Synthesis and Luminescent Properties of 1,4,5-Triphenylimidazole—Phenothiazine Fluorophores

Long Qian1 · Hongyan Yang2 · Yuling Zhao2 · Yongchun Guo1 · Tianzhi Yu1

Received: 14 January 2022 / Accepted: 31 May 2022 / Published online: 21 June 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
Two blue donor–acceptor fluorophores with 1,4,5-triphenylimidazole as the electron-transporting unit and phenothiazine as the hole-transporting unit were synthesized by grafting 1,4,5-triphenylimidazole moieties onto 3- and 3,7-position of the phenothiazine core and characterized by spectroscopic methods. Their thermal stability, photophysical, electrochemical and electroluminescence properties were systematically investigated. These compounds exhibit good thermal stability and show blue emission in dichloromethane solution and thin solid films. The solution-processed doped devices were fabricated by using these fluorophores as the emitting dopant in 1,3-bis(N-carbazolyl)benzene host, in which the device fabricated from the fluorophore containing two 1,4,5-triphenylimidazole moieties exhibited blue emission with a luminance of 648 cd/m² and external quantum efficiency of 1.48%.

Keywords Imidazole derivative · Phenothiazine · Photoluminescence · Electroluminescence

Introduction
Organic electroluminescence diodes (OLEDs) are becoming one of the leading technologies for full-color displays and environment-friendly light source due to the thinness, high brightness, wider viewing angle, lower power consumption, higher color gamut, faster response speed, better flexibility, wider operating temperature range and lower cost [1–6]. Over the last decades, great development of the light-emitting materials and device structures for high-performance OLEDs has been made in both scientific research and commercial applications [7–15]. Generally, OLED light-emitting materials can be divided into two main types according to their chemical and photophysical properties: small molecule light-emitting materials and polymeric light-emitting materials [16–23]. Compared with polymeric light-emitting materials, small molecule luminescent materials are easier to synthesize and purify, and their structure can be fine-tuned through appropriate molecular design. OLEDs based on small molecules can be fabricated either by vacuum deposition method or by solution spin-coating method [24–26]. Among the small-molecule luminescent materials, luminescent materials with high photoluminescence quantum (ΦPL) and excellent charge transport characteristics can effectively improve the electroluminescence (EL) efficiency [17, 27].

Phenothiazine (PTZ) and its derivatives are a class of electron-rich aromatic heterocyclic compounds containing nitrogen and sulfur atoms, which have been widely used in various optoelectronic applications due to their unique optical, electronic properties, flexibility of functionalization, low cost, and commercial availability [28–30]. In the field of organic semiconductor materials for optoelectronics, phenothiazine (PTZ) has been commonly used as a strong electron donating group. It is well-known that anthracene has high fluorescence efficiency, but it is easy to crystallize, thus the OLEDs based on simple structural anthracene derivatives usually exhibit low performance. Unlike anthracene with a planar conformation, PTZ core is a butterfly conformation that could restrain the formation of ground state aggregates and excimers, making PTZ a well-known building block for OLEDs [31, 32]. Due to the strong electron donating ability of phenothiazine, the D–A or D–π–A type emitters based on phenothiazine have been designed and synthesized for OLEDs. Kwon and co-workers [33]
designed and synthesized two isomeric D–A fluorescent molecules based on phenothiazine–quinolone framework, 2-(4-phenyl-2-quinolyl)-10-methylphenothiazine (2PQMPT) and 3-(4-phenyl-2-quinolyl)-10-methylphenothiazine (3PQMPT), for green organic light-emitting diodes, and it was found that the device performances of the isomer 3PQMPT (25,020 cd/m² of $L_{\text{max}}$), 2.50% of EQE of $L_{\text{max}}$ were superior to that of the isomer 2PQMPT (10,590 cd/m² of $L_{\text{max}}$) with D–A type structure, and the optimized non-doped OLED device used PhBBPP as emitting layer showed a luminous efficiency of 12.1 cd/A, and an external quantum efficiency (EQE) of 4.0%. Recently, Zhao et al. [35] reported three new bipolar molecules containing phenothiazine and phenanthroimidazole moieties, PI-PTZ (10-butyl-3-(phenanthroimidazol-2-yl)phenothiazine), PPI-PTZ (10-butyl-3-((4-tert-butyl)phenyl)phenanthroimidazol-2-yl) phenothiazine) and PPI-PTZ-PPI (10-butyl-3,7-bis((4-tert-butyl)phenyl)phenanthroimidazol-2-yl)phenothiazine), and the optimized doped device based on PPI-PTZ-PPI exhibited a maximum brightness of 30,180 cd/m², a maximum external quantum efficiency (EQE) of 4.0% and a maximum current efficiency of 10.65 cd/A.

The twisted 1,4,5-triphenylimidazole as an acceptor could cause a wider band-gap and lead to deeper blue emission than the planar and rigid phenanthroimidazole acceptor, and the twisted 1,4,5-triphenylimidazole could also hamper the tight π–π intermolecular interactions. Therefore, it was often used to construct blue-emitting materials [36, 37]. Based on the structural feature of 1,4,5-triphenylimidazole, in this work, we have synthesized two blue D–A fluorophores containing 1,4,5-triphenylimidazole as the electron-acceptor and phenothiazine as the electron-donor by grafting 1,4,5-triphenylimidazole moieties onto 3- and 3,7-position of the phenothiazine core to investigated the effect of the number of electron-acceptors on the optoelectronic properties of the materials.

## Experimental

### Materials and Methods

Phenothiazine, 1-bromobutane, benzyl and 4-tert-butyllaniline were obtained from Energy Chemical (China). All the other reactants and solvents were obtained from commercial sources. All organic solvents used in this study were dried with the suitable desiccants and freshly distilled prior to the relevant reactions.

The NMR spectrum was measured on Bruker 500. The UV–vis absorption spectrum was recorded on a Shimadzu UV–2550 spectrometer. The cyclic voltammogram was performed on an electrochemical analyzer (CHI Instruments 760 B). At room temperature, using Edinburgh instrument FLS920 integrating sphere and Xe lamp, the quantum yield of photoluminescence was measured by the absolute method. At room temperature, the Edinburgh instrument FLS920 was used with a microsecond flash lamp as the excitation source (repetition frequency 90 Hz), and the photoluminescence decay lifetime was measured by a time-correlated single photon counting spectrometer.

The synthesis process of the intermediates, 10-butyl-10H-phenothiazine-3-carbaldehyde and 10-butyl-10H-phenothiazine-3,7-dicarbaldehyde, were described in our previous paper [35].

### Synthesis and Characterization of the Compounds

#### 10-Butyl-3-(1-(4-(tert-butyllphenyl))-4,5-diphenyl-1H-imidazol-2-yl)-10H-phenothiazine (PTZ-PIM)

In a 250 mL three-necked flask, benzil (0.82 g, 3.90 mmol), 4-tert-butyllaniline (0.64 g, 4.29 mmol), 10-butyl-10H-phenothiazine-3-carbaldehyde (1.00 g, 3.53 mmol) and CH₃COONH₄ (9.30 g, 0.12 mol) were dissolved in 60 mL of glacial acetic acid, and then the reaction mixture was stirred at 120 °C for 24 h under a nitrogen atmosphere. After cooling to room temperature, the reaction mixture was poured into ice water and filtered to obtain a yellow solid. The crude product was purified by silica gel chromatography using dichloromethane/petroleum ether (1:3, v/v) to obtain a pale yellow solid (1.90 g, 89%). m.p. > 240 °C. $^1$H NMR (500 MHz, CDCl₃, δ, ppm): 7.59 (d, J = 7.6 Hz, 2H, Ar–H), 7.28 (d, J = 8.6 Hz, 2H, Ar–H), 7.25 – 7.15 (m, 8H, Ar–H), 7.12 (d, J = 7.7 Hz, 3H, Ar–H), 7.08 (s, 1H, Ar–H), 7.03 (d, J = 7.2 Hz, 1H, Ar–H), 6.95 (d, J = 8.5 Hz, 2H, Ar–H), 6.78 (d, J = 8.8 Hz, 2H, Ar–H) 3.78 (t, J = 7.0 Hz, 2H, N-CH₂), 1.76 – 1.70 (m, 2H, -CH₂), 1.45 – 1.37 (m, 2H, -CH₂), 1.29 (s, 9H, -C(CH₃)₃), 0.92 (t, J = 7.5 Hz, 3H, -CH₃). $^{13}$C NMR (126 MHz, CDCl₃, δ, ppm): 151.7, 138.1, 134.5, 134.3, 131.1, 130.7, 128.3, 128.2, 128.0, 127.8, 127.5, 127.2, 126.6, 126.1, 115.3, 114.7, 34.8, 31.2, 20.1, 13.9. HRMS: Calcd. for C₄₁H₃₇N₃S: 606.2937 [M + H]$^+$; Found: 606.2937. Anal. Calcd. for C₄₁H₃₇N₃S: C, 81.28; H, 6.49; N, 6.94. Found: C, 81.43; H, 6.46; N, 6.91.
at 120 °C for 24 h under a nitrogen atmosphere. After cooling to room temperature, the reaction mixture was poured into ice water and filtered to obtain a white solid. The crude product was purified by silica gel chromatography using dichloromethane/petroleum ether (1:1, v/v) to obtain a pale white solid (2.15 g, 70%). m. p. > 250 °C. 1H NMR (500 MHz, CDCl₃, δ, ppm): 7.57 (d, J = 7.1 Hz, 3H, Ar–H), 7.39 (d, J = 8.6 Hz, 2H, Ar–H), 7.32 (d, J = 8.7 Hz, 3H, Ar–H), 7.28 (d, J = 8.6 Hz, 5H, Ar–H), 7.25 – 7.14 (m, 12H, Ar–H), 7.11 (d, J = 7.8 Hz, 3H, Ar–H), 7.00 (s, 2H, Ar–H), 6.94 (d, J = 8.6 Hz, 3H, Ar–H), 6.61 (d, J = 8.7 Hz, 2H, Ar–H), 3.72 (t, J = 7.2 Hz, 2H, -N-CH₂–), 1.71 – 1.61 (m, 2H, -CH₂–), 1.43 – 1.36 (m, 2H, -CH₂–), 1.29 (s, 18H, -C(CH₃)₃), 0.91 (t, J = 7.5 Hz, 3H, -CH₃). 13C NMR (126 MHz, CDCl₃, δ, ppm): 168.3, 151.8, 147.2, 146.1, 144.4, 135.3, 134.3, 131.1, 130.7, 130.6, 128.6, 128.3, 128.1, 127.9, 127.8, 127.5, 127.3, 126.6, 126.1, 125.8, 123.9, 119.8, 114.5, 47.1, 34.7, 34.4, 31.4, 31.3, 28.7, 24.5, 20.0, 13.8. HRMS: Calcd. for C₆₆H₆₁N₅S, 956.4720 [M + H]⁺; Found: 956.4720. Anal. Calcd. for C₆₆H₆₁N₅S: C, 82.89; H, 6.43; N, 7.32. Found: C, 83.03; H, 6.45; N, 7.30.

Results and Discussion

Synthesis

The synthetic routes of PTZ-PIM and PIM-PTZ-PIM were shown in Scheme 1. These compounds were synthesized by a facile multicomponent reaction of the monoaldehyde or dialdehyde of 10-butyl-10H-phenothiazine with benzyl, 4-tert-butylaniline and ammonium acetate in acetic acid medium in good yields (70% yield), in which the key intermediates, 10-butyl-10H-phenothiazine-3-carbaldehyde and 10-butyl-10H-phenothiazine-3,7-dicarbaldehyde, were prepared through Vilsmeier-Haack formylation of...
10-butyl-10H-phenothiazine [35]. The final compounds PTZ-PIM and PIM-PTZ-PIM were purified on a silica gel column to obtain pure solid products, and were characterized by NMR (1H and 13C), high-resolution mass spectrometry and elemental analysis. Both compounds are soluble in common organic solvents, such as toluene, dichloromethane, chloroform, ethyl acetate, acetone, tetrahydrofuran and DMF.

### Photophysical, electrochemical properties and thermal stabilities of the compounds

Figure 1 shows the UV–vis absorption and photoluminescence (PL) spectra of PTZ-PIM and PIM-PTZ-PIM in dichloromethane solution (1.0×10⁻⁵ mol/L) and comparison of the photoluminescence spectra of PTZ-PIM and PIM-PTZ-PIM in solution and solid films, and the related data are listed in Table 1.

In their absorption spectra, the stronger absorption bands at 260 nm for PTZ-PIM and 272 nm for PIM-PTZ-PIM were attributed to the π–π* transitions of imidazole and the substituted benzene rings [35]. The moderately intense absorption bands located in the range of 280 – 360 nm could be the π–π* transitions of imidazole and the substituted benzene rings [38]. Compared with PTZ-PIM, the absorption spectrum of PIM-PTZ-PIM was red-shifted due to more conjugation of A–D–A type structure for PIM-PTZ-PIM than that of A–D type structure for PTZ-PIM. The optical absorption edges (λ_onset) of PTZ-PIM and PIM-PTZ-PIM in dichloromethane solution were estimated to be at ca. 443 nm and 461 nm, the corresponding optical band gaps of PTZ-PIM and PIM-PTZ-PIM were about 2.80 eV and 2.69 eV, respectively, from the equation: $E_{opt} = 1241/\lambda_{onset}$.

As shown in Fig. 1, PTZ-PIM and PIM-PTZ-PIM exhibited strong blue emission with a maximum peak at 459 nm and 476 nm in dilute chloromethane solution, while their PL spectra in thin solid films were obviously blue-shifted, and the maximum emission peaks of PTZ-PIM and PIM-PTZ-PIM in thin solid films were observed at 443 nm and 469 nm, respectively. The presence of the butterfly conformational PTZ core and the twisted 1,4,5-triphenylimidazole units in PTZ-PIM and PIM-PTZ-PIM could efficiently limit π-conjugation and inhibit the intermolecular aggregations, which could cause the blue-shifts of their PL spectra in thin solid films than that in dilute chloromethane solution. In addition, the fluorescence quantum yields (Φ_f) of PTZ-PIM and PIM-PTZ-PIM in dichloromethane solutions (1.0×10⁻⁶ mol/L) were measured to be 18.49% and 28.92%, respectively, at room temperature under air atmosphere, and their decay lifetimes (τ) were measured to be 5.6 and 5.8 ns, which belong to typical fluorescent materials.

In order to investigate the influence of solvent polarity on the PL spectra of the compounds, the steady-state fluorescence spectra of PTZ-PIM and PIM-PTZ-PIM were measured in different polar solvents (1.0×10⁻⁵ mol/L) (Fig. 2). Compared with the PL spectra of PTZ-PIM in different solvents, from low polarity toluene to high polarity DMF, the PL spectrum of PIM-PTZ-PIM in toluene, dichloromethane, tetrahydrofuran and dimethylformamide exhibits obvious solvatochromic effects, and the emission band of PIM-PTZ-PIM is obviously red-shifted from 452 nm in toluene to 477 nm in DMF, and the total redshift of 25 nm was observed. For PTZ-PIM, its emission peak is located at 452 nm in toluene and red-shifted to 458 nm in DMF. As the solvent polarity increases, the emission peak of PTZ-PIM was only red-shifted 8 nm. The results were indicated that PIM-PTZ-PIM has a more obvious charge transfer characteristic.

Figure 3 shows the PL spectra of PTZ-PIM and PIM-PTZ-PIM at different concentrations (1.0×10⁻⁷ – 1.0×10⁻³ mol/L) in dichloromethane solution. When the concentrations of PTZ-PIM and PIM-PTZ-PIM were lower than 1.0×10⁻⁷ mol/L and higher than 1.0×10⁻³ mol/L, the emission bands of

### Table 1 Photophysical, thermal and electrochemical properties of the compounds

| Compound       | λ_(UV-vis) (nm) | λ_(PL) (nm) | T_g (°C) | T_a (°C) | Φ_f (%) | τ (ns) | $E_{OX}$ (V) | $E_{opt}$ (eV) | HOMO/LUMO (eV) |
|----------------|----------------|-------------|----------|----------|---------|--------|-------------|--------------|---------------|
| PTZ-PIM        | 260, 291, 319, 375 | 459/443     | 365      | 226      | 18.49   | 5.6    | 1.11        | 2.80         | -5.39/-2.59   |
| PIM-PTZ-PIM    | 272, 323, 392   | 476/469     | 378      | 202      | 28.92   | 5.8    | 1.12        | 2.69         | -5.40/-2.71   |

*aMeasured in dichloromethane solution. *bMeasured in thin solid films.
the compounds were very weak. With the increase of the concentrations, the relative emission intensity of the compounds gradually increased. When the concentrations were $1.0 \times 10^{-5}$ mol/L, the relative emission intensity of the compounds reached the maximum. At higher than $1.0 \times 10^{-5}$ mol/L of their concentrations, the relative emission intensity of the compounds decreases owing to the intermolecular aggregation. Furthermore, at lower than $1.0 \times 10^{-3}$ mol/L, the emission spectra of the compounds did not significantly change within the entire range of the concentration changes.

The thermal stabilities of PTZ-PIM and PIM-PTZ-PIM were measured by thermogravimetric and differential thermal analyses (TG–DTA) under nitrogen atmosphere (Fig. 4). As shown in Fig. 4, PTZ-PIM and PIM-PTZ-PIM show excellent thermal stability, and they exhibit higher thermal decomposition temperatures (corresponding to a 5% weight loss) of 365 °C for PTZ-PIM and 378 °C for PIM-PTZ-PIM. From their differential thermal analyses, their glass transition temperatures are 226 °C and 202 °C, respectively.

The electrochemical properties of PTZ-PIM and PIM-PTZ-PIM were investigated by cyclic voltammetry. The cyclic voltammograms of the compounds are shown in Fig. 5. The first oxidation potentials ($E_{\text{OX}}$) of PTZ-PIM and PIM-PTZ-PIM were about 1.11 and 1.12 V, respectively. Under the same condition, the measured Fe/Fc$^+$ potential was 0.52 V. Thus, the HOMO energy levels of PTZ-PIM and PIM-PTZ-PIM were calculated.
Theoretical Calculation

The optimized molecular geometries and the HOMO and LUMO density maps of PTZ-PIM and PIM-PTZ-PIM were calculated by the density functional theory (DFT) calculation at B3LYP/6-31G(d) level (Fig. 6). From their optimized molecular geometries, it was found that these compounds exhibit a highly distorted configuration, which could effectively inhibit the intermolecular aggregations and weaken the π-π intermolecular interactions. For PTZ-PIM, the dihedral angles of 17.0° between the imidazole ring and the adjacent benzene ring of the phenothiazine unit, 40.1° between the benzene ring substituted at the N-1 position of the imidazole ring and the imidazole ring, and 24.9° and 3.3° between the benzene rings substituted at the 4-position and 5-position of the imidazole ring and the imidazole ring were observed, respectively. For PIM-PTZ-PIM, the dihedral angles between the imidazole rings and the adjacent benzene rings of the phenothiazine unit, between the benzene rings substituted at the N-1 position of the imidazole rings and the imidazole rings, and between the benzene rings substituted at the 4-position and 5-position of the imidazole rings and the
imidazole rings were $7.3(7.5)^\circ$, $37.7(40.5)^\circ$, $26.9(24.9)^\circ$ and $1.7(2.2)^\circ$, respectively. From their electron distributions of the molecular orbitals, the electron distributions in their HOMOs are almost centralized on the whole molecules except for the benzene rings at the N-1 position of the imidazole rings, and the electron distributions are somewhat more abundant on the phenothiazine cores. In their LUMOs, the electron distributions are concentrated in the whole molecules, but the majority of electron densities distributed on 1,4,5-triphenylimidazole units, and only a small part of them located on the phenothiazine cores. In addition, the calculated HOMO/LUMO energy levels of PTZ-PIM and PIM-PTZ-PIM are -4.37/-1.34 and -4.26/-1.45 eV, respectively.

The data of photophysical, electrochemical and thermal properties of PTZ-PIM and PIM-PTZ-PIM are listed in Table 1.

**Electroluminescence Investigation**

To investigate the electroluminescent properties of the compounds, the doped devices with a configuration as ITO/PEDOT:PSS (30 nm)/mCP:PTZ-PIM or PIM-PTZ-PIM (x wt%, 25 nm)/TPBi (35 nm)/Liq (2 nm)/Al (150 nm) were fabricated, in which the PEDOT:PSS (30 nm) layer and the emitting layer mCP:PTZ-PIM (x wt%, 25 nm) or PIM-PTZ-PIM (x wt%, 25 nm) were spin-coated, and other layers are made by evaporation. The device structure and the energy levels of the materials are depicted in Fig. 7.
Figures 8 and 9 show the current density–voltage–luminance (J–V–L) characteristics and current/power efficiency–luminance (CE/PE–L) curves of the devices fabricated from PTZ-PIM and PIM-PTZ-PIM at different concentrations, and the key performance parameters of their devices are summarized in Table 2.

The doped devices based on PTZ-PIM and PIM-PTZ-PIM exhibited the turn-on voltage from 5.6 to 6.4 V. Among the compounds, the device based on PIM-PTZ-PIM exhibited the best performances with a maximum current efficiency (CE\textsubscript{max}) of 2.45 cd/A, a maximum power efficiency (PE\textsubscript{max}) of 1.48 lm/W, a maximum brightness (L\textsubscript{max}) of 648 cd/m\textsuperscript{2} and a maximum external quantum efficiency (EQE\textsubscript{max}) of 1.48% at 15 wt% doping concentration. From Table 2, it was found that the devices based on PTZ-PIM showed poor EL performances in comparison to that of PIM-PTZ-PIM, which was consistent with the higher photoluminescence quantum yield of PIM-PTZ-PIM in solution than that of PTZ-PIM. The device based on PTZ-PIM exhibited the best EL performances with 1.37 cd/A of CE\textsubscript{max}, 0.68 lm/W of PE\textsubscript{max}, 638 cd/m\textsuperscript{2} of L\textsubscript{max} and 1.13% of EQE\textsubscript{max} at 20 wt% doping concentration.

### Table 2 EL performances of PTZ-PIM and PIM-PTZ-PIM

| Concentration | VO\textsubscript{el} (V) | EL\textsubscript{max} (nm) | L\textsubscript{max} (cd/m\textsuperscript{2}) | LE\textsubscript{max} (cd/A) | PE\textsubscript{max} (lm/W) | EQE\textsubscript{max} (%) |
|---------------|----------------|---------------------------|---------------------------------|-----------------|----------------|------------------------|
| **PTZ-PIM**   |                |                           |                                 |                 |                |                        |
| 5 wt%         | 6.4            | 449                       | 283                             | 0.44            | 0.19          | 0.36                   |
| 10 wt%        | 6.4            | 450                       | 348                             | 0.84            | 0.38          | 0.69                   |
| 15 wt%        | 6.0            | 452                       | 435                             | 0.78            | 0.39          | 0.64                   |
| 20 wt%        | 5.6            | 452                       | 638                             | 1.37            | 0.68          | 1.13                   |
| 25 wt%        | 5.5            | 455                       | 652                             | 1.29            | 0.47          | 0.90                   |
| **PIM-PTZ-PIM** |               |                           |                                 |                 |                |                        |
| 5 wt%         | 6.2            | 465                       | 404                             | 1.36            | 0.89          | 0.89                   |
| 10 wt%        | 6.4            | 469                       | 460                             | 2.26            | 1.44          | 1.44                   |
| 15 wt%        | 5.8            | 469                       | 648                             | 2.45            | 1.48          | 1.48                   |
| 20 wt%        | 5.8            | 470                       | 647                             | 1.91            | 1.24          | 1.24                   |
Conclusions

Two blue D–A fluorophores, PTZ-PIM and PIM-PTZ-PIM, were synthesized by grafting 1,4,5-triphenylimidazole moieties onto 3- and 3,7-position of the phenothiazine core and characterized by NMR, high-resolution mass spectrometry and elemental analysis. These compounds exhibit strong blue emission and good thermal stability. The doped devices based on PIM-PTZ-PIM had better EL performances than that of PTZ-PIM because of more conjugation of A–D–A type structure for PIM-PTZ-PIM than that of A–D type structure for PTZ-PIM, which was consistent with the higher photoluminescence quantum yield of PIM-PTZ-PIM in solution than that of PTZ-PIM. The doped device fabricated from PIM-PTZ-PIM exhibited a maximum brightness of 648 cd/m², a maximum current efficiency of 2.45 cd/A and a maximum external quantum efficiency of 1.48% at 15 wt% doping concentration.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant 61864005) and Innovation Star Project for Excellent Postgraduates in Gansu Province (2021CXZX-550).

Authors’ Contributions Tianzhi Yu developed the idea of the study, participated in its design and coordination and helped to draft the manuscript. Long Qian and Hongyan Yang contributed to the acquisition and interpretation of data. Yuling Zhao and Yongchun Guo did some testing works.

Funding This work was supported by the National Natural Science Foundation of China (Grant 61864005, from Tianzhi Yu) and Innovation Star Project for Excellent Postgraduates in Gansu Province (2021CXZX-550, from Long Qian).

Data Availability The authors confirm that the data supporting the findings of this study are available within the article.

Code Availability Not applicable.

Declarations

Ethics Approval Not applicable

Consent to Participate Not applicable

Consent for Publication Consent for publication was obtained from all participants.

Conflicts of Interest We declare that there are no conflicts of interest/competing interests.

References

1. Yang X, Ding LM (2021) Organic semiconductors: commercialization and market. J Semicond 42:090201
2. Pode R (2020) Organic light emitting diode devices: An energy efficient solid state lighting for applications. Renew Sust Energ Rev 133:110043
3. Sun N, Jiang CM, Li QK, Tan DC, Bi S, Song JH (2020) Performance of OLED under mechanical strain: a review. J Mater Sci: Mater Electron 31:20688–20729
4. Li W, Li YQ, Shen Y, Zhang YX, Jin TY, Chen JD, Zhang XH, Tang JX (2019) Releasing the trapped light for efficient silver nanowires-based white flexible organic light-emitting diodes. Adv Optical Mater 7:1900985
5. Chen HW, Lee JH, Lin BY, Chen S, Wu ST (2018) Liquid crystal display and organic light-emitting diode display: present status and future perspectives. Light: Sci. Appl 7:17168
6. Geffroy B, le Roy P, Prat C (2006) Organic light-emitting diode (OLED) technology: materials, devices and display technologies. Polym Int 55:572–582
7. Goushi K, Yoshida K, Sato K, Adachi C (2012) Organic light-emitting diodes employing efficient reverse intersystem crossing for triplet-to-singlet state conversion. Nat Photonics 6:253–258
8. Ouyama H, Goushi K, Shizu K, Nomura H, Adachi C (2012) Highly efficient organic light-emitting diodes from delayed fluorescence. Nature 492:234–238
9. Guo F, Karl A, Xue QF, Tam KC, Forberich K, Brabec CJ (2017) The fabrication of color-tunable organic light-emitting diode displays via solution processing. Light: Sci Appl 6:e17094
10. Nakanotani H, Higuchi T, Furukawa T, Masui K, Morimoto K, Numata M, Tanaka H, Sagara Y, Yasuda T, Adachi C (2014) High-efficiency organic light-emitting diodes with fluorescent emitters. Nat Commun 5:4016
11. Ying L, Ho CL, Wu HB, Cao Y, Wong WY (2014) White polymer light-emitting devices for solid-state lighting: materials, devices, and recent progress. Adv Mater 26:2459–2473
12. Yang XL, Xu XB, Zhou GJ (2015) Recent advances of the emitters for high performance deep-blue organic light-emitting diodes. J Mater Chem C 3:913–944
13. Fung MK, Li YQ, Liao LS (2016) Tandem organic light-emitting diodes. Adv Mater 28:10381–10408
14. Konidena RK, Lee JY (2019) Molecular design tactics for highly efficient thermally activated delayed fluorescence emitters for organic light emitting diodes. Chem Rev 19:1499–1517
15. Sun YR, Giebink NC, Kanno H, Ma BW, Thompson ME, Forrest SR (2006) Management of singlet and triplet excitons for efficient white organic light-emitting devices. Nature 440:908–912
16. Bian MY, Chen ZJ, Qu B, Xiao LX (2019) Highly efficient blue electroluminescent materials and devices with mesoscopic structures. Chem Rev 19:1562–1570
17. Wei Q, Fei NN, Islam A, Lei T, Hong L, Peng RX, Fan X, Chen L, Gao PQ, Ge ZY (2018) Small-molecule emitters with high quantum efficiency: mechanisms, structures, and applications in OLED devices. Adv Optical Mater 6:1800512
18. Yang ZY, Mao Z, Xie ZL, Zhang Y, Liu SW, Zhao J, Xu JR, Chi ZZ, Aldred MP (2017) Recent advances in organic thermally activated delayed fluorescence materials. Chem Soc Rev 46:915–1016
19. Im Y, Byun SY, Kim JH, Lee DR, Oh CS, Yook KS, Lee JY (2017) Recent progress in high-efficiency blue-light-emitting materials for organic light-emitting diodes. Adv Funct Mater 27:1603007
20. Zou JH, Liu J, Wu HB, Yang W, Peng JB, Cao Y (2009) High-efficiency and good color quality white light-emitting devices based on polymer blend. Org Electron 10:843–848
21. Xue SF, Yao L, Shen FZ, Gu C, Wu HB, Ma YG (2012) Highly efficient and fully solution-processed white electroluminescence based on fluorescent small molecules and a polar conjugated polymer as the electron-injection material. Adv Funct Mater 22:1092–1097
22. Li CS, Nobuyasu RS, Wang YK, Dias FB, Ren ZJ, Bryce MR, Yan SK (2017) Solution-processable thermally activated delayed fluorescence white OLEDs based on dual-emission polymers with tunable emission colors and aggregation-enhanced emission properties. Adv Optical Mater 5:1700435

23. Wang YJ, Zhu YH, Xie GH, Zhan HM, Yang CL, Cheng YX (2017) Bright white electroluminescence from a single polymer containing a thermally activated delayed fluorescence unit and a solution-processed orange OLED approaching 20% external quantum efficiency. J Mater Chem C 5:10715–10720

24. Liu H, Liu FT, Lu P (2020) Multiple strategies towards high-efficiency white organic light-emitting diodes by the vacuum deposition method. J Mater Chem C 8:5636–5661

25. Ban XX, Chen F, Zhao YQ, Zhu AY, Tong ZW, Jiang W, Sun YM (2018) Strategy for the realization of highly efficient solution-processed all-fluorescence white OLEDs-encapsulated thermally activated delayed fluorescent yellow emitters. ACS Appl Mater Interfaces 10:37335–37344

26. Huang J, Xu Z, Cai ZY, Guo JJ, Guo JL, Shen PC, Wang ZM, Zhao ZJ, Ma DG, Tang BZ (2019) Robust luminescent small molecules with aggregation-induced delayed fluorescence for efficient solution-processed OLEDs. J Mater Chem C 7:330–339

27. Liao QX, Yang X, Zhang R, Cheng J, Li J, Chen SY, Zhu J, Li L (2017) Solution-processed small-molecular white organic light-emitting diodes based on a thermally activated delayed fluorescence dendrimer. J Mater Chem C 5:10001–10006

28. Gangadharg PS, Reddy G, Prasanthkumar S, Giribabu L (2021) Phosphine functional materials for organic optoelectronic applications. Phys Chem Chem Phys 23:14969–14996

29. Al-Ghamdi SN, Al-Ghamdi HA, El-Shishtawy RM, Asiri AM (2021) Advances in phenothiazine and phenoxazine-based electron donors for organic dye-sensitized solar cells. Dyes Pigments 194:109638

30. Onoabedje EA, Egu SA, Ezekonkwo MA, Okoro UC (2019) Highlights of molecular structures and applications of phenothiazine & phenoxazine polycycles. J Mol Struct 1175:956–962

31. Al-Busaidi II, Haque A, Al Rasbi NK, Khan MS (2019) Phenothiazine-based derivatives for optoelectronic applications: A review. Synth Met 257:116189

32. Revoju S, Matuahina A, Canil L, Salonen H, Hiltunen A, Abate A, Vivo P (2020) Structure-induced optoelectronic properties of phenothiazine-based materials. J Mater Chem C 8:15486–15506

33. Kwon TW, Kulkarni AP, Jenekhe SA (2008) Synthesis of new light-emitting donor–acceptor materials: Isomers of phenothiazine–quinoline molecules. Synth Met 158:292–298

34. Ahn S, Cha YB, Kim M, Ahn KH, Kim YC (2015) Synthesis, characterization, and electroluminescence properties of a donor–acceptor type molecule for highly efficient non-doped green organic light-emitting diodes. Synth Met 199:8–13

35. Zhao YL, Yang HY, Ma HL, Li YM, Qian L, Yu TZ, Su WM (2020) Photo- and electro-luminescence properties of the organic bipolar molecules containing phenothiazine and phenanthroimidazole moieties. Synth Met 265:116406

36. Li WJ, Yao L, Liu HC, Wang ZM, Zhang ST, Xiao R, Zhang HH, Lu P, Yang B, Ma YG (2014) Highly efficient deep-blue OLED with an extraordinarily narrow FHWM of 35 nm and a y coordinate < 0.05 based on a fully twisting donor–acceptor molecule. J Mater Chem C 2:4733–4736

37. Fan SG, You J, Miao YQ, Wang H, Bai QY, Liu XC, Li XG, Wang SR (2016) A bipolar emitting material for high efficient non-doped fluorescent organic light-emitting diode approaching standard deep blue. Dyes Pigments 129:34–42

38. Gao Z, Wang ZM, Shan T, Liu YL, Shen FZ, Pan YY, Zhang HH, He X, Lu P, Yang B, Ma YG (2014) High-efficiency deep blue fluorescence emitters based on phenanthro[9,10-d] imidazole substituted carbazole and their applications in organic light emitting diodes. Org Electron 15:2667–2676

39. Cardona CM, Li W, Kaifer AE, Stockdale D, Bazan GC (2011) Electrochemical considerations for determining absolute frontier orbital energy levels of conjugated polymers for solar cell applications. Adv Mater 23:2367–2371

40. Yu TZ, Zhu ZY, Bao YJ, Zhao YL, Liu XX, Zhang H (2017) Investigation of novel carbazole-functionalized coumarin derivatives as organic luminescent materials. Dyes Pigments 147:260–269

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.