Induced Aggregation of AIE-Active Mono-Cyclometalated Ir(III) Complex into Supramolecular Branched Wires for Light-Emitting Diodes

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Aggregation-induced emission (AIE) is commonly observed in irregular bulk form. Herein, unique aggregation properties of an AIE-active complex into branched supramolecular wires are reported for the first time. Mono-cyclometalated Ir(III) complex shows in-plane J-aggregation at the air-water interface owing to the restriction of intramolecular vibration of bidentate phenylpyridinato and intramolecular rotations of monodentate triphenylphosphine ligands at air-water interface. As a consequence, a large enhancement of luminescence comparable to the solid state is obtained from the monolayers of supramolecular wires. This unique feature is utilized for the fabrication of light-emitting diodes with low threshold voltage using supramolecular wires as active layer. This study opens up the need of ordered assembly of AIE complexes to achieve optimal luminescence characteristics.

1. Introduction

Aggregation behavior of molecules has been studied to a great extent over more than half a century.^[1] Aggregated states of luminophores are used in a vast variety of optoelectronic applications.^[2] In most of the cases, luminophores emit strongly in solution phase, however, aggregation generally

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causes quenching of luminescence yield of conventional luminophores/luminogens.^[3] The luminescence quenching issue is detrimental particularly when the luminophores are used in solid state for practical device fabrication. In contrary, in the aggregation-induced emission (AIE) phenomenon, weakly emissive or nonemissive luminophores become emissive upon aggregate formation.^[4] The AIE effect adds advantages in fabricating solid-state optoelectronic devices since intense luminescence can be realized in solid state. Broadly, AIE phenomenon arises mostly due to restriction of intramolecular rotations (RIR) and intramolecular vibrations (RIV) processes. In solution phase, the intramolecular rotations and intramolecular vibrations are allowed which makes the AIE-active complexes nonemissive in nature. However, the intramolecular rotations and vibrations are restricted in aggregated state enabling the excited state to decay through radiative pathways. As a result, a strong emission can be realized from the aggregated states of the AIE-active complexes. In most of the cases, AIE phenomena have been realized by using nonsolvent to induce aggregation in liquid phase or using closely packed proximal effect in solid state.^[5] However, attempts to fabricate highly ordered aggregates of AIE-active complexes at the air-water interface using Langmuir-Blodgett (LB) technique have not been reported yet.

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Fabrication of highly ordered aggregates can restrict conformation of AIE-active complexes in an efficient way to facilitate radiative pathways for enhanced luminescence by orders of magnitude compared to solution phase or comparable to solid state. Advantageously, the LB technique offers such sophisticated processability to fabricate tailormade aggregation of the AIE-active molecules by controlling packing, orientation, and ordering of molecules.^[6]

Cyclometalated complexes of Ir(III) are promising AIE active materials with high quantum efficiency due to efficient triplet emission.^[7] Ir(III) complexes containing bidentate 2-phenylpyridinato (ppy) ligands have been widely studied as efficient phosphorescent materials emitting lights in red, green, and blue regions.^[8] The emission color can be tuned by modification of *ppy* or by introducing diverse ancillary ligands.^[7b,8] Due to the confined geometry at the air-water interface and possible interaction with water subphase, the interchromophoric interactions of cyclometalated complexes of Ir(III) can be manipulated through aggregation in a controllable and efficient way. Consequently, the photophysical properties can be tuned by precise tailoring of molecular orientations within an aggregated assembly by changing the surface pressure.^[9] Herein we report on the fabrication of branched supramolecular wires using a cyclometalated complex of Ir(III), (Ir(ppy)) (PPh₃)₂(H)(Cl), Cyclo-Ir). The supramolecular wire assembly spans over 50 µm² retaining close packing. Insight investigation reveals formation of in-plane J-aggregates of Cyclo-Ir at air-water interface. Large enhancement of photoluminescence (PL) from supramolecular wires in comparison to the solution is obtained owing to the RIR and RIV within the ordered aggregates. This unique feature is utilized for fabricating lightemitting diodes (LEDs) with low threshold voltage using supramolecular wire assembly of Cyclo-Ir as active layer.

2. Results

Cyclo-Ir consists of six coordinate environment on Ir(III) (Figure 1a, Supporting Information, for the synthesis details). Two coordinates are fulfilled by 2-phenylpyridinato ligand (ppy). Monodentate PPh₃ groups remain in axial positions. Other two coordinate positions are fulfilled by hydride and chloride ions. Hence, Cyclo-Ir is mainly hydrophobic in nature, however, weak interaction between hydrogen or chlorine moieties with water molecules is expected, which helps formation of a stable monolayer at the air-water interface (Figure S1, Supporting Information). Interestingly, spreading a homogeneous solution of Cyclo-Ir in chloroform onto the air-water interface resulted in the formation of branched supramolecular wires at a low surface pressure (π) = 5 mN m⁻¹, as evident from the atomic force microscopy (AFM) imaging (Figure 1b). Zoom-in AFM image (Figure S2, Supporting Information) shows that the wire structure consists of smaller aggregated structures at this stage. The supramolecular wires tend to orient unidirectionally with an increased packing density at higher surface pressure of $\pi = 10 \text{ mN m}^{-1}$ (Figure 1c). These wires gradually aligned parallel to the barrier upon increasing the surface pressure to $\pi = 15 \text{ mN m}^{-1}$ (Figure 1d) and became more densely packed at $\pi = 20 \text{ mN m}^{-1}$ (Figure 1e). Evidently, the increase in the surface pressure effectively fills void in the monolayer and align the branched supramolecular wires in one direction. Cross-sectional analyses indicate uniform height $(3.5 \pm 0.5 \text{ nm})$ and width $(80 \pm 10 \text{ nm})$ of the wires at different surface pressures suggesting an in-plane monomolecular layer conformation of Cyclo-Ir irrespective of compression stages (Figures S2–S6, Supporting Information).

The UV-vis absorption spectrum of a solution of Cyclo-Ir (Figure S7a, Supporting Information) shows peaks at 347 and



Figure 1. a) Molecular structure of Cyclo-Ir complex and its equivalent cartoon. AFM topography image of Cyclo-Ir at air–water interface b) randomly oriented supramolecular wires at 5 mN m⁻¹, c) aligned supramolecular wires at 10 mN m⁻¹, d) close-packed supramolecular wires at 15 mN m⁻¹, and e) highly close-packed oriented supramolecular wires spanning over $5 \times 5 \ \mu\text{m}^2$ at 20 mN m⁻¹. The monolayer was lifted on freshly cleaved mica for AFM measurements.





380 nm, respectively, which can be assigned to ligand-centered ${}^{1}\pi$ - π * and MLCT transitions.^[7b] A broadening of absorption spectra of the monolayer films at different surface pressures is observed (Figure S7a, Supporting Information). The increase in the absorbance with increasing surface pressure implies improved compactness of the monolayer at air-water interface. UV-vis absorption spectra with increased number of monolayer (multilayer) show similar broadening in comparison to the solution spectrum (Figure S7b, Supporting Information). The solution PL spectrum of Cyclo-Ir is nearly nonemissive in diluted form (Figure S7c, Supporting Information). However, weak PL peaks at 465 and 495 nm, respectively, appear at higher concentrations (10^{-4} M) with quantum yield (QY) 0.8%. Notably, an earlier report on synthesis reveals 11% QY of the same AIE complex in solution phase, although the concentration was not reported.^[10] In contrast, PL spectra of the monolayer films lifted at surface pressures ranging from $\pi = 5$ to 25 mN m⁻¹ reveal interesting features of aggregated states (Figure 2a). As a result, intense PL peaks at 465 and 495 nm

are observed even at low surface pressure of $\pi = 5 \text{ mN m}^{-1}$, which gradually increases upon increasing the surface pressure (Figure 2a). Interestingly, a new broad PL peak starts appearing at 530 nm from lower surface pressure $\pi = 10$ mN m⁻¹. A gradual increase in intensity of this PL peak is evidenced at higher surface pressures till $\pi = 25$ mN m⁻¹ (Figure S7d, Supporting Information). The development of surface pressure induced longer wavelength peaks indicates J-aggregate formation within the monolayer.^[11] Rapid enhancement of overall PL intensity takes place with the increase in the surface pressure suggesting AIE phenomena to occur within the monolayer by activating RIR and RIV processes (Figure S7d, Supporting Information). Such RIR and RIV processes improve probability of radiative transitions enhancing the PL intensities rapidly. The relative PL QYs are ranging from ≈34% to 39% within the surface pressure range of $5-25 \text{ mN m}^{-1}$.

To elucidate the internal structures of the supramolecular wires, we have carried out small-angle X-ray diffraction (XRD) measurements (Figure 2b). The peak at 10.3°



Figure 2. a) PL spectra for monolayer films deposited at different surface pressure. b) Small-angle XRD pattern of 15 layer LB film. c) Modeling showing the formation of J-aggregates and branched supramolecular wires of Cyclo-Ir at the air–water interface. (i) Random orientation of the Cyclo-Ir complexes at the initial stage of compression. (ii) Formation of supramolecular wires with increasing surface pressure. The end-to-end separation between the adjacent *ppy* rings of Cyclo-Ir complexes along the length of supramolecular wire measured from XRD is marked in the figure. Both the top and side views are shown in the figure. (iii) Alignment of the supramolecular wires at the air–water interface at higher surface pressure.

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(d = 0.94 nm) corroborates with the end-to-end separation of the adjacent Cyclo-Ir complexes reflecting the 1D growth of the supramolecular wires (Figure S8, Supporting Information). Broad peak at 22.8° (d = 0.43 nm) can be assigned to multiple scattering from aromatic stacking.^[12] A periodicity along the thickness of the multilayer LB films is reflected from the peak at 2.9° (d = 2.72 nm), which corroborates with the thickness measured using AFM at different surface pressures (Figures S2–S5, Supporting Information). Based on the XRD and AFM observations, we modeled the aggregate formation and their long-range ordering in the form of branched supramolecular wires at air-water interface (Figure 2c). At low surface pressure, Cyclo-Ir complexes linger in random orientation at air-water interface with hydrogen and chlorine atoms remaining in contact with the water subphase while ppy rings are exposed at the other extremity. Under this conformation, adjacent phenyl rotors attached to the central Ir atom remain in edge-on conformation with the water surface. Cyclo-Ir complexes come into proximity with the increase in the surface pressure to stack in the J-aggregate structure. Implicit here is the existence of stronger π - π interactions among ppy rings and hydrogen bonding of chlorine and hydrogen atoms with water molecules leading to aggregates at the supramolecular level. Finally, the surface pressure brings supramolecular aggregates into closer proximity eventually fulfilling the voids in the monolayer, as evidenced from the AFM observations (Figure 1). The influence of compression induced packing of Cyclo-Ir is also supported by the Kelvin probe measurement across the monolayer (Figure S1, Supporting Information).^[13] A sudden increase of the surface potential suggests an orientation of the effective dipoles in a direction perpendicular to the plane of air–water interface.^[13] Control experiments carried out by the drop-casting of Cyclo-Ir from homogeneous solution on solid substrates results in globular aggregates (Figure S9, Supporting Information), which justifies the advantage of surface pressure for controlled aggregation at air–water interface leading to branched supramolecular wires.

AIE effect is further extended by stacking the multilayers of Cyclo-Ir at fixed surface pressure $\pi = 25$ mN m⁻¹. Intense PL is obtained from the multilayer films in comparison to solution phase (**Figure 3**a). The PL spectra for the multilayers show peaks at 465, 495, and 540 nm, respectively. Drastic increase in the PL intensity is observed with increasing the number of monolayer (Figure 3b). The intensities of PL peaks are enhanced by orders of magnitude in comparison to the solution phase. For instance, the peak intensity of five-layer



Figure 3. a) PL spectra of LB films with different number of layers deposited at 25 mN m⁻¹. Photographs of resultant LB films on quartz substrate under UV illumination. The number of layers is denoted in the inset. b) Comparison of the PL peak intensities at 465 nm (black curve), 495 nm (red curve), and 540 nm (blue curve) with number of layers. c) Confocal laser scanning microscopy (CLSM) image of monolayer of supramolecular wires at 20 mN m⁻¹ showing intense luminescence. d) Frontier molecular orbitals (HOMO and LUMO) showing corresponding energy levels.



film (Figure 3a) is greatly intense with QY $\approx 37\%$ than concentrated 10⁻³ molar solution (Figure S7c, Supporting Information) and shows emission color like solid state (OY \approx 51%).^[7b] The branched supramolecular wires strongly emit homogeneous green fluorescence upon excitation with 405 nm laser (Figure 3c). The formation of supramolecular aggregates of Cyclo-Ir is likely the driving force for the green emission in monolayer form since it hardly emit in monomer form because of irregular conformation. Increasing the number of monolayer rigidify the packing density thereby hindering the vibration of the ppy and rotation of PPh₃ rotors. Additionally, the van der Waals forces, interlayer hydrogen bonding, and intermolecular forces are dominant that facilitates strong AIE behavior by RIR and RIV processes. We have measured the time-resolved PL spectra of Cyclo-Ir in solution and ninemonolayer film (Figure S10, Supporting Information). PL lifetime of Cyclo-Ir in solution (≈9 ns) is very fast compared to aggregated wires. Long lived excited state with a mean lifetime of \approx 750 ns of aggregated wires indicates phosphorescent nature in ambient temperature.^[7b,c] Although organometallic chelates of Ir(III) complexes are prone to be phosphorescent, we envisioned that the intersystem crossing is highly efficient in the ordered aggregated branched supramolecular wires by preventing active molecular vibrations and rotations.

We demonstrate fabrication of LED using multilayer LB films (15-monolayer) of supramolecular wires of Cyclo-Ir

as active layer. Efficient band matching of Cyclo-Ir within the device is estimated from the density functional theory (DFT), which reveals the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of Cyclo-Ir (Figure 3d, Figure S11, Supporting Information). DFT calculations demonstrate localization of electron density around Ir(III), chlorine, and N-ligand whereas LUMO is located near to N-based ligand bound to Ir(III) and benzene. An energy gap of ≈ 3.8 eV is estimated from the HOMO-LOMO energetic differences (Figure 3d). However, this gap is expected to reduce upon formation of J-aggregates as evidenced from the emission spectra (Figure 2a), where longer wavelength PL band generates with increasing surface pressure.^[11] A schematic representation of the LED device along with the energetic positions of the components is shown in Figure S12 (Supporting Information). The simple device architecture contains Cyclo-Ir supramolecular wires as active component, electron transport layer of bathophenanthroline (BPhen), and N,N-di(naphthalene-1-yl)-N,N'-diphenylbenzidine (NPD) as hole transport layer. Subsequently, the recombination of charge carriers takes place within the Cyclo-Ir layers by external bias. Current density-voltage characteristics and the photograph of working device are presented in Figure 4a. Importantly, a significantly low turn-on voltage of ≈3 V is obtained in comparison to a vacuum thermal evaporated analogous AIE complex.^[10]



Figure 4. a) Current density versus voltage curve of the LED. Inset shows the photograph of working LED. b) Bias-dependent EL spectra of the device along with the solid-state PL spectrum. c) Luminance versus voltage (black dotted line) and external quantum efficiency versus voltage (red square line) characteristics of LED. d) Calculated CIE chromaticity coordinates of the emissive colors under different bias voltages. The bias voltages are shown in the inset.

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We found that Cyclo-Ir degrades at its sublime temperature resulting in a black nonuniform patchy layer, which prevented us from device fabrication using thermal evaporation route. Hence, as control experiment, we prepared spin-cast devices of Cyclo-Ir in bulk conditions (Figure S13, Supporting Information). A lower turn-on voltage is evidenced from the devices prepared by LB route in comparison to the spin-cast route. The low turn-on voltage of the devices prepared by LB route arises from the successive conjugation of Cyclo-Ir into supramolecular wire structures favoring the easy injection of charge carriers from electron and hole transport layers into the active material and followed by radiative recombination of charge carriers at even lower voltages. The devices show bright and stable electroluminescence (EL) over a wide range of operating voltages (Figure 4b). The EL retraces the PL suggesting that the EL is occurring from the Cyclo-Ir supramolecular wires (Figure 4b). A comparison of EL spectra with the spin-cast device reveals a narrower full width at half maximum (FWHM) of the EL spectra and improved current efficiency for the devices prepared by LB technique (Figure S13c,d, Supporting Information). Luminance is detectable from threshold voltage of 3 V showing luminance of ≈ 260 Cd m⁻² at 13 V (Figure 4c). Improved external quantum efficiency (EQE, 0.35%) of the device is obtained in comparison to the spin-cast device of Cyclo-Ir (Figure S13e, Supporting Information). This significant improvement of the device performance can be attributed to the controlled aggregated structure of Cyclo-Ir into branched supramolecular wires obtained using LB technique. Corresponding Commission Internationale de l'eclairage (CIE) chromaticity coordinates diagram indicates nearly bias independent green color of the LED at different voltages (Figure 4d).

3. Conclusions

In conclusion, we have established a supramolecular strategy that steers branched supramolecular wires of monomolecular thickness of AIE-active Cyclo-Ir over a large area. Controlled J-aggregation facilitates AIE phenomenon by inhibiting the ligand rotation and vibration. As a result, a large enhancement of PL compared to solution phase is obtained even from the monolayer. The multilayers consisting of much lesser amount of Cyclo-Ir complex show luminescence equivalent to its powder form, which is beneficial for fabricating LED with low threshold voltage. These findings emphasize the importance of controlled organization of AIE complexes to explore optimal luminescence properties for efficient lighting and sensing applications.

4. Experimental Section

Synthesis of Iridium (III) Complex: The iridium complex, [Ir(ppy)-(PPh₃)₂(H)(Cl)] (Cyclo-Ir), was synthesized in a single-pot reaction through the formation of an intermediate [Ir(PPh₃)₂(P^C)(Cl)(H)], (Scheme S1, Supporting Information).^[7c] In a stirred solution of



IrCl₃.3H₂O (0.5025 mmol) in 2-ethoxy ethanol (6 mL), phosphine (1.507 mmol) was added, and the reaction mixture was refluxed at 130 °C for 4–7 h. Then, 2-phenylpyridine (1.252 mmol) was added to the reaction mixture, which was further refluxed for 3–12 h. The reaction mass was then brought to room temperature. The resulting solid mass was triturated and washed several times with hexane followed by ethanol to obtain solid Cyclo-Ir complex, which was purified through recrystallization from a mixture of DCM and hexane (1:1).

For the intermediate [lr(PPh₃)₂(P^C)(Cl)(H)] ¹HNMR (400 MHz, CDCl₃) δ 7.57 (dd, *J* = 14.0, 7.5 Hz, 1H), 7.45–7.37 (m, 9H), 7.24–7.19 (m, 5H), 7.08 (dt, *J* = 17.0, 8.1 Hz, 12H), 6.99 (t, *J* = 7.5 Hz, 12H), 6.82–6.75 (m, 4H), –19.27 (dt, *J* = 29.2, 8.5 Hz, 1H); ¹³CNMR (101 MHz, CDCl₃) δ 207.00, 206.95, 135.30, 135.20, 135.10, 135.05, 135.00, 132.67, 132.40, 132.16, 132.13, 132.06, 131.96, 129.56, 129.19, 128.57, 128.45, 127.16, 127.11, 127.06, 127.01, 126.90, 30.94; ³¹P NMR (162 MHz, CDCl₃) δ –2.41, –7.54, –9.54. Anal. Calc. for C₅₄H₄₅P₃ClIr (MW = 1013.80): C, 63.92; H, 4.44. Found. C, 63.90; H, 4.47.

For the complex, $[Ir(ppy)(PPh_3)_2(H)(CI)]$ ¹H NMR (400 MHz, CDCl₃) δ 8.86 (d, J = 5.5 Hz, 1H), 7.35–7.22 (m, 14H), 7.10 (t, J = 7.3 Hz, 7H), 7.05–6.98 (m, 12H), 6.57–6.47 (m, 2H), 6.29 (d, J = 7.8 Hz, 1H), 5.97–5.80 (m, 1H), –16.72 (t, J = 16.8 Hz, 1H). ¹³C NMR (101 MHz, CDCl₃) δ 166.31, 149.61, 143.46, 135.28, 134.10, 134.05, 133.99, 132.03, 131.77, 131.51, 130.04, 128.88, 127.26, 127.21, 127.16, 122.36, 120.43, 119.21, 117.00; ³¹PNMR (162 MHz, CDCl₃) δ 9.25. Anal. Calc. for C₄₇H₃₉N-P₂ClIr (MW = 906.80): C, 62.20; H, 4.30; N, 1.54. Found. C, 62.18; H, 4.33; N, 1.55.

Langmuir Trough Experiments: A Langmuir trough from Nima Technologies was used for all experiments at the air–water interface. Iridium (III) complex was dissolved in chloroform at a concentration of 1 mg mL⁻¹. For taking pressure (π)–area (A) isotherm measurements, 120 µL of iridium (III) complex solution was spread at the air–water interface, and the barrier was compressed at a speed 7 cm² min⁻¹ after allowing 15 min for evaporation of solvent. Surface potentials (ΔV) at the air–water interface were measured using Trek Electrometer 320. The same volume of Ir (III) complex was spread for surface potentials (ΔV)–area (A) isotherm at the air–water interface.

Spectroscopic Characterizations: To study the aggregationinduced emission, steady-state electronic UV-vis absorption and fluorescence emission spectra of solid film on top of piranha solution (3:1 mixture of sulfuric acid and hydrogen peroxide) cleaned quartz substrate were taken. Here, two different sets of sample were prepared, one is deposition done at fixed surface pressure with increasing number of monolayer and another is done at different surface pressure by fixing the layer number at one monolayer. All the deposition were done by LB deposition by using conventional deeper at a speed of 2 mm min⁻¹. Steady-state UV-vis absorption was taken by using Shimadzu UV-vis 2401PC spectrophotometer and steady-state fluorescence was taken by using Horriba Nanolog spectrophotometer. The fluorescence lifetime measurements were done in a time correlation single photon counting (TCSPC) system. The samples were excited at 380 nm using a picoseconds diode laser (IBH Nanoled-07) in an IBH Fluorocube apparatus. The repetition rate is 1 MHz and the fluorescence decays were collected on a Hamamatsu MCP photomultiplier (C487802). The fluorescence decays were analyzed using IBH DAS6 software.

QY Measurement: PL QYs were calculated using an analytical approach following the equation given below.^[14] The formula provides an approximated total percentage of radiative recombination from the system and hence forms an integral part of this analysis

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$$\Phi_{f} = \frac{\int_{\lambda_{em}}^{\lambda_{em}} \frac{[I_{x}(\lambda_{em}) - I_{b}(\lambda_{em})]}{S(\lambda_{em})} \lambda_{em} d\lambda_{em}}{\int_{\lambda_{ex} + \Delta\lambda} \frac{I_{bx} + \Delta\lambda}{S(\lambda_{ex})} \frac{[I_{b}(\lambda_{ex}) - I_{x}(\lambda_{ex})]}{S(\lambda_{ex})} \lambda_{ex} d\lambda_{ex}} = \frac{N_{em}}{N_{abs}}$$
(1)

where the total number of emitted photons (N_{em}) is obtained by integrating the blank-corrected [$I_b(\lambda_{em})$] and spectrally corrected [$I_x(\lambda_{em})$] emission spectrum of the sample. The number of absorbed photons (N_{abs}) is obtained by integrating the difference between excitation light resulting from measurements with the blank [$I_b(\lambda_{ex})$] and the sample [$I_x(\lambda_{ex})$]. $s(\lambda_{em})$ and $s(\lambda_{ex})$ are spectral responsivity of the emission and excitation channel, respectively.

Atomic Force Microscopy and Confocal Microscopy: Monolayer film of iridium (III) complex was lifted from air–water interface on top of freshly cleaved mica by normal LB deposition at different surface pressure. The morphology of the monolayer film of iridium (III) complex was characterized by AFM using a multimode scanning probe microscope with NanoScope IV controller (M/s Veeco, USA) operating in the tapping mode with Si cantilevers of 10 nm nominal tip radius. Fluorescence microscopy images were captured using confocal laser scanning microscope (Leica TCS SP8) with a UV laser as excitation source. Here, two objectives, $40\times/1.30$ NA oil objective and $63\times/1.4$ with oil objective, were used.

LED Device Fabrication: A thin layer (60 nm) of NPD hole injection layer was deposited by vacuum thermal evaporation onto patterned indium tin oxide (ITO) coated glass substrates. On top of the NPD thin film, 15 layers of Cyclo-Ir complex were deposited as active materials by LB method from air–water interface. Then, 40 nm of bathophenanthroline (BPhen) layer was deposited by vacuum thermal evaporation on top of the iridium (III) complex layer. Finally, aluminium (Al) electrodes were deposited by vacuum thermal evaporation on the top of the BPhen layer. *I–V* catheterization of all the LEDs was done by Keithley 2420 source meter. Luminous output of the LEDs was measured with a Konica Minolta LS-110 luminance meter.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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