Z. Chen, W. Yan, X. Ai, Y. Liu, G. Xu, Photoinduced electron transfer from the excited J-aggregate state of a thiacarbocyanine dye to TiO2 colloids, J Colloid Interface Sci 254 (2002) 195–199. https://doi.org/http://dx.doi.org/10.1006/jcis.2002.8566.
167. A. Liess, A. Arjona-Esteban, A. Kudzus, J. Albert, A. Krause, A. Lv, M. Stolte, K. Meerholz, F. Würthner, Ultranarrow Bandwidth Organic Photodiodes by Exchange Narrowing in Merocyanine H- and J-Aggregate Excitonic Systems, Adv Funct Mater 29 (2019) 1805058. https://doi.org/10.1002/adfm.201805058.
168. S.B. Anantharaman, K. Strassel, M. Diethelm, A. Gubicza, E. Hack, R. Hany, F.A. Nüesch, J. Heier, Exploiting supramolecular assemblies for filterless ultra-narrowband organic photodetectors with inkjet fabrication capability, J Mater Chem C Mater 7 (2019) 14639–14650. https://doi.org/10.1039/C9TC04773E.
169. S.T. Bailey, G.E. Lokey, M.S. Hanes, J.D.M. Shearer, J.B. McLafferty, G.T. Beaumont, T.T. Baseler, J.M. Layhue, D.R. Broussard, Y.-Z. Zhang, B.P. Wittmershaus, Optimized excitation energy transfer in a three-dye luminescent solar concentrator, Solar Energy Materials and Solar Cells 91 (2007) 67–75. https://doi.org/10.1016/j.solmat.2006.07.011.
170. Yu.P. Piryatinskii, V.G. Nazarenko, O. V. Yatsun, Controllable electrochromic effect in a liquid-crystal cell with J aggregates, Technical Physics Letters 25 (1999) 761–762. https://doi.org/10.1134/1.1262626.
171. A. Adamow, L. Sznitko, E. Chrzumnicka, J. Stachera, A. Szukalski, T. Martynski, J. Mysliwiec, The ultra-photostable and electri-

cally modulated Stimulated Emission in perylene-based dye doped liquid crystal, Sci Rep 9 (2019) 2143. https://doi.org/10.1038/s41598-019-38484-z.

172. A. Biadasz, K. Rytel, K. Kędzierski, A. Adamski, M. Kotkowiak, A. Stachowiak, B. Barszcz, H.Y. Jeong, T.-D. Kim, The liquid crystal induced J-type aggregation of diketopyrrolopyrrole derivatives in monolayer, J Mol Liq 285 (2019) 598–606. https://doi.org/10.1016/j.molliq.2019.04.093.
173. I.I. Grankina, O.M. Samoilov, N.A. Kasian, I.Yu. Ropakova, S.S. Hrankina, S.L. Yefimova, L.N. Lisetski, O. V. Sorokin, Spectral features of the dispersion of carbocyanine dye J-aggregates in a liquid crystal matrix, Opt Mater Express 13 (2023) 1741. https://doi.org/10.1364/OME.491678.
174. O. Sorokin, I. Grankina, O. Samoilov, N. Kasian, S. Hrankina, L. Lisetski, S. Yefimova, Influence of Dispersion in Liquid Crystal on Optical Properties of Cyanine Dye J-Aggregates, in: 2023 IEEE 13th International Conference Nanomaterials: Applications & Properties (NAP), IEEE, 2023: pp. NP01-1-NP01-4. https://doi.org/10.1109/NAP59739.2023.10310901.
175. Y. Wang, J. Shi, J. Chen, W. Zhu, E. Baranoff, Recent progress in luminescent liquid crystal materials: design, properties and application for linearly polarised emission, J Mater Chem C Mater 3 (2015) 7993–8005. https://doi.org/10.1039/C5TC01565K.
176. H. Coles, S. Morris, Liquid-crystal lasers, Nat Photonics 4 (2010) 676–685. https://doi.org/10.1038/nphoton.2010.184.
177. J. Mysliwiec, A. Szukalska, A. Szukalski, L. Sznitko, Liquid crystal lasers: the last decade and the future, Nanophotonics 10 (2021) 2309–2346. https://doi.org/10.1515/nanoph-2021-0096.
178. J. Voskuhl, M. Giese, Mesogens with aggregation-induced emission properties: Materials with a bright future, Aggregate 3 (2022). https://doi.org/10.1002/agt2.124.
179. W.J. Harrison, D.L. Mateer, G.J.T. Tiddy, Liquid-Crystalline J-Aggregates Formed by Aqueous Ionic Cyanine Dyes, J Phys Chem 100 (1996) 2310–2321. https://doi.org/10.1021/jp952532l.
180. S. Herbst, B. Soberats, P. Leowanawat, M. Lehmann, F. Würthner, A Columnar Liquid-Crystal Phase Formed by Hydrogen-Bonded Perylene Bisimide J-Aggregates, Angewandte Chemie International Edition 56 (2017) 2162–2165. https://doi.org/10.1002/anie.201612047.
181. S. Herbst, B. Soberats, P. Leowanawat, M. Stolte, M. Lehmann, F. Würthner, Self-assembly of multi-stranded perylene dye J-aggregates in columnar liquid-crystalline phases, Nat Commun 9 (2018) 2646. https://doi.org/10.1038/s41467-018-05018-6.
182. T. Ma, Z. Wang, C. Song, N. Song, J. Ren, B. Liu, H. Zhang, H. Zhang, D. Lu, J-Aggregate Behavior of Poly(9,9- dioctyluorenyl-2,7-diyl)-alt -co-(bithiophene). (F8T2) in Crystal and Liquid Crystal Phases, The Journal of Physical Chemistry C 123 (2019) 24321–24327. https://doi.org/10.1021/acs.jpcc.9b07311.
183. Y. Ma, A. Dicce, N.R. Reddy, J. Fang, Liquid-crystalline ordering of davydov-split aggregates of cyanine dyes, Colloids Surf A Physicochem Eng Asp 642 (2022) 128713. https://doi.org/10.1016/j.colsurfa.2022.128713.
184. A.P. Demchenko, Photobleaching of organic fluorophores: quantitative characterization, mechanisms, protection, Methods Appl Fluoresc 8 (2020) 022001. https://doi.org/10.1088/2050-6120/ab7365.
185. A. Nabok, Organic and inorganic nanostructures, Artech House, Boston, 2005. http://us.artechhouse.com/Organic-and-Inorganic-Nanostructures-P866.aspx (accessed March 9, 2018).
186. D. Möbius, Scheibe Aggregates, Advanced Materials 7 (1995) 437–444. https://doi.org/10.1002/adma.19950070503.
187. T.L. Penner, D. Möbius, Photoinduced Electron-Transfer Processes in Monolayer Assemblies. Supersensitization in a Three-Component System, J Am Chem Soc 104 (1982) 7407–7413. https://doi.org/10.1021/ja00390a004.
188. D. Möbius, H. Kuhn, Energy transfer in monolayers with cyanine dye Sheibe aggregates, J Appl Phys 64 (1988) 5138–5141. https://doi.org/10.1063/1.342421.
189. J.A. Tuszyński, M.F. Jørgensen, D. Möbius, Mechanisms of exciton energy transfer in Scheibe aggregates, Phys Rev E 59 (1999) 4374–4383. https://doi.org/10.1103/PhysRevE.59.4374.
190. L. Wolthaus, A. Schaper, D. Möbius, Brickstone arrangement in J-aggregates on an amphiphilic merocyanine dye, Chem Phys Lett 225 (1994) 322–326. https://doi.org/10.1016/0009-2614(94)87088-8.
191. Y. Yonezawa, H. Kurokawa, T. Sato, Excitation energy transfer between J-aggregates of cyanine dyes in mixed monolayer assemblies, J Lumin 54 (1993) 285–295. https://doi.org/10.1016/0022-2313(93)90087-4.

192. A. Yamaguchi, N. Kometani, Y. Yonezawa, Spectroscopic properties of the mixed J-aggregate of unsymmetric merocyanine dyes in wide temperature range, Thin Solid Films 513 (2006) 125–135. https://doi.org/10.1016/j.tsf.2006.01.059.
193. H. Ishizawa, T. Sato, M.I. Sluch, A.G. Vitukhnovsky, Y. Yonezawa, Preparation and fluorescence properties of mixed J-aggregates of quinocyanine dyes, Thin Solid Films 284–285 (1996) 134–137. https://doi.org/10.1016/S0040-6090(95)08289-1.
194. A. Yamaguchi, N. Kotnetani, Y. Yonezawa, Luminescence properties of the mixed J-aggregate of oxacyanine dye and thiacyanine dye. Formation of a persistence-type aggregate, Journal of Physical Chemistry B 109 (2005) 1408–1414. https://doi.org/10.1021/jp0405557.
195. Y. Yonezawa, A. Yamaguchi, N. Kometani, Spectroscopic properties of persistence-type dye aggregate in wide temperature range, Colloids Surf A Physicochem Eng Asp 284–285 (2006) 223–228. https://doi.org/10.1016/j.colsurfa.2006.01.004.
196. M.I. Sluch, A.G. Vitukhnovsky, Y. Yonezawa, H. Ishizawa, T. Sato, Anomalous behavior of the J-aggregate of quinocyanine dyes in the mixed Langmuir-Blodgett films, Phys Scr 56 (1997) 125–128. https://doi.org/10.1088/0031-8949/56/1/017.
197. Y. Yonezawa, A. Yamaguchi, N. Kometani, Exciton delocalization of the J-aggregate of oxacyanine dye and thiacyanine dye in LB films, Phys Status Solidi B Basic Res 242 (2005) 803–806. https://doi.org/10.1002/pssb.200460002.
198. D. Noukakis, M. Van der Auweraer, F.C. De Schryver, Mechanism of Photosensitized Charge Injection from Organic Dyes Incorporated in Langmuir-Blodgett Films into SnO2, J Phys Chem 98 (1994) 11745–11750. https://doi.org/10.1021/j100096a019.
199. Á. Gil, I. Arístegui, A. Suárez, I. Sández, D. Möbius, Effect of additives on J-aggregate formation of a merocyanine and energy transfer in monolayers at the air-water interface, Langmuir 18 (2002) 8527–8534. https://doi.org/10.1021/la026095v.
200. S. Chakraborty, P. Debnath, D. Dey, D. Bhattacharjee, S.A. Hussain, Formation of fluorescent H-aggregates of a cyanine dye in ultrathin film and its effect on energy transfer, J Photochem Photobiol A Chem 293 (2014) 57–64. https://doi.org/10.1016/j.jphotochem.2014.07.018.
201. P. Debnath, S. Chakraborty, S. Deb, J. Nath, D. Bhattacharjee, S.A. Hussain, Reversible Transition between Excimer and J-Aggregate of Indocarbocyanine Dye in Langmuir-Blodgett (LB) Films, Journal of Physical Chemistry C 119 (2015) 9429–9441. https://doi.org/10.1021/acs.jpcc.5b02111.
202. P. Debnath, S. Chakraborty, S. Deb, J. Nath, B. Dey, D. Bhattacharjee, S.A. Hussain, Stability of J-aggregated species in an indocarbocyanine dye in Langmuir–Blodgett Films, J Lumin 179 (2016) 287–296. https://doi.org/10.1016/j.jlumin.2016.07.027.
203. K. Tani, C. Ito, Y. Hanawa, M. Uchida, K. Otaguro, H. Horiuchi, H. Hiratsuka, Photophysical Property and Photostability of J-Aggregate Thin Films of Thiacyanine Dyes Prepared by the Spin-Coating Method, J Phys Chem B 112 (2008) 836–844. https://doi.org/10.1021/jp077088o.
204. K. Tani, K. Matsuzaki, Y. Kodama, M. Fukita, T. Kodaira, H. Horiuchi, T. Okutsu, H. Hiratsuka, Photophysical property of the J-aggregate thin film of an oxacyanine dye prepared by the spin-coating method and enhancement of its photostability by use of polydimethylsilane, J Photochem Photobiol A Chem 199 (2008) 150–155. https://doi.org/10.1016/j.jphotochem.2008.05.011.
205. I. Scheblykin, L. Lepnev, A. Vitukhnovsky, M. Van der Auweraer, Electroluminescence and optical properties of poly(phenylenevinylene)/J-aggregate composites, J Lumin 94–95 (2001) 461–464. https://doi.org/10.1016/S0022-2313(01)00337-4.
206. H. Fukumoto, Y. Yonezawa, Layer-by-layer self-assembly of polyelectrolyte and water soluble cyanine dye, Thin Solid Films 327–329 (1998) 748–751. https://doi.org/10.1016/S0040-6090(98)00779-2.
207. N. Kometani, H. Nakajima, K. Asami, Y. Yonezawa, O. Kajimoto, Excited-state dynamics of the mixed J-aggregate of two kinds of cyanine dyes in layer-by-layer alternate assemblies, Chem Phys Lett 294 (1998) 619–624. https://doi.org/10.1016/S0009-2614(98)00919-1.
208. N. Kometani, H. Nakajima, K. Asami, Y. Yonezawa, O. Kajimoto, Luminescence Properties of the Mixed J-Aggregate of Two Kinds of Cyanine Dyes in Layer-by-Layer Alternate Assemblies, J Phys Chem B 104 (2000) 9630–9637. https://doi.org/10.1021/jp001614t.
209. A.V. Sorokin, N.V. Pereverzev, V.M. Liakh, I.A. Borovoy, S.L. Yefimova, Plasmon enhancement of thiacyanine J-aggregates luminescence in

polymer films, Functional Materials 22 (2015) 316–321. https://doi.org/10.15407/fm22.03.316.
210. A. V. Sorokin, A.A. Zabolotskii, N. V. Pereverzev, I.I. Bespalova, S.L. Yefimova, Y. V. Malyukin, A.I. Plekhanov, Metal-Enhanced Fluorescence of Pseudoisocyanine J-Aggregates Formed in Layer-by-Layer Assembled Films, The Journal of Physical Chemistry C 119 (2015) 2743–2751. https://doi.org/10.1021/jp5102626.
211. A. V. Sorokin, I.Y. Ropakova, I.I. Grankina, I.A. Borovoy, S.L. Yefimova, Y. V. Malyukin, Unusual enhancement of dye luminescence by exciton resonance of J-Aggregates, Opt Mater (Amst) 96 (2019) 109263. https://doi.org/10.1016/j.optmat.2019.109263.
212. A. V. Sorokin, I.I. Grankina, I.I. Bespalova, A. V. Aslanov, S.L. Yefimova, Y. V. Malyukin, Plasmon-Induced Suppression of Exciton Self-Trapping in Polymer-Bound Pseudoisocyanine J-Aggregates, The Journal of Physical Chemistry C 124 (2020) 10167–10174. https://doi.org/10.1021/acs.jpcc.0c00583.
213. A. Sorokin, R. Grynyov, I. Grankina, I. Bespalova, S. Yefimova, Y. Malyukin, Plasmon-Enhanced Fluorescence of Carbocyanine J-Aggregates in Layered Polymer Films, in: Proceedings of the 2020 IEEE 10th International Conference on "Nanomaterials: Applications and Properties", NAP 2020, 2020. https://doi.org/10.1109/NAP51477.2020.9309537.
214. Y. Obara, K. Saitoh, M. Oda, T. Tani, Room-Temperature Fluorescence Lifetime of Pseudoisocyanine (PIC) J Excitons with Various Aggregate Morphologies in Relation to Microcavity Polariton Formation, Int J Mol Sci 13 (2012) 5851–5865. https://doi.org/10.3390/ijms13055851.
215. M. Vácha, K. Hashizume, T. Tani, Sub-micron scale spectroscopy and microscopy of individual mesoscopic systems at cryogenic temperatures, J Lumin 86 (2000) 195–200. https://doi.org/10.1016/S0022-2313(00)00163-0.
216. D.A. Higgins, J. Kerimo, D.A. Vanden Bout, P.F. Barbara, A Molecular Yarn: Near-Field Optical Studies of Self-Assembled, Flexible, Fluorescent Fibers, J Am Chem Soc 118 (1996) 4049–4058. https://doi.org/10.1021/ja960105v.
217. D.A. Higgins, P.J. Reid, P.F. Barbara, Structure and exciton dynamics in J-agregates studied by polarization dependent near-field scanning optical microscopy, Journal of Physical Chemistry 100 (1996) 1174–1180. https://doi.org/10.1021/jp9518217.
218. T. Tani, Y. Yamaguchi, M. Saeki, M. Oda, M. Vacha, Local reflection micro-spectroscopy of excitons in fibril-shaped molecular J-aggregates prepared in PVA thin films, J Lumin 102–103 (2003) 27–33. https://doi.org/10.1016/S0022-2313(02)00542-2.
219. T. Tani, M. Saeki, Y. Yamaguchi, T. Hayashi, M. Oda, Microscopic exciton properties of fibril-shaped molecular J-aggregates prepared in ultra-thin polymer films, J Lumin 107 (2004) 339–346. https://doi.org/10.1016/j.jlumin.2003.12.002.
220. A. V. Sorokin, A.A. Zabolotskii, N. V. Pereverzev, S.L. Yefimova, Y. V. Malyukin, A.I. Plekhanov, Plasmon Controlled Exciton Fluorescence of Molecular Aggregates, The Journal of Physical Chemistry C 118 (2014) 7599–7605. https://doi.org/10.1021/jp412798u.
221. C.D. Geddes, ed., Metal-Enhanced Fluorescence, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2010. https://doi.org/10.1002/9780470642795.
222. R. Badugu, J.R. Lakowicz, Plasmon-Controlled Fluorescence Methods and Applications, in: J.C. Lindon, G.E. Tranter, D.W. Koppenaal (Eds.), Encyclopedia of Spectroscopy and Spectrometry, 3rd ed., Elsevier, 2017: pp. 676–694. https://doi.org/10.1016/B978-0-12-409547-2.12087-6.
223. J.R. Lakowicz, K. Ray, M. Chowdhury, H. Szmacinski, Y. Fu, J. Zhang, K. Nowaczyk, Plasmon-controlled fluorescence: a new paradigm in fluorescence spectroscopy, Analyst 133 (2008) 1308–1346. https://doi.org/10.1039/b802918k.
224. M.S. Tame, K.R. McEnery, Ş.K. Özdemir, J. Lee, S.A. Maier, M.S. Kim, Quantum plasmonics, Nat Phys 9 (2013) 329–340. https://doi.org/10.1038/nphys2615.
225. P. Vasa, C. Lienau, Strong Light–Matter Interaction in Quantum Emitter/Metal Hybrid Nanostructures, ACS Photonics 5 (2018) 2–23. https://doi.org/10.1021/acsphotonics.7b00650.
226. T. Itoh, Y.S. Yamamoto, Y. Ozaki, Plasmon-enhanced spectroscopy of absorption and spontaneous emissions explained using cavity quantum optics, Chem Soc Rev 46 (2017) 3904–3921. https://doi.org/10.1039/C7CS00155J.