

## WARM AS WELL AS COOL HYBRID WHITE ORGANIC LIGHT-EMITTING DIODE DOUBLES AS A TRIO OF HOST AND A BLUE DELAY FLUORESCENT EMISSION

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### Abstract:

A novel white natural sources light-emitting diode (WOLED) was invented by incorporating a new blue through heat triggered delayed fluorescent substance, 4,6-di(9H-carbazol-9-yl)-isophthalonitrile (DCzIPN), as a dual blue emitter and a host for a yellow phosphorescent the point of emission. This hybrid WOLED achieved an impressive exterior quantum efficacy exceeding 20%. DCzIPN exhibited a significant quantum effectiveness of 16.4% as a blue emitter and 24.9% as a host for a yellow phosphorescent emitter. The WOLEDs, which combine DCzIPN host and the source layers, demonstrated a remarkable external quantum efficiency of 22.9%. These devices achieved a warm white colour coordinate of (0.39, 0.43) and a quantum effectiveness of 21.0% for cool white colour coordinates (0.31, 0.33). These impressive results were achieved by carefully controlling the thickness of the yellow emitting layers.

**Keywords:** fluorescent, 4,6-di(9H-carbazol-9-yl)isophthalonitrile (DCzIPN), quantum efficiency, colour coordinates

### 1.0 Introduction

Research has been conducted on white organic light-emitting diodes (WOLEDs) for their potential usage in displays and lighting. These WOLEDs are now being used in large-sized televisions and specialised lighting applications. Nevertheless, present WOLEDs still face some obstacles that must be addressed. One of the most crucial challenges is power consumption, which is influenced by both the driving voltage and the efficiency of the devices. WOLEDs necessitate low driving voltage and great efficiency in order to minimise power consumption. Specifically, achieving high efficiency is crucial in minimising power usage because to the low efficiency of the existing fluorescent blue material utilised in WOLEDs for display and illumination purposes.

There are two methods to enhance the efficiency of the WOLEDs. A technique involves incorporating phosphorescent materials that emit light in the red, green, and blue spectrums<sup>1–8</sup>. Phosphorescent emitting materials with high quantum efficiency can achieve a high external quantum efficiency of over 20%. However, all phosphorescent white organic light-emitting diodes (WOLEDs) have challenges due to the limited availability and poor stability of blue triplet emitters. Another approach involves the integration of blue fluorescent materials with red and green phosphorescent materials, which have high triplet energy [9–13]. The blue-emitting materials are specifically engineered to possess high triplet energy, enabling efficient energy

transfer to red and green phosphorescent emitting materials. This allows for the capture and utilisation of triplet excitons, resulting in red and green emission. In theory, the internal quantum efficiency of the WOLEDs can achieve 100% with this method, as it allows for the utilisation of both singlet and triplet excitons of blue fluorescent materials for light emission. Nevertheless, the WOLEDs incorporating the fluorescent blue emitter have an exterior quantum efficiency that remains below 20% primarily due to loss mechanisms, including triplet-triplet fusion and reverse energy transfer from phosphorescent emitters to the blue fluorescent emitter. To circumvent the limitations of the aforementioned methods, one can utilise a thermally activated delayed fluorescent (TADF) emitter, which has the ability to capture both singlet and triplet excitons for the purpose of emitting fluorescent light [14–22]. A blue thermally activated delayed fluorescence (TADF) emitter exhibits superior quantum efficiency compared to a blue fluorescent emitter. It can efficiently capture triplet excitons from red and green phosphorescent emitters due to its theoretical internal quantum efficiency of 100% and high triplet energy, which enables effective energy transfer to the red and green phosphorescent emitters.

Thus, WOLEDs utilising TADF emitters have the potential to achieve comparable external quantum efficiency as phosphorescent WOLEDs. While a basic WOLED utilising the TADF emitter has been previously documented [23,24], there is a need to further the creation of a highly efficient WOLED based on the TADF emitter. A novel hybrid white organic light-emitting diode (WOLED) was created by integrating a blue thermally activated delayed fluorescence (TADF) emitter with a yellow phosphorescent emitter. This new WOLED exhibits exceptional efficiency. A novel blue thermally activated delayed fluorescence (TADF) emitter, 4,6-di(9H-carbazol-9-yl)isophthalonitrile (DCzIPN), was synthesised with the dual functionality of serving as a TADF emitter and a host for the yellow triplet emitter. This synthesis aimed to develop a new hybrid white organic light-emitting diode (WOLED). DCzIPN exhibited an external quantum efficiency of 16.4% as a blue emitter in the blue device and an external quantum efficiency of 24.9% as a triplet host for the yellow triplet emitter in the yellow device. The study showed that the hybrid WOLEDs, which had a yellow emitting layer made of DCzIPN host material sandwiched between blue TADF emitting layers doped with DCzIPN, achieved a high external quantum efficiency of 22.9% and a warm white colour coordinate of (0.39, 0.43). By controlling the thickness of the yellow emitting layer, the quantum efficiency was further improved to 21.0% and a cool white colour coordinate of (0.31, 0.33) was achieved. This study presents the initial evidence of a hybrid white organic light-emitting diode (WOLED) that combines a blue thermally activated delayed fluorescence (TADF) emitting material with a yellow triplet emitter. The hybrid WOLEDs achieved an external quantum efficiency of over 20% and produced both warm and cool white colours. This study demonstrated that hybrid WOLEDs utilising TADF emitters can achieve equivalent performance to WOLEDs that rely solely on phosphorescent materials.

## 2.0 Operation of HWOLED

### 2.1 Fabrication of a Blue TADF emission

There is no text provided. Typically, blue TADF emitters need to have a high singlet energy of approximately 2.7 eV and a triplet energy ranging from 2.4 eV to 2.7 eV in order to achieve efficient blue TADF emission. The transformation of triplet electrons into singlet excitons can be achieved through an up-conversion process, where the triplet excited state is transformed into a singlet excited state. In order to achieve blue emission, the singlet frequency should be approximately 2.7 eV. The blue TADF emitter has a larger triplet energy compared to yellow triplet emitters. This characteristic makes it suitable for use as the host materials in phosphorescent organic light-emitting diodes (OLEDs). Hence, the TADF blue emitter demonstrates a remarkable quantum efficiency when used as an emitter in blue devices and as a host in yellow phosphorescent OLEDs. By combining the TADF emitter-doped blue emitting layer with a yellow phosphorescent emitting layer, with the TADF emitter acting as a host, it is possible to create highly efficient hybrid WOLEDs with no the need for a the interlayer among the blue and yellow releasing layers.



Figur 1: DCzIPN synthesising technique.

A novel TADF blue emitter, DCzIPN, was synthesised to create high-efficiency blue TADF devices, yellow phosphorescent devices, and hybrid WOLEDs. The synthetic strategy of DCzIPN is depicted in Figure 1. The DCzIPN TADF emitter was synthesised using 1,5-dibromo-2,4-difluorobenzene, which was obtained through the bromination of 1-bromo-2,4-difluorobenzene. The compound 1,5-dibromo-2,4-difluorobenzene underwent cyanation using CuCN to yield 4,6-difluoroisophthalonitrile, which was further reacted with carbazole using sodium hydride. The synthetic yield of DCzIPN was 82%, and the final product was purified via vacuum train sublimation. The chemical structure of DCzIPN was verified using  $^1\text{H}$  and  $^{13}\text{C}$  nuclear magnetic resonance spectroscopy, mass analysis, and elemental analysis. The DCzIPN purity exceeded 99% as determined by high performance liquid chromatography analysis. The photophysical characteristics of DCzIPN were examined using ultraviolet-visible (UV-Vis) and photoluminescence (PL) spectrometers. Figure 2 displays the UV Vis absorption, solid PL in

polystyrene (PS), and low temperature PL spectra of DCzIPN. The DCzIPN compound exhibited significant p-p\* absorption at a wavelength of 229 nm, whereas a less pronounced n-p\* absorption was seen up to 410 nm. The solid PL emission of DCzIPN in PS (1 wt%) exhibited peak locations at 447 nm and 455 nm, corresponding to singlet and triplet energies of 2.77 eV and 2.72 eV, respectively, at low temperatures.

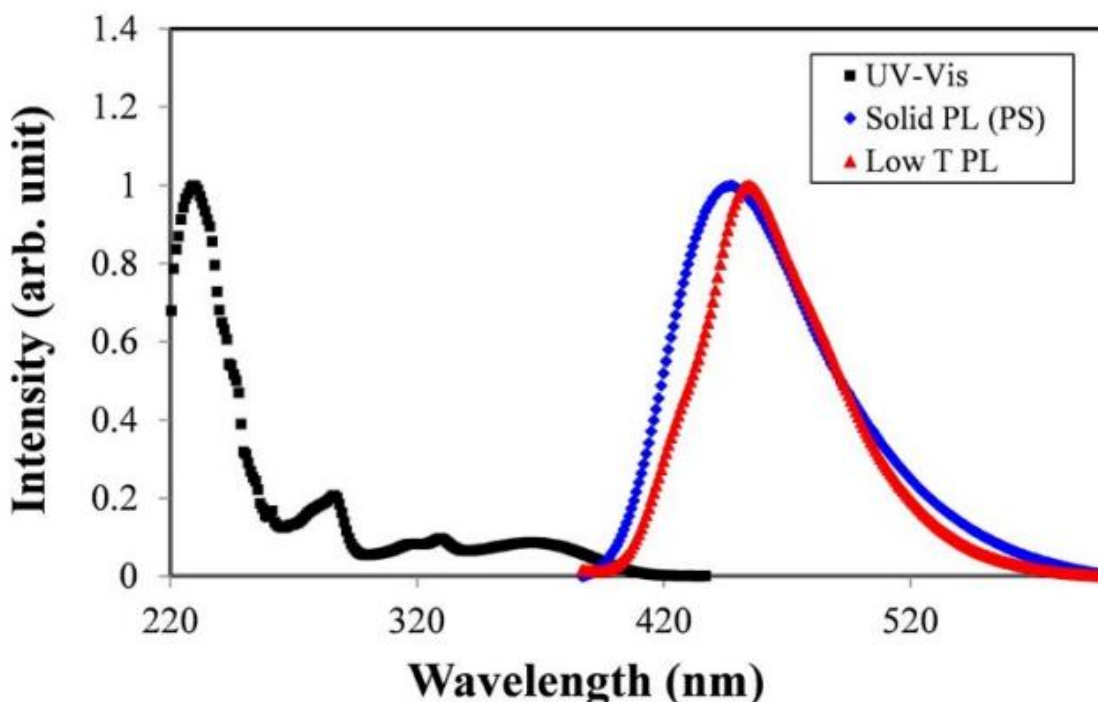


Figure 2 Cold-temperature spectrum of PL in tetrahydrofuran of DCzIPN, UV-Vis adsorption, and solids PL in polyurethane.

The singlet and triplet energy levels of DCzIPN differed by 0.05 eV, potentially leading to the activation of TADF emission in DCzIPN. The absolute photoluminescence quantum efficiency of DCzIPN was shown to be 0.35 when measured using an integrating sphere in toluene. In contrast, when measured in an N,N'-dicarbazolyl-3,5-benzene matrix, the quantum efficiency was found to be 0.87.

The TADF emission of DCzIPN was verified using transient and time-resolved photoluminescence (PL) measurement. The Figure 3 displays the transient photoluminescence spectrum of DCzIPN. The excited state lifetime of delayed light emission was determined to be 1.2 milliseconds based on the fitting of the decay curve. Figure 4 displays both the immediate and postponed photoluminescence spectra of DCzIPN. The interval between measurements for the acquisition of the delay photoluminescence (PL) was 10 milliseconds. The prompt photoluminescence (PL) and delayed photoluminescence (PL) spectrum were superimposed, indicating the fact that postponed PL emission is derived by delayed fluorescence emission. The molecular orbital distribution of DCzIPN was studied by performing a molecular simulation using the B3LYP/6-31G\* basis sets of the Gaussian 09 programme. The results of this

simulation are reported in Figure 5. The HOMO and LUMO of DCzIPN were distributed between the carbazole unit, which donates electrons, and the CN unit, which withdraws electrons, respectively. Despite the separation of the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) in DCzIPN, caused by its donor-acceptor nature, there is still orbital overlap between the HOMO and LUMO in the core phenyl ring. This suggests that the light-emitting properties of DCzIPN would be enhanced by a radiative transition process.

The ionisation potential (IP) and electron affinity (EA) of DCzIPN were assessed by cyclic voltammetry (CV) experiments. The oxidation potential and reductive potential of DCzIPN were measured to be 1.46 V and -1.34 V, respectively. The ionisation potential (IP) and electron affinity (EA) were measured to be -6.26 eV and -3.56 eV, respectively, relative to the oxidation potential and reduction potential. The DCzIPN host exhibited profound IP and EA as a result of the potent electron-withdrawing nature of the two CN groups. The difference in ionisation potential (IP) and electron affinity (EA) of DCzIPN was 2.80 eV due to its very pronounced electron donor-acceptor structure.

## **2.2 Reliability for single colour electronic devices.**

With its high single-molecule energy of 2.77 eV with deferred fluorescence emissions characterised by an average lifetime of 1.2 ms, DCzIPN demonstrates potential as a blue thermally activated delayed fluorescence (TADF) emitter. Furthermore, DCzIPN possesses a significant triplet energy of 2.72 eV, allowing efficient energy transfer to a yellow triplet emitter. Additionally, it has a short IP-EA gap of 2.80 eV, facilitating the injection of holes and electrons from the hole and electron transport layers. These properties make DCzIPN suitable as a host material for a yellow triplet emitter. The DCzIPN emitter was incorporated into the mCP host material with an ideal doping concentration of 15% in order to create a blue TADF (Thermally Activated Delayed Fluorescence) device with enhanced efficiency. Additionally, it was doped with iridium(III) bis(4-phenylthieno[3,2-c]pyridinato-N,C2')acetylacetonate (PO-01) at a doping concentration of 5% to produce yellow phosphorescent OLEDs (Organic Light-Emitting Diodes) with improved efficiency. The device structure of the blue and yellow devices consisted of indium tin oxide (ITO) with a thickness of 150 nm, followed by a layer of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) with a thickness of 60 nm. On top of that, there was a layer of 4,4'-(cyclohexane-1,1-diyl)bis(N-phenyl-N-p-tolylaniline) (TAPC) with a thickness of 20 nm, and finally a layer of mCP with a thickness of 10 nm. The structure consists of mCP:DCzIPN or DCzIPN: PO-01 (25 nm) as the first layer, diphenylphosphine oxide-4-(triphenylsilyl)phenyl (TSPO1, 35 nm) as the second layer, LiF (1 nm) as the third layer, and Al (200 nm) as the fourth layer.

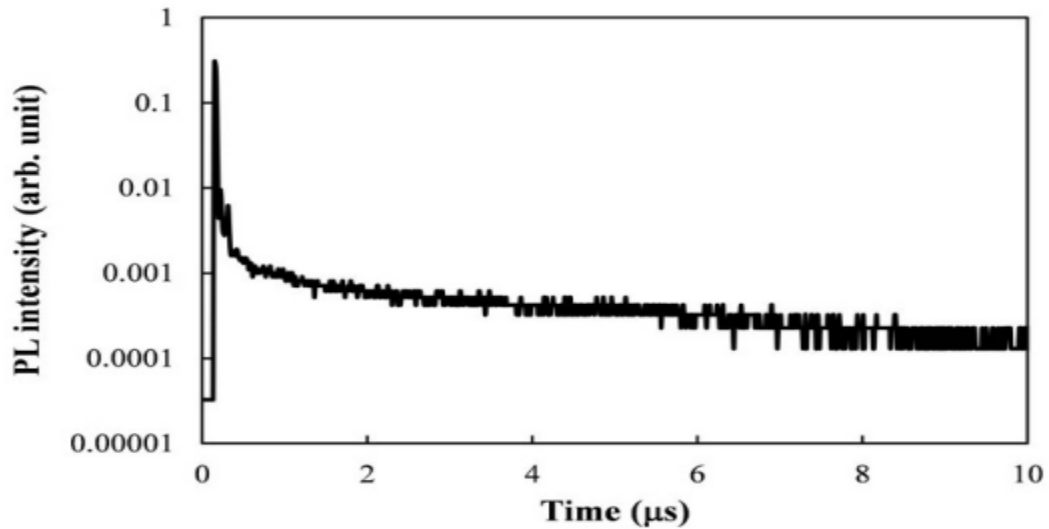


Figure 3 illustrates a transient PL decay curves for postponed emission of DCzIPN distributed in polyurethane. The stimulation wavelengths were 355 nm.

Figure 6 showcases the chemical and physical compositions of the organic materials employed in the production of the tool. Figure 7 displays the current density-voltage-luminance curves for the blue TADF and yellow phosphorescent OLEDs. The yellow phosphorescent OLED exhibited a higher current density compared to the blue device because of the narrow gap of DCzIPN, which resulted in improved charge injection capabilities. The yellow devices had an initial voltage of 2.0 V, but the blue devices had a turn-on value of 3.5 V. This difference in voltage can be attributed to the energy barrier for charge injection. The yellow device exhibited a high luminance, with an operating voltage of 5.5 V at a luminance level of 1,000 cd/m<sup>2</sup>.

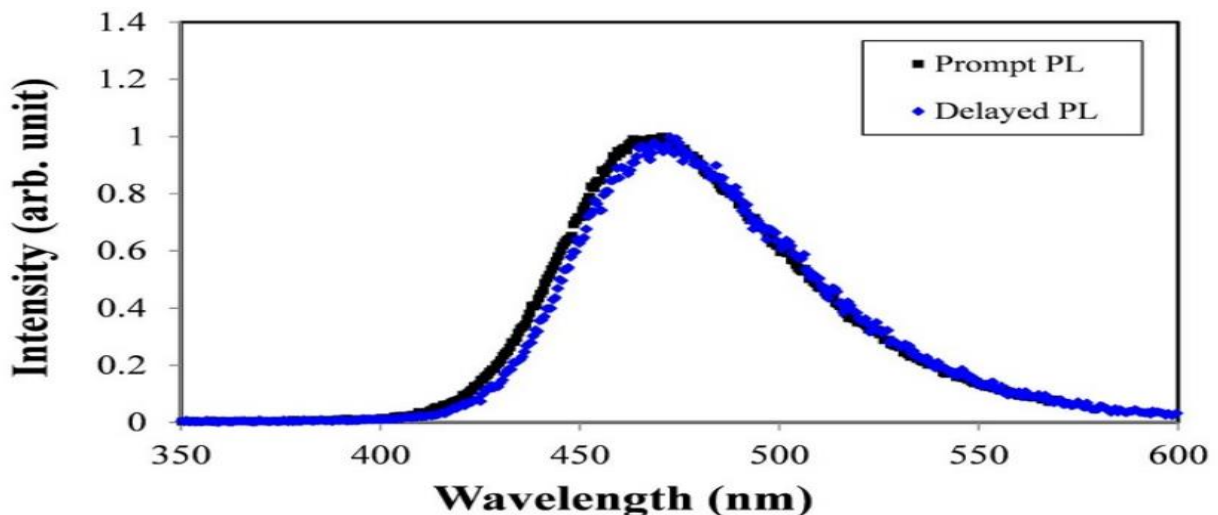


Figure 4: Immediate and postponed PL spectra of DCzIPN. The delay in period was 10 milliseconds.

Figure 8 displays the quantum efficiency-luminance curves for the blue and yellow devices. The DCzIPN TADF OLEDs achieved a maximum quantum efficiency of 16.4%. However, the efficiency decreased at high brightness levels. The photoluminescence quantum efficiency (PL QE) of the DCzIPN TADF emitter, when doped at a concentration of 15% in a mCP matrix, was measured to be 0.87. This value was found to be equivalent or even superior than the PL QE of other TADF emitters mentioned in the literature<sup>14</sup>. The high PL QE of the blue DCzIPN device can be attributed to this result. Moreover, the achievement of a high quantum efficiency can be attributed to the confinement of excitons and charges within the emitting layer. The yellow phosphorescent OLED, utilising DCzIPN as the host material, demonstrated a maximum quantum efficiency of 24.9%, surpassing the reported efficiency in previous studies. The exceptional quantum efficiency of the yellow device can be attributed to factors such as charge balance, exciton confinement, and efficient energy transfer. DCzIPN exhibits bipolar charge transport characteristics, as evidenced by the hole and electron only device data presented in Figure 9. This property allows for the balanced movement of both holes and electrons within the emitting layer. The quantum efficiency of the yellow device was increased by confining excitons within the emitting layer using high triplet energy materials such as mCP for hole transport (with an energy of 2.90 eV), TSPO1 for electron transport (with an energy of 3.39 eV), and DCzIPN as the host material (with an energy of 2.72 eV). This confinement helped suppress the non-radiative decay of the yellow triplet emitter. In addition, the efficient transfer of energy with a transfer efficiency of 97% at a doping concentration of 3% also significantly contributed to the increase in quantum efficiency. Based on this outcome, it may be inferred that DCzIPN successfully captured the emission of triplet excitons from the yellow triplet emitter without any interference or reduction in their energy.

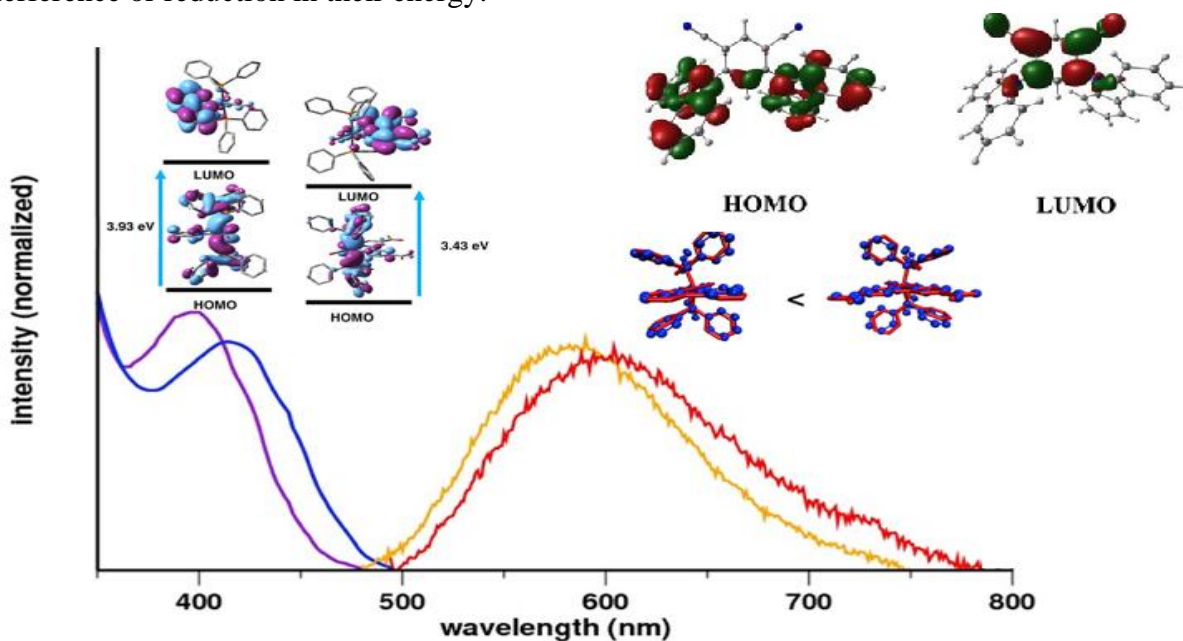


Figure 5 demonstrates the HOMO and LUMO electrons distributions of DCzIPN.

Figure 10 displays the Electroluminescence (EL) spectra of the blue and yellow OLEDs. The DCzIPN blue device had a peak maximum of 462 nm in its electroluminescence (EL) spectrum. The colour coordinate of the device was (0.17, 0.19), indicating its colour. Additionally, the device showed a single emission peak with minimal vibrational emission. The yellow phosphorescent device exhibited a peak emission at a wavelength of 558 nm, with a secondary peak at 585 nm. The colour coordinate of the device was determined to be (0.48, 0.51). Both the blue and yellow devices exhibited exclusive emission of dopant materials, with no emission detected from the host materials.

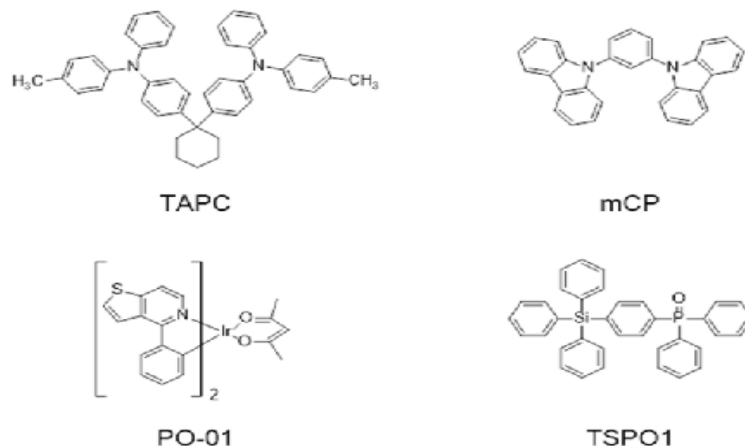


Figure 6 shows the molecular compositions of the organic components employed for sensor manufacturing.

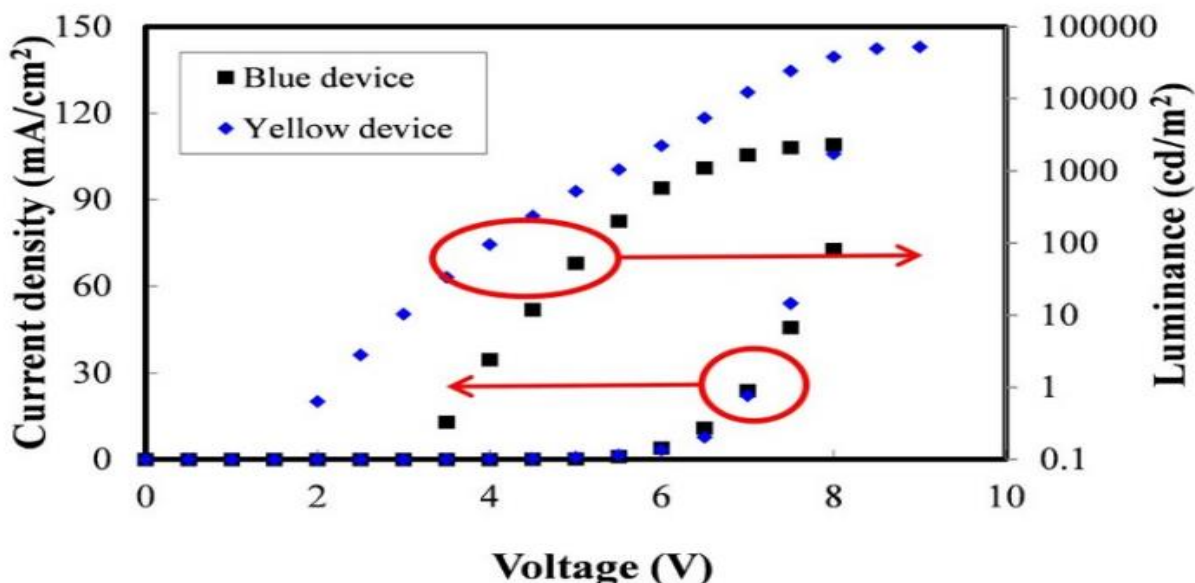


Figure 7: Curve of blues the TADF process and yellow phosphorescent OLED electrical density-voltage-luminance.



### 2.3 The Device characteristics of the hybrid white OLEDs

DCzIPN demonstrated a high quantum yield in blues TADF OLEDs and yellow phosphorescent OLEDs. Consequently, hybrids WOLEDs were developed by directly stacked the blue TADF OLED and the yellow phosphorescent OLEDs, without the need for an interlayer which is often required in hybrid WOLEDs. There is no need for the interlayer because it has been demonstrated that DCzIPN is capable of functioning as both a blue emitter and a host for a yellow emitter. The non-radiative quenching process between the blue and yellow emitting layers would be minimal, as the emitted intensity of DCzIPN is efficiently transmitted to the yellow a triplet emitters. Two equipment, Equipment I and Equipment II, were created to control the emission colour of the WOLEDs. Each device has three emitting layers, with the yellow emission layer inserted within the blue emitting layer. The device structure of WOLEDs consisted of the following layers: ITO (150 nm) as the bottom electrode, PEDOT:PSS (60 nm), TAPC (20 nm), mCP (10 nm), mCP:DCzIPN (15-x/2 nm), DCzIPN:PO-01 (x nm), mCP:DCzIPN (15-x/2 nm), TSPO1 (35 nm), LiF (1 nm), and Al (200 nm) as the top electrode. In device I, the width of the entire emission layer were 30 nm, while in device II, the thicknesses of the yellow emitting layer (x) were 1.5 nm and 3.0 nm, respectively.

Figure 11 displays the current density-voltage-luminance curves of the hybrid WOLEDs. The current density of device II was greater than that of device I. This higher current density in device II can be attributed to the yellow emitting layer having a higher current density than the blue emitting layer, as depicted in Figure 7. This is due to the employment of a thicker yellow emitting layer in device II. The brightness exhibited a similar trend to that of the current density.

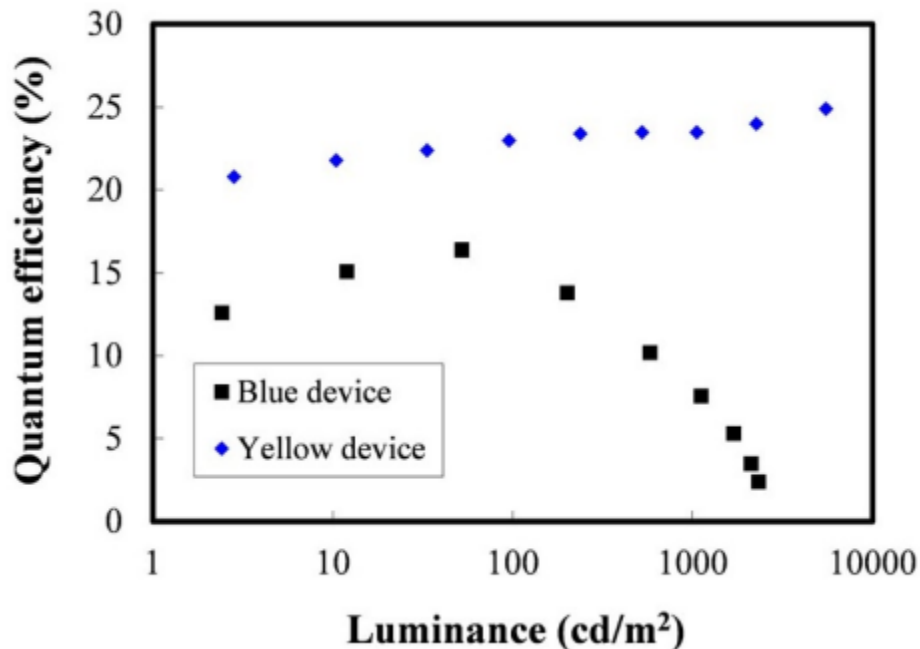


Figure 8 shows quantum efficiency-luminance ratios for blue TADF or yellow phosphorescent OLEDs

Figure 12 and 13 display the quantum efficiency-luminance curves and EL spectra of the hybrid WOLEDs at an intensity of 1,000 cd/m<sup>2</sup>. The maximum quantum efficiencies of device I and device II were 21.0% and 22.9%, respectively. The colour coordinates of device I and device II were (0.31,0.33) and (0.39,0.43), respectively. Both device I and device II exhibited a high quantum efficiency due to the absence of non-radiative quenching of singlet and triplet excitons by the yellow phosphorescent emitting layer in the DCzIPN blue emitter. The higher quantum efficiency of device II, in comparison to device I, can be attributed to the pronounced yellow emission in device II. The quantum efficiency of the yellow phosphorescent OLED was higher than that of the blue TADF OLED, as indicated by the data from the blue and yellow device. Consequently, an increased recombination of charges in the yellow emitting layer would result in a higher quantum efficiency, leading to a strong yellow emission and high quantum efficiency in apparatus II. Device I exhibited a lesser quantum efficiency compared to device II. However, despite its strong blue intensity, device I achieved a high fractional efficiency of 21.0%, surpassing the quantum efficiency of other WOLEDs with cool white color<sup>25</sup>. For other cool white colour WOLEDs, the quantum efficiency was poor due to the subpar quantum efficiency of blue electronics. To address the issue of low quantum efficiency, one potential solution is to utilise the DCzIPN TADF emitter, which has a quantum efficiency of 16.4%.

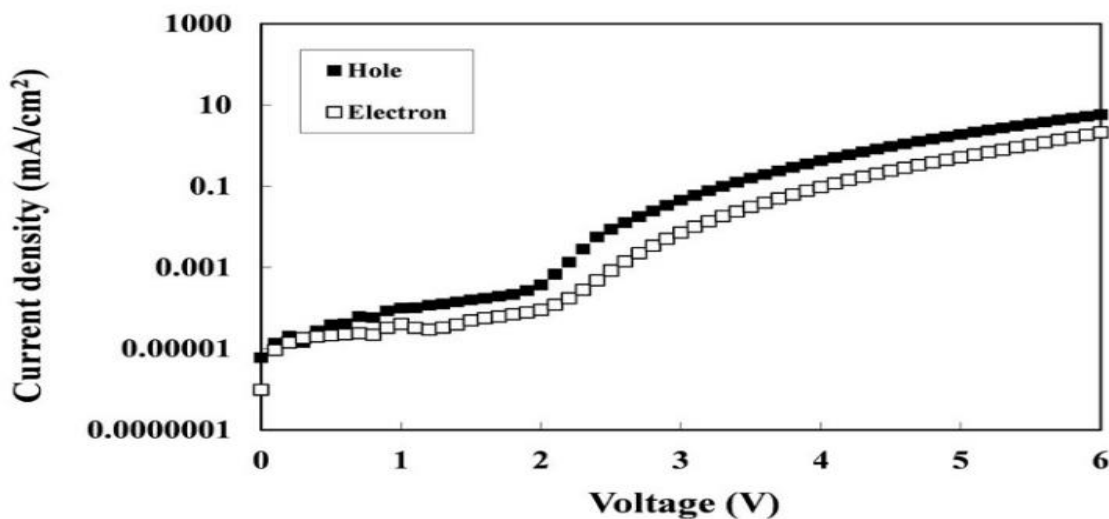


Figure 9 DCzIPN hole or electrons just current density-voltage waveforms.

The EL spectra of device I and device II, which vary depending on luminance, are displayed in Figure 14. The device exhibited a significant blue emission at a brightness of 1,000 cd/m<sup>2</sup>. However, this emission was diminished at luminances of 100 cd/m<sup>2</sup> and 5,000 cd/m<sup>2</sup> due to the recombination zone shift occurring at different luminances. Device II exhibited a mild blue emission at an intensity of 1,000 cd/m<sup>2</sup>.

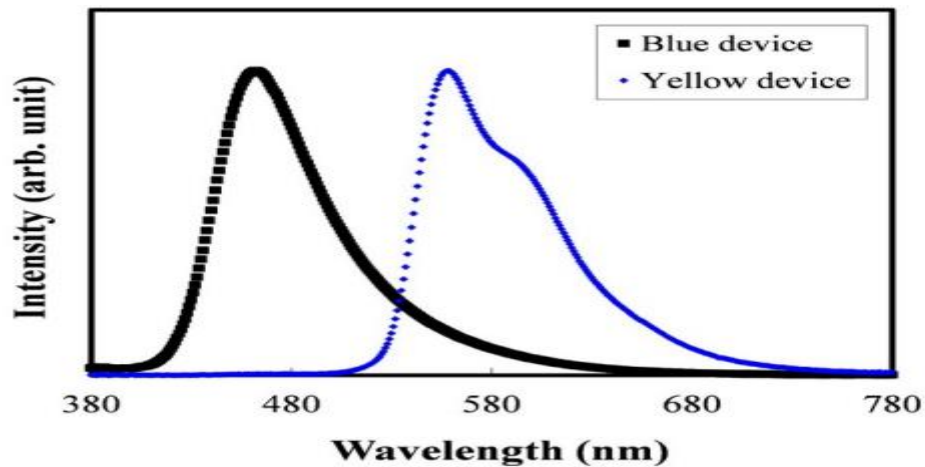


Figure 10: EL spectrum for blue TADF and yellow phosphorescent OLEDs.

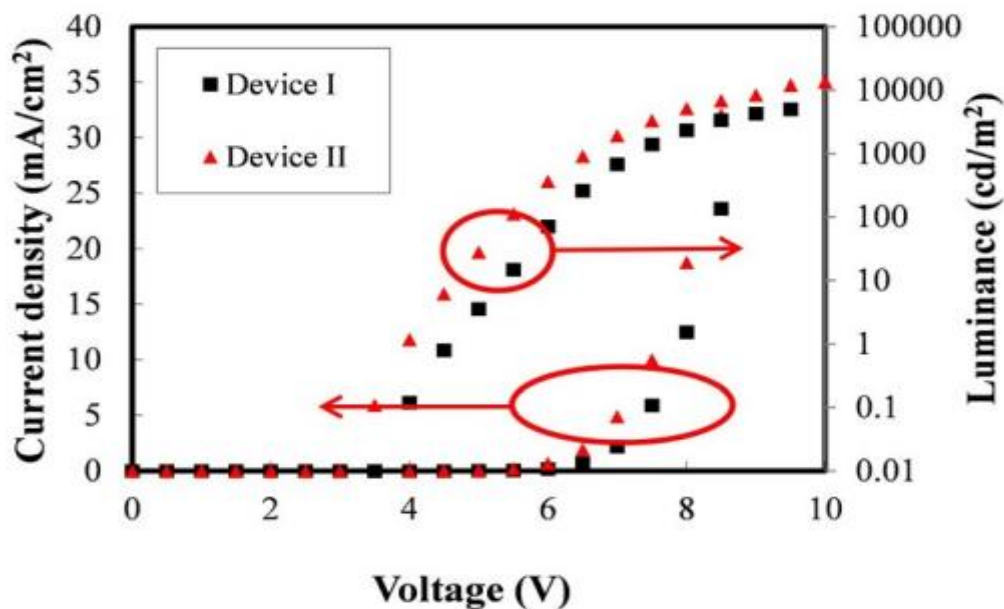


Figure 11 illustrates electricity density-voltage-luminance charts for hybrid WOLEDs with varying yellow emission layers widths.

However, a strong blue emission was found at intensities of 100  $\text{cd}/\text{m}^2$  and 5,000  $\text{cd}/\text{m}^2$ , which can be attributed to a change in the recombination zone.

#### 2.4 Mechanism manufacturing.

The electronic framework for the blue and yellow electronics consisted of the following layers: ITO (150 nm), PEDOT:PSS (60 nm), TAPC (20 nm), mCP (10 nm), mCP:DCzIPN or DCzIPN:PO-01 (25 nm), TSPO1 (35 nm), LiF (1 nm), and Al (200 nm). The doping concentrations of DCzIPN and PO-01 were 5 weight percent and 15 weight percent, respectively. The device architecture of Hybrid WOLEDs consisted of ITO with a thickness of 150 nm. The layer stack consists of PEDOT:PSS (60 nm) and TAPC (20 nm). The size of the particles is 10

nanometers. The device I consists of the following layers: mCP:DCzIPN (5 nm), DCzIPN:PO-01 (1.5 nm), mCP:DCzIPN (23.5 nm), TSPO1 (35 nm), LiF (1 nm), Al (200 nm), and ITO (150 nm). The device II consists of the following layers: PEDOT:PSS (60 nm), TAPC (20 nm), mCP (10 nm), mCP:DCzIPN (13.5 nm), DCzIPN:PO-01 (3.0 nm), mCP:DCzIPN (13.5 nm), TSPO1 (35 nm), LiF (1 nm), and Al (200 nm). The doping concentrations of DCzIPN and PO-01 were 5 weight percent and 15 weight percent, respectively. The devices were fabricated using the vacuum thermal evaporation procedure, with the exception of the PEDOT:PSS layer which was deposited using the spin coating process. The doping concentration of the dopant materials was regulated by altering the relative deposition rate of the host and dopant materials. The OLEDs were enclosed inside a glove box using a glass cover with a CaO getter attached, following the deposition of LiF and Al. The encapsulation glass and the substrate were joined together using epoxy adhesive through a process of ultraviolet light cures.

### 3.0 Discussion

The DCzIPN TADF emission was specifically engineered with a donor-acceptor architecture in order to minimise the energy difference between single-molecule and a triplet states, enabling effective reverse intersystem crossing. Additionally, the attachment of two carba zoles to isophthalonitrile allows for the emission of light that is blue. The DCzIPN's donor-acceptor configuration facilitated the creation of a blue TADF emitter that exhibits high translational effectiveness. Previous reports have described blue emitters that share chemical architectures containing two CN and two carbazole units. However, these emitters exhibited low quantum efficiency and did not produce a pure blue emission<sup>14</sup>. Nevertheless, the present chemical configuration, consisting of two CN units and two car bazole units positioned at the meta position of benzene, has yielded a notable quantum efficiency of 16.4% and a deep blue colour coordinate of (0.17, 0.19), with a peak emission wavelength of 462 nm. The DCzIPN TADF emitter can serve as a host material for the PO-01 triplet emitter by effectively capturing triplet excitons, thanks to its high triplet energy, and enhancing recombination efficiency due to its donor-acceptor structure. The quantum efficiency of the DCzIPN:PO-01 device has the potential to reach the maximum external quantum efficiency of the PO-01 device. Hence, the DCzIPN demonstrated efficacy as both a TADF emitter and a host material for phosphorescent OLEDs.

The dual functionality of DCzIPN as both a thermally activated delayed fluorescence (TADF) emitter and a triplet host is advantageous for the development of white organic light-emitting diodes (OLEDs) due to the potential simplification of the device structure by reducing the amount of materials required. Within the two-color white OLED structure, DCzIPN serves as both a deep blue emitter and a host for a yellow phosphorescent emitter. Thus, it is possible to create a new white OLED device structure by incorporating DCzIPN in both the blue and yellow emitting layers, eliminating the need for any interlayer.

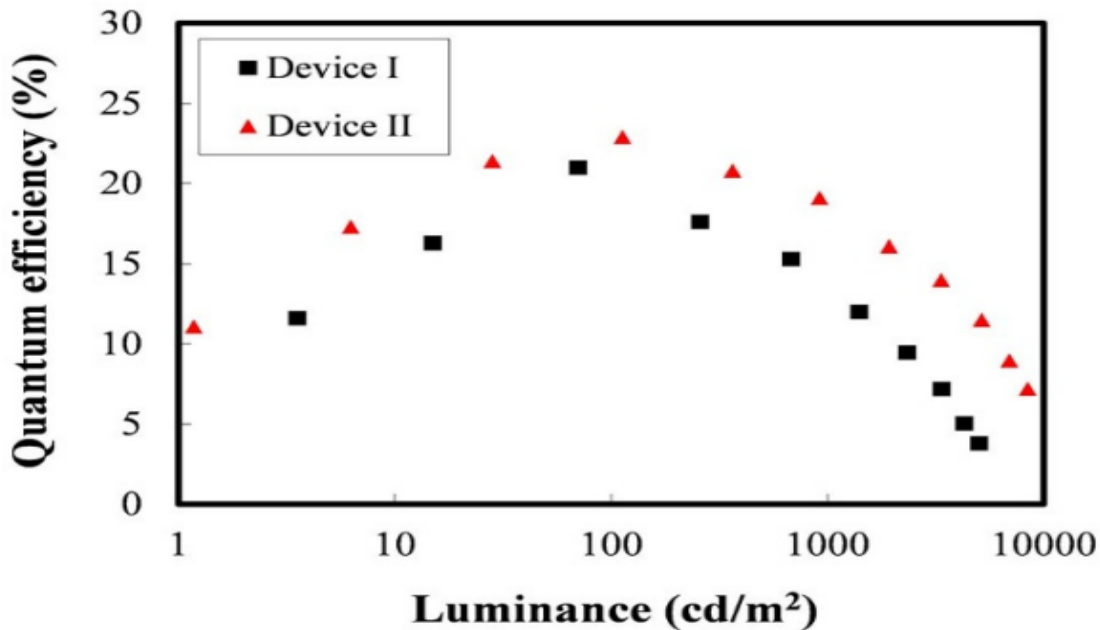


Figure 12 illustrates quantum efficiency-luminance graphs for hybrid WOLEDs with varying yellow emission layers thicknesses.

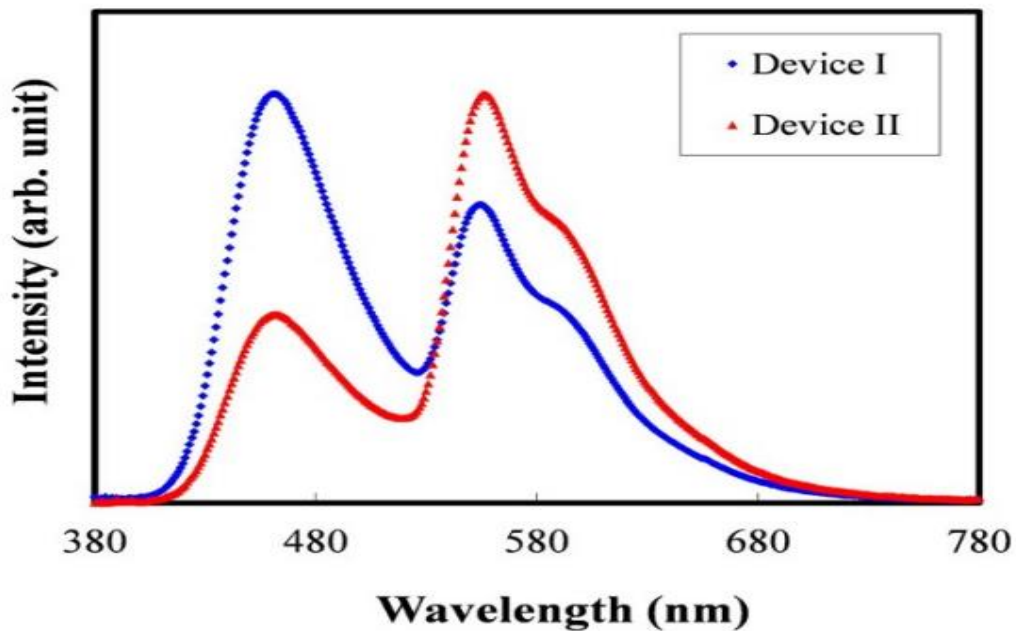


Figure 13 illustrates EL spectra for hybrids WOLEDs whose yellow emitting layer thickness. The quantum effectiveness value achieved in the novel white OLED architecture surpasses that of conventional hybrids WOLEDs<sup>25</sup> as well as outperforms all phosphorescent WOLEDs<sup>26,27</sup>. By adjusting the amount of material of the emission layers in the WOLEDs, specifically by placing a yellow phosphorescent OLED between two DCzIPN TADF blue OLEDs, it is possible

to control the emissions spectrum produced by the WOLEDs. This allows for the production of light that ranges from cool white to warm, whilst still maintaining a high level of quantum efficiency in the hybrid OLEDs. Hence, the integration of the blue Thermally Activated Delayed Fluorescence (TADF) device with the yellow phosphorescent Organic Light-Emitting Diode (OLED) device proved to be successful in enhancing the quantum efficiency and controlling the colour coordinates of White Organic Light-Emitting Diodes (WOLEDs). This paper is a significant achievement in the field of hybrid white inorganic diodes that emit light since it demonstrates external quantization efficiency of over 20% for devices that generate both cool as well as white light.

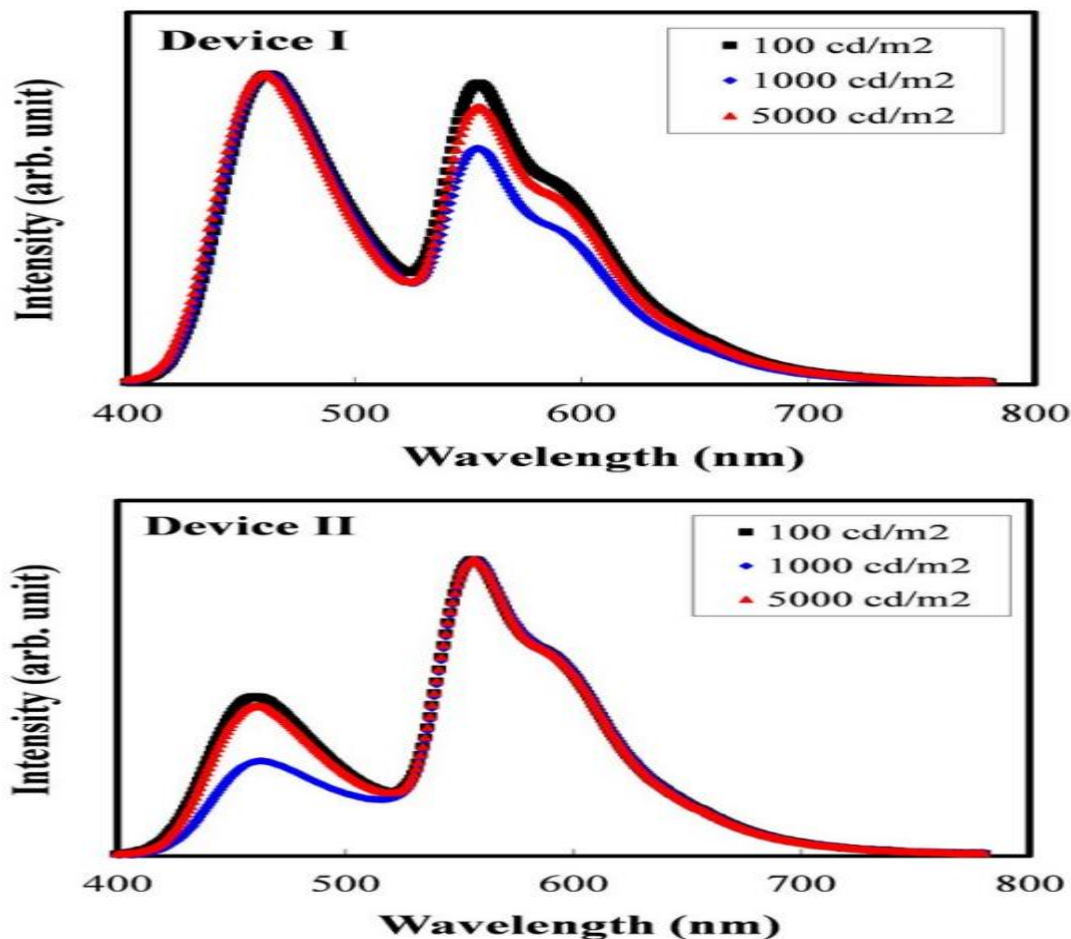


Figure 14 illustrates the EL spectrum of hybrid WOLEDs based on their illumination. Ultimately, we successfully created high-efficiency hybrid WOLEDs by incorporating a new DCzIPN blue emitter. This emitter served as both a blue TADF emitter and a host for the yellow phosphorescent triplet emitter. The yellow phosphorescent emitting layer was embedded within the blue TADF emitting layer. Modulating the thickness of the yellow emitting layer enables control over the electroluminescent (EL) emission spectra of the white organic light-emitting diodes (WOLEDs), allowing for a transition from a cool white to a warm white light. The cool white colour WOLED attained a high quantum efficiency of 21.0% with a colour coordinate of

(0.31, 0.33), whereas the warm white colour WOLED acquired a high quantum efficiency of 22.9% with a colour coordinate of (0.39, 0.43). The quantum efficiency of the hybrid WOLEDs achieved in this study surpassed that of earlier hybrid WOLEDs produced with fluorescent blue emitting materials and was on par with the performance of all phosphorescent WOLEDs. Hence, the integration of TADF and phosphorescent transmitters in hybrid WOLEDs presents a viable option to improve the quantum yield of both traditional hybrid WOLEDs and phosphorescent WOLEDs.

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