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## Bulky 9-phenylfluorene fuctionalized 2,6-bis(N-carbazolyl)pyridine with high triplet energy level as host for blue thermally activated delayed fluorescence devices

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The first 2,6-bis(N-carbazolyl)-pyridine-based compound with large steric hindrance was employed as host for blue TADF OLEDs with stable EL spectrum under different driving voltages at doping concentration as high as 30%.

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# Bulky 9-phenylfluorene fuctionalized 2,6-bis(N-carbazolyl)pyridine with high triplet energy level as host for blue thermally activated delayed fluorescence devices

9-phenylfluorene Abstract: А fuctionalized new 2,6-bis(N-carbazolyl)-pyridine compound 2,6-bis(3-(9-phenyl-fluoren-9-yl)-carbazol-9-yl)pyridine (2,6-PFCzPy) with large steric hindrance and high triplet energy level has been successfully prepared by introducing 3-(9-phenyl-fluoren-9-yl)-carbazole unit into the 2,6-position of pyridine group via Ullmann reaction. Cyclic voltammetry (CV) was used to study the electrochemical properties of the compound and obtain HOMO (-5.85 eV), LUMO (-2.09 eV), and energy gap ( $E_g$ , 3.57 eV). The 2,6-CzPy-based compound was employed as host to fabricate blue thermally activated delayed fluorescence (TADF) organic light-emitting diodes (OLEDs) for the first time with the maximum EQEs of 6.2% at the doping concentration as high as 30%. The electroluminescent (EL) spectra show almost no changes along with the driving voltage ranging from 5.1 to 15.1 V at high doping concentration, which indicates the 2,6-CzPy-based three dimensional bulky compound could successfully suppress the excimer emission of the guest in high doping ratio.

Key words: Host, 2,6-bis(N-carbazolyl)-pyridine, steric hindrance,

thermally activated delayed fluorescence

## 1. Introduction

Organic light-emitting diodes (OLEDs) have developed rapidly in the light of both organic semiconductors and device technologies in academic and industry in the past three decades since the innovative discovery reported by Tang and VanSlyke in 1987 [1], because of their particular advantages such as low cost, light weight, ultra thinner, low driving-voltage, flexibility and fast response in the application of flat panel display and solid-state lightings [2-3]. Despite the successful application of high-efficient phosphorescent organic light-emitting diodes (PhOLEDs) due to their nearly 100% theoretical internal quantum efficiencies via harvesting both triplet and singlet excitons caused by spin-coupling [4], high cost and rarely global resources of scarce metals restrict their commercial application in OLEDs [5-7]. Moreover, the phosphor emitters often encounter instability in practical applications for full-color display and solid-state lighting [8]. Therefore, metal-free emitters with high efficiency are vital for realizing high-efficient and inexpensive device in large scale production and commercialization. According to this point of view, purely organic thermally activated delayed fluorescence (TADF) metal-free luminophores are the most prospective candidates due to their ability of upconverting the lowest triplet ( $T_1$ ) excitons to the lowest singlet-state ( $S_1$ ) through reverse intersystem crossing (RISC), thus generating ideal 100% IQE [9]. However, TADF emitters are similar to phosphor luminophores that often suffer self-quenching and triplet-triplet (TT) annihilation in solid-state at high concentration [10]. Consequently, TADF dyes are also necessary to be dispersed into a suitable host matrix to control intermolecular interactions for avoiding the de-excitation pathways (such as triplet-triplet annihilation and/or concentration quenching) of emission excitations, which could greatly enhance the device performance [11-13]. Moreover, the singlet excitations with microsecond and/or millisecond liftimes are prospectively discovered due to part of them originated from the triplet state, which often leads to the fast decay of device efficiency at high current density [14]. Thus, it is urgent to explore excellent host materials for TADF emitters, especially for blue-emitting device.

On the other hand, the host should possess both higher singlet and triplet states than the singlet states of the TADF emitters due to all the emissive excitons of the TADF emitters derived from their singlet state [15]. Otherwise the excitonic energy of TADF emitter could exothermically transfer to the host [14]. In the case of blue TADF devices, it is a great challenge to realize a host with high  $T_1$  above 2.8 eV to ensure energy effectively transfer from host to blue TADF emitter. In pursuit of this requirement, the  $\pi$ -conjugation extent of the host should be

minimized by meta-/ortho-lingkage, sp<sup>3</sup> carbon, other insulating linkages (such as triarylphosphine and tetraaryl silane) to destroy  $\pi$  conjugation [16]. For example, Ye et al. manifested that the host materials of fluorene-coupled D- $\sigma$ -A type molecules with high triplet energy levels  $(T_1 > 2.80 \text{ eV})$  could obtain the maximum EQEs of 17% [15]; while Xu and his group reported a series of dibenzothiophene-based phosphine oxide as host materials through ortho- and/or meta-linkage for blue TADF OLEDs with maximum EQEs and PE (power efficiency) of 21.6% and 33.7 lm W<sup>-1</sup> [17]. Huang and Tao demonstrated a series of carbazole/pyridine hybrids by one-step approach with ortho- and/or meta-linkage to achieve triplet energy level ( $T_1 > 2.90$  eV), using (2,6-CzPy) 2,6-bis(N-carbazolyl)pyridine and 2,4,6-tri(Ncarbazolyl)pyridine (2,4,6-CzPy) as hosts with the maximum EQEs of 18.0% for blue PhOLEDs [18]. Although both of the synthesis method and molecular structure of 2,6-CzPy is convenient and simple owning high  $T_1$ , which has been successfully used as host for high perfromance of PhOLEDs [18], the 2,6-CzPy and/or 2,6-CzPy-based compounds have seldom been employed as host for TADF OLEDs [19a], especially for blue TADF OLEDs. Therefore, it is prospective to obtain high performance devices with low cost by exploring 2,6-CzPy-based compounds as hosts for blue TADF OLEDs due to its simple synthesis method and molecular structure as well as high  $T_1$ . The planar molecular

configuration of 2,6-CzPy can construct ordered and compact packing short intermolecular distance, which can not suppress due to concentration quenching and triplet-triplet annihilation of guest at high doping ratio. In addition, the low morphological stability of 2,6-CzPy (T<sub>s</sub>, 75 °C) would impair the performance of device [18]. Therefore, the research of 2,6-CzPy-based novel hosts with bulky steric hindrance and stable morphology is anticipated to inhibit concentration quenching and triplet-triplet annihilation of guest in solid state for high performance device. One of the effective methods is design and synthesis of 2,6-CzPy-based compounds with bulky 9-arylfluoren-9-ol moiety (AFM) to solve this problem, which is available for good solubility, high thermal and morphological stability, controllable intermolecular interaction and promising carrier transport ability [19b]. Herein, 9-phenylfluoren-9-ol moiety (PFM) has been introduced into 2,6-CzPy via the sp<sup>3</sup>-hybridized carbon linkage by Friedel-Crafts reaction to enhance its thermal and morphological stability, which is demonstrated by TGA (T<sub>d</sub>, 334 °C) and DSC curves (No detectable melting point and glass transition temperature ranging from 40 to 150 °C) with the desirable thermal and morphological stability. Meanwhile, the sp<sup>3</sup> atom lingkage between PFM and 2,6-CzPy limits the  $\pi$ -conjugation in the whole molecule retaining high T<sub>1</sub> (2.83 eV) and controllable electrochemical properties, which has been demonstrated by the density functional theory (DFT) calculations and triplet energy

levels of 2,6-CzPy and **2,6-PFCzPy** [18]. The novel compound 2,6-bis(3-(9-phenyl-fluoren-9-yl)-carbazol-9-yl)pyridine (**2,6-PFCzPy**) with 3D bulky steric hindrance is used as host for blue TADF OLEDs for the first time.

## 2. Experimental Section

### 2.1 Materials and Methods

All chemical reagents and solvents were bought from Xi'an Polymer Light Technology Corp or Alfa Aesar and used directly without further purification. 3-(9-Phenyl-fluoren-9-yl)-carbazole (PFCz) was prepared according to the facile synthesis of complicated 9,9-diarylfluorenes reported by Xie and Huang [20]. The reaction was carried out under nitrogen atmosphere. <sup>1</sup>H and <sup>13</sup>C NMR spectra were recorded on a JNM-ECS 600 and 150 MHz spectrometer, respectively, in deuterated chloroform relative to tetramethylsilane internal standard. as MALDI-TOF MS spectrum was executed on a reflective mode. The ultraviolet-visible (UV-vis) absorption spectra were studied by using a Shimadzu UV-3600. The photoluminescence (PL) spectra were measured in frozen dichloromethane at 77 k with Edinburgh FLS 920 fluorescence. Cyclic voltammetric measurements (CVs) were performed by using a traditional three-electrode construction and an electrochemical workstation (CHI660C, China) by a glass carbon working electrode

dripped with thin film of 2,6-PFCzPy, a Pt wire counter electrode, a reference electrode (Ag/Ag<sup>+</sup>, referenced against ferrocene/ferrocenium (FOC)) in degassed acetonitrile solution with 0.1 mol·L<sup>-1</sup> of Bu<sub>4</sub>NPF<sub>6</sub> at room temperature. The HOMO, LUMO, and HOMO-LUMO energy gap  $(E_{\sigma})$  of the compound were calcuated with ferrocene (Fc/Fc<sup>+</sup>, 0.03 V) according to the formulas: HOMO =  $-[E_{ox} - E(Fc/Fc^{+}) + 4.8]$  eV, LUMO = -[ $E_{red}$  - E(Fc/Fc<sup>+</sup>) + 4.8] eV, where oxidation potential is set at -4.8 V against zero vacuum level referenced to the ferocenium/ferrocene using ferrocene as internal standard [21a]. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) curves were performed on a Perkin Elmer DSC 8500 unit and a TA Q2000 instrument, respectively, under nitrogen flow at a heating rate of 10 °C min<sup>-1</sup>. The molecular structure optimization and electronic properties of the compound were performed by density functional theory (DFT) calculations with Gaussian 09 program package at B3LYP/6-31G (d, p) level [21b], and the corresponding HOMO and LUMO spatial distributions were also obtained. Vibrational frequency analysis was also performed at this level of theory. This result showed that the optimized structure corresponded to a minimum of potential energy surface with no imaginary frequency.

2.2 Synthesis of 2,6-bis(3- (9-phenyl-fluoren-9-yl)-carbazol-9-yl)pyridine
(2,6-PFCzPy)

2,6-Dibromopyridine (0.24 g, 1 mmol), 3-(9-phenyl-fluoren-9-yl)carbazole (1.02 g, 2.5 mmol), potassium carbonate (3.45 g, 25 mmol), cuprous iodide (0.05 g, 0.25 mmol) and 18-crown-6 (0.03 g, 0.13 mmol) and 50 mL 1,2-dichlorobenzene were added successively into a dry three-necked flask under nitrogen atmosphere and away from light and refluxed for 24h. After cooling to room temperature, the solvent was removed by decompressing distillation around 140 °C. The residue was washed by water and extracted with CH<sub>2</sub>Cl<sub>2</sub> for several times. The organic phase was collected and dried by anhydrous Na<sub>2</sub>SO<sub>4</sub>. Then, the organic solution was condensed by a rotary evaporation apparatus under reducing pressure and purified by column chromatography on silica gel with the eluents of ethyl acetate and petroleum ether (ratio of volume, 8:1) to obtain white powder; yield: 44%. LC-MS (EI) m/z 890.3537 [M<sup>+</sup>]; <sup>1</sup>H NMR (600 MHz, CDCl<sub>3</sub>, ppm):  $\delta$  8.03 (t, J = 7.80 Hz, 1H), 7.91 (t, J = 7.50 Hz, 4H), 7.87 (d, J = 2.10 Hz, 2H), 7.82 (d, J = 8.50 Hz, 2H), 7.78 (d, J = 7.80 Hz, 4H), 7.53 (d, J = 7.80 Hz, 2H), 7.46 (d, J = 7.80 Hz, 4H),7.35 (t, J = 7.80 Hz, 4H), 7.32 (t, J = 8.40 Hz, 2H), 7.26 (m, 10H), 7.21 (m, 8H). <sup>13</sup>C NMR (150 MHz, CDCl<sub>3</sub>):  $\delta$  (ppm) 151.75, 151.54, 146.52, 140.41, 140.18, 139.73, 139.03, 138.35, 128.28, 127.78, 127.52, 127.14, 126.68, 126.34, 124.51, 124.40, 121.16, 120.27, 119.32, 114.72, 112.06, 111.73.

## 3. Results and discussions

## 3.1 Synthesis and thermal stability

The molecular structure and synthetic route of 2,6-bis(3-(9-phenylfluoren-9-yl)-carbazol-9-yl)pyridine (2,6-PFCzPy) are displayed in Scheme 1. The raw material 3-(9-phenyl-fluoren-9-yl)-carbazole (PFCz) was synthesized by the previous work reported by Xie and Huang [20]. The product **2,6-PFCzPy** was prepared by introducing two bulky PFCz units into the 2,6-position of pyridine moiety via Ullmann reaction under nitrogen ambience and avoiding light. Two PFCz units were linkaged at the 2,6-position of pyridine moiety to ensure the high  $T_1$  (2.83 eV) of the compound, and the bukyl 9-phenyl-fluoren-9-yl is to construct steric hindrance. It is noteworthy that most host materials of carbazole/pyridine hybrides are derived from 2,6-CzPy just with different linkage position or midified with distinct groups, whereas the carbazole/pyridine hybrides with 3D steric hindrance effects have rarely been reported. The chemical structure of the compound is fully characterized by <sup>1</sup>H NMR, <sup>13</sup>C NMR, LC-MS, which has good solubility in common solvents such as, Dimethyl sulfoxide, N,N-dimethylformamide, Dichloromethane, and Chloroform, et al. The compound shows good thermal stability that is proved through its high decomposition temperature (T<sub>d</sub>, 334  $^{\circ}$ C; corresponding to 5% weight loss) characterized by thermogravimetric curve (Fig. 1a), which shows higher thermal stability than that of 2,6-CzPy is probably due to

the increased molecular weight [18]. The glass transition temperature was determined through differential scanning calorimetry, which exhibited no detectable crystallization and glass transition phenomena in the heat ranging from 40 to 150 °C (**Fig. 1b**). Compared to the glass temperature of 2,6-CzPy ( $T_g$ , 75 °C), the enhanced glass temperature of 2,6-PFCzPy is probably ascribed to the twisted 3D bulky steric hindrance effect.

## 3.2 Optical properties

The photophysical properties of the 2,6-PFCzPy were elaborately studied by ultraviolet-visible (UV-vis) absorption and photoluminescence (PL) measurements in diluent dichloromethane (DCM) solution at room temperature (Fig. 2). As can be seen from Fig. 2, 2,6-PFCzPy displays five main absorption peaks at about 231, 240, 252, 300 and 350 nm. The strongest absorption peak around 231 nm could be ascribed to the  $\pi$ - $\pi$ \* transition of phenyl unit; The middle absorption bands around 240, 252 and 300 nm are assigned to the the  $\pi$ - $\pi$ \* transition of pyridine, fluorene and carbazole, respectively. The weakest absorption peak around 340 nm is belonged to the n- $\pi^*$  transition of carbazole moiety. In order to evaluate the potential appliaction of 2,6-PFCzPy as host material for TADF the phosphorescent spectrum was measured in frozen OLEDs. dichloromethane. The  $T_1$  (2.83 eV) of the compound was obtained from the highest-energy vibronic subband of phosphorescent spectrum (Fig. S1), which was higher than the general triplet energy level (2.80 eV) of

blue TADF emitters to restrict the triplet excitons in the emitting layer [15]. This indicates **2,6-PFCzPy** can be used as host for blue TADF OLEDs. The singlet energy level (S<sub>1</sub>, 3.47 eV) is calculated by the threshold value of absorption spectrum in DCM solution, while the energy gap ( $\Delta E_{ST}$ ) is obtained from the difference between T<sub>1</sub> and S<sub>1</sub> (0.64 eV).

3.3 The frontier orbital and electrochemical properties of the compound

DFT calculation was carried out to further understand the structure and molecular orbitals (MOs) of the compound. As shown in Table 1, although 2,6-CzPy was functionalized with bukyl PFCz, the highest occupied molecular orbital (HOMO, -5.36 eV) is still located on carbazole moiety with slightly extended on part of pyridyl group, whereas the lowest unoccupied molecular orbital (LUMO, -1.07 eV) is mainly distributed on the pyridyl group. The HOMO and LUMO energy levels are almost no change compared to the corresponding energy levels of 2,6-CzPy [18], which is probably ascribed to the sp<sup>3</sup> linkage between carbazole and PFM. The controllable energy levels is beneficial to enhancing the thermal and morphological stability of the host by bulky PFM group for stable device. In addition, the little spatial overlap between the HOMO and LUMO of 2,6-PFCzPy is also helpful to achieve high-efficient device [22].

To research the electrochemical characteristics of **2,6-PFCzPy**, cyclic voltammetry measurements were performed to estimate the value of HOMO (-5.85 eV) and LUMO (-2.09 eV) of the compound (**Table 2**). The LUMO energy level of 2,6-PFCzPy is high in accord with that of 2,6-CzPy, while the HOMO of 2,6-PFCzPy is slightly lower 0.22 eV than that of 2,6-CzPy (-5.63 eV) [18]. The slim variations of HOMO and LUMO levels between **2,6-PFCzPy** and 2,6-CzPy further proved the minute influence caused by the sp<sup>3</sup> linkage between carbazole and PFM. The energy gap ( $E_g$ , 3.76 eV) was obtained from the difference between the HOMO and LUMO energy levels, which was approximate to the result ( $E_g$ , 3.47 eV) calculated from the threshold of absorption spectrum.

## 4. Electroluminescent properties

In view of its good thermal stability and stable morphology as well as high  $T_1$  of the hybrid, blue TADF OLEDs (device A and B) were fabricated using both 2,6-PFCzPy and 2,6-CzPy as host materials to investigate the influence of steric hindrance with the following configuration: ITO/MoO<sub>3</sub>(6 nm)/NPB(50 nm)/mCP (5 nm)/ EML (30 wt%, 20 nm)/DPEPO (35 nm)/Bphen (40 nm)/LiF (1 nm)/Al (100 nm) (shown in Fig. 3). In the devices, 2,6-PFCzPy (device A) and 2,6-CzPy (device employed with B) were hosts DMAC-DPS as (bis[4-(9,9-dimethyl-9,10-dihydroacridine)-phenyl]sulfone) as guest for blue TADF OLEDs, respectively. MoO<sub>3</sub> and LiF are served as hole and electron-injecting layers, with ITO and Al as the anode and cathode, (N,N'-dicarbazole-3,5-benzene) respectively. mCP and Bphen (bathophenanthroline) act as exciton blocking (EBL) and electron (ETL), NPB transporting layers respectivly, with (4,4'-bis[N-(1-naphthyl)- Nphenylamino]biphenyl) as hole-transporting layer (HTL). Bis(2-(diphenylphosphino)phenyl)ether oxide (DPEPO) was used to restrict excitons inside the emitting layer (EML). The luminance-voltage-current density (L-V-C), current efficiency-voltage, EQE-Luminance curve and EL spectra of the **2,6-PFCzPy** and **2,6-CzPy** hosted blue TADF OLEDs are shown in Fig. 4 and Fig. S3. All the relevant device data are summarized in Table 3. As illustrated in Fig. 4a, the device A displays turn-on voltage at about 4.7 V (defined as the voltage at L = 1 cd m<sup>-2</sup>) that is lower than that of device B ( $V_{on} = 5.0$  V), which is probably originated from the more balanced energy levels between EML and EBL of device A compared with that of device B, prompting the charge trapping and exciton recombination on DMAC-DPS ascendant in collecting charger carriers. This is confirmed by the higher luminance of device A than that of device B when the driving voltage ranged from 4.0 to 12.0 V, which is further demonstrated by the V-J curves that displayed higher J of device A compared to that of device B as the operation voltage aggrandized from 4.0 to 13.0 V. The higher luminance and J value of 2,6-PFCzPy-based device A is in

accord with higher exciton concentration due to larger and well balanced excitons in its EML compared to that of 2,6-CzPy-based device B, which indicates the introducing bulky PFM into 2,6-CzPy could suppress concentration favourably quenching and triplet-triplet annihilation of guest at high doping concentration. As can be seen in Fig. 4 and Fig. S3, the maximum luminance, current efficiency, and EQE of devices A and B are 1356/6459 cd m<sup>-2</sup>, 14.4/21.0 cd A<sup>-1</sup>, and 6.2/10.36%, respectively. Although the maximum performance of device A is lower than that of device B, device A possesses better characteristics at low driving voltage. In addition, the luminance of the device A is 1000 cd  $m^{-2}$  when the driving voltage of device is at 10.8 V, which implies the applicability of the device in portable equipment. The big driving voltage of device A is probably ascribed to large barrier carrier injection of the LUMO energy levels between host and guest, which is further confirmed by the driving voltage of device B with the luminance of 1000 cd m<sup>-2</sup> at about 12.0 V. Meanwhile, the electroluminescence (EL) spectra of the device of A and B exhibit electroluminescence characteristics with emission peaks around 486 and 478 nm, which is bathochromic-shift around 24 and 16 nm, respectively, compared with DPEPO-based devices reported by Xu [23], probably due to the difference of polarity between the hosts [24]. The change of EL spectra of device A is negligible as the driving voltages increases from 5.1 to

15.1 V with the doping concentration of 30% w.t., which indicates excellent color stability. This result demonstrates the bukyl steric hindrance of the host could supress excimer emission of the guest successfully. The maximum EQE of the device A descends to one half of itself as the luminance increases from 0.88 to 336 cd m<sup>-2</sup> (**Fig. 4c**). The rapid roll-off is probably caused by the unbalanced excitons and/or the insufficient energy transfer from host to guest. The high-efficient TADF OLEDs based on bukyl steric hindrance functionalized 2,6-CzPy derivatives is on-going by optimizing the molecular structure with improved charge carriers balance and device configuration.

## **5.** Conclusions

In this work, a novel 2,6-bis(N-carbazolyl)pyridine (2,6-CzPy) with large steric hindrance was successfully synthesized by combining two 3-(9-phenyl-fluoren-9-yl)-carbazole groups with pyridine unit *via* Ullmann reaction. TGA and DSC curves manifest the bulky steric hindrance effect is beneficial for improving the thermal and morphological stability compared to that of 2,6-CzPy. The blue TADF OLEDs was first fabricated using 2,6-CzPy-based compounds as host with maximum EQE of 6.2% at doping concentration as high as 30% without any change of EL spectra as the driving voltages increased from 5.1 to 15.1 V, which suggests the 3D bulky steric hindrance of the

compound could suppress the excimer emission of the guest at high doping concentration successfully. The high performance TADF OLEDs is expected to be achieved by modifying the molecular structure of 2,6-PFCzPy and optimizing the device conformation on the basis of the aforementioned guidelines in this work.

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## **Appendix A. Supplementary material**

Supplementary data associated with this article can be found in the online version at <u>http://dx.doi.org/</u>.

## **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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Scheme 1 Synthetic route to 2,6-PFCzPy







Fig. 2 The UV-vis and PL spectra of the compound in DCM solution.

**Table 1.** HOMO and LUMO surfaces from DFT calculations



Table 2. Electrochemical properties and triplet energy levels of the host

Compound	HOMO	LUMO	E <sub>g</sub>	T <sub>1</sub>
	(eV)	(eV)	(eV)	(eV)
2,6-PFCzPy	-5.85	-2.09	3.76	2.83

Device	Host	$L^{a}$ (cd m <sup>-2</sup> )	$CE^{a}(cd A^{-1})$	$EQE^{a}(\%)$
А	2,6-PFCzPy	1356	14.4	6.2
В	2,6-CzPy	6459	21.0	10.36

Table 3. Device performance of the blue TADF OLEDs



**Fig. 3** (a) Schematic configuration of the OLEDs and the corresponding molecular structures of the main organic materials, (b) Energy-band diagrams of the OLEDs.







**Fig. 4** (a) Luminance-voltage-current density of devices A (squares) and B (spheres) with black color for luminance and blue color for current density, (b) Current efficiency-Voltage of devices A (black squares) and B (red spheres), and (c) EQE-Luminance curves and EL spectra (inset) of device A

•The first 2,6-bis(N-carbazolyl)-pyridine-based compound with large steric hindrance was used as host for blue TADF OLEDs

•Stable blue EL spectra were achieved under different driving voltages at high doping concentration of 30%.

•The enhanced thermal and morphological stability was achieved with high triplet energy level (T1, 2.83 eV) and controllable electrochemical properties.

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The authors declare that they have no conflicts of interest.

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Xiang-Hua Zhao and Hui Xu conceived the project; Xiang-Hua Zhao performed the experiments and wrote the paper; Chun-Miao Han fabricated the devices; Yue Li, Ming-Gui Bai and Jin-Can Yang provided the data of cyclic voltammogram, UV, PL, TGA and DSC; Shun-Dong Yuan and Ling-Hai Xie analysed the data of devices; Zhi-Jie Xu calculated the compound.

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