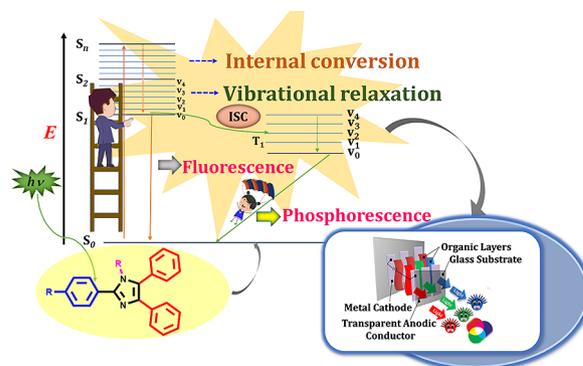


A Review on the Milestones of Blue Light-Emitting Materials in India

Nisha Odedara^a
 Niteen Borane^a
 Rahul Patel^a
 Rajamouli Boddula^{a*}

^a Tarsadia Institute of Chemical Science (TICS), Uka Tarsadia University, Bardoli – 394 350, Gujarat, India

* rajamouliboddula@gmail.com



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Abstract Since 1987 in the field of optoelectronics, organic light-emitting diodes (OLEDs) have secured their position because of their extreme use in panels of lighting applications such as TV and smartphone displays. At present, OLEDs are at top-notch position in the lighting market for their promising features. The field of OLEDs is rapidly growing day by day in academia and industry due to the success of OLEDs in the form of excellent efficiency, feasible methods, excellent lifetime, color purity, and superb device architecture. As a result, OLEDs are new profitable leading devices of the 21st century. However, the OLED industry has evolved in optoelectronics in the last 30 years and is advancing rapidly just because of the development in OLED materials (fluorescent, phosphorescent, thermally activated delayed fluorescent, and blue light-emitting materials). Blue light-emitting materials have achieved incredible popularity nationally and internationally. At the international level, USA, Japan, Korea, and Germany are at the top of the list in the production of OLEDs. India has also seen rapid progress in OLED development in the last 12 years and details of research in blue OLEDs by key players of India are involved in this report.

- 1 Introduction
- 1.1 OLED Construction
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- 4 Present Scenario of Blue OLEDs
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Key words: optoelectronics, blue emitters, organic materials

1 Introduction

In the field of optoelectronics, organic light-emitting diodes (OLEDs) have gained lots of attention due to their potential applications in electrical displays for lighting applications. The fact is that over the past 30 years, the OLED industry has expanded rapidly and so it is a leading technology today. In addition, as a result, the research in optoelectronics has achieved a high peak in the fields of academia and industry. OLEDs also offer new sustainable techniques for lighting and displays. An active research has led to the use of smart OLED devices as a versatile SSL (solid-state lighting) source for smart lighting devices. OLEDs have been in focus in recent years and offer some great features that make them superior to well-known and established technologies such as liquid crystal displays (LCDs). For example, an OLED device does not require a backlight as its pixels produce light, so it is called a self-emissive device. However, in LEDs, screens use a backlight to radiate pixels.¹ In addition, OLEDs are considered ideal devices as they do not consume power. It permits “actual (true) black” and thinner and lighter displays. Moreover, experimental research has proven that OLEDs show high efficiency, good resolution, and a broad viewing angle. Additionally, the flexibility of the display is its extra feather, so that it can be bendable and foldable like a roll paper, which opens a new door to feasible designing.² However, OLEDs are not completely perfect and the drawback is their material and device structure. First of all, most of the materials used in OLEDs are highly cost-effective, but modifying the device structure can minimize the cost and has the potential to be even cheaper than LCDs. Due to their continuous progress, currently there are almost very limited issues remaining regarding OLEDs. Another major issue is the short lifetime and the reason for that is the reduction of the driving voltage. This has been observed especially in blue OLEDs, as they have shorter lifetimes as compared with red and green OLED devices but sufficient enough to provide better

Bio sketches



Nisha Odedara received her B.Sc. degree from B. P. Baria Science college, Navsari, Gujarat, and her M.Sc. degree from V. S. Patel Arts and Science College, Bilimora, Gujarat. She joined our group as a Ph.D. Student in December 2019 at the Tarsadia Institute of Chemical Science, Uka Tarsadia University, Bardoli, Surat, Gujarat. Currently, she is working on synthesis and photophysical properties of bipolar blue fluorophores for organic light-emitting diode.



Niteen Borane received his B.Sc. degree from Gajamal Tulshiram Patil (GTP) College Nandurbar (North Maharashtra University, Jalgaon), Maharashtra, and his M.Sc. degree from the School of Chemical Sciences, North Maharashtra University, Jalgaon, Maharashtra. He joined Dr. Rajamouli Boddula's Optoelectronic material group as a Ph.D. scholar in 2020 at the Tarsadia Institute of Chemical Science, Uka Tarsadia University, Bardoli, Surat, Gujarat. Currently, he is working on the synthesis of novel bipolar antenna-based ligand-modified hybrid nanostructured graphene/carbon for optoelectronics.



Rahul Patel received his B.Sc. degree from Government College Daman, Daman, India, and his M.Sc. degree at the Tarsadia Institute of Chemical Science, Uka Tarsadia University, Bardoli, Surat, Gujarat.



Dr. Rajamouli Boddula has been an Assistant Professor at the Tarsadia Institute of Chemical Science, Uka Tarsadia University, Gujarat, India since 2017. Dr. Rajamouli was born and brought up in Telangana. He completed his Master's in Chemistry (Organic) in Andhra University, Andhra Pradesh in 2010. He received his Ph.D. in chemistry from the National Institute of Technology, Rourkela, India in 2017 where he focused on lanthanide materials for organic light-emitting diodes, theoretical calculations, and sensing phenomena. Then Dr. Rajamouli worked as a Postdoctoral Research Associate at CSIR-Indian Institute of Chemical Technology (IICT), Hyderabad, India in 2021, where he focused on peptide molecules for optoelectronics, aggregation, and mechanoluminescence. He was then a Postdoctoral Fellow at Konkuk University, South Korea in 2022, where he worked on solid-state materials and microfluidics. Rajamouli joined the company GVK BioSciences in 2011 as a Senior Chemist, where he worked on the synthesis of drug molecules in the R&D department. His honors and awards include recognition as a Young Scientist Award, outstanding achievement award, best oral, best poster awards, and certificate of appreciation. Dr. Rajamouli is a life member of a professional body. His research interest lies in the areas of organic photonics and electronics, the AIE-ACQ phenomenon, mechanoluminescence, and theoretical calculations (DFT).

resolution and efficiency.³ In addition, sometimes devices also encounter issues regarding thermal stability and this will remain an open challenge for scientists to do further research.

1.1 OLED construction

OLEDs have multiple thin layers of organic materials (Figure 1). When a current is applied to the anode, light is emitted from the surface by a process called electrophosphorescence. OLEDs work on the principle of electroluminescence (EL) and this can only happen in multilayer OLED devices.⁴ There are many thin and functional layers sand-

wiched between the electrodes in this multilayer device. The details of the layers are explained below:

1. **Substrate layer:** This is a transparent, thin conductive layer of sheet of glass made of clear plastic or foil.
2. **Anode layer:** This layer attracts the electrons in the active layer. When a current passes through the device, holes take place in the room of electrons. This layer is also known as the transport layer as thin layers are deposited onto the anode surface.
3. **Conductive layer:** A layer from where the hole starts moving is known as a conductive layer, which is an important part of the OLED device structure. This layer is made up of polymers, where the polymers act as emitting diodes. Besides organic plastics, derivatives of *p*-phenylene vinylene and polystyrene are also used to construct this layer. Generally, polyaniline is used in OLEDs as a conductive layer. This layer is also known as an electroluminescent layer.
4. **Emissive layer:** Electron transports from the anode through this layer, and it is slightly different from the conductive layer. This layer is also made up of organic plastic molecules. In addition, these molecules consist of some polyfluorene and poly-*p*-phenylene processing variables which normally emit green and blue light. To conduct electricity, the layer is further coated with a special organic molecule.
5. **Cathode layer:** Electrons are injected into this layer when current passes through the device. Calcium, aluminum, and magnesium are used to construct this layer.

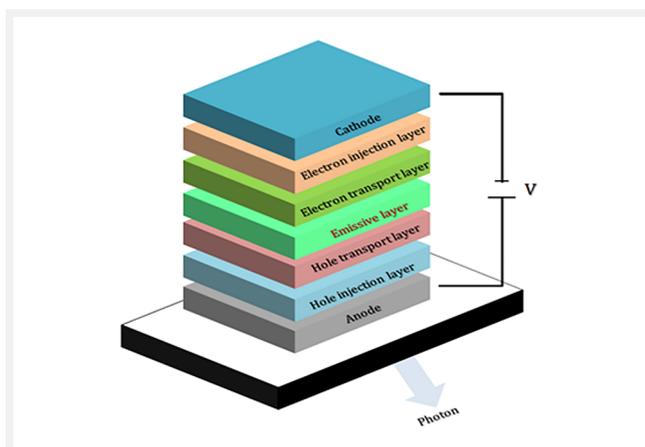


Figure 1 An OLED device structure.

1.2 Working of OLEDs

To conduct electricity, the emissive and conductive layers play an important part in the whole device structure. Usually, special organic molecules are used in these two layers to

function properly. Other than this, anodes and cathodes are used to connect OLEDs as they are the main source of electrons. Generally, anodes and cathodes are used to connect OLEDs, and the main source of device operation is electricity.⁵

The emissive layer becomes more negatively charged and the conductive layer becomes more positively charged when electricity is applied to the OLED. The emissive layer captures the electron flow which is withdrawn by the conducting layer, and so, the hole flow increases. Just because of the electrostatic force, holes and electrons start combining as the holes are more mobile than the electrons. This process emits light near the emissive layer and it can emit light with a particular frequency in the visible region (Figure 2).

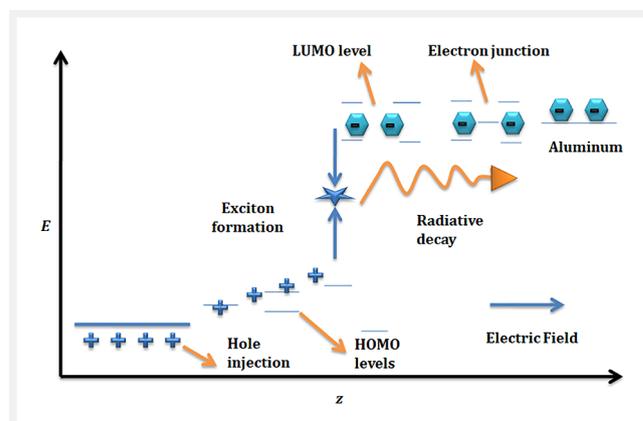


Figure 2 Working principle of an OLED.

2 OLED Development

The progress in the world of OLEDs is mounted on “various generations.” For more than 30 years, the OLED technology has evolved in optoelectronics and it has advanced because of generation-based OLED materials. The “fluorescent emitters” are known as the first generation, whereas “phosphorescent emitters” are considered as the second generation, and the third generation leans on light-emitting TADF (thermally activated delayed fluorescence) emitters. Later on, “next-generation (blue light-emitting diodes)” OLED emitters were introduced to the market after successfully and firmly establishing the three generations for a long time. These generations are further divided into RGB (red, green, blue) colors – for example, green, orange-red and blue emitters – which play a crucial role in color purity and high efficiency in OLED devices. As per most of the reported values, the color of the OLED is defined by the EL wavelength of the emitter.⁶ However, for better stability and cost-effectiveness, the blue OLED is in great demand because it is a complementary color of white and the OLED that emits white light is

brighter in color than the rest of the uniform color. By considering this fact, the Commission Internationale de l'Éclairage (CIE) set some criteria, such as (x, y) must be $(0.33, 0.33)$ for white color resolution.⁷ As these coordinates are important to achieve for a desired color for display applications, they have been therefore added to most of the research interests in OLEDs. As a reason, we can say that blue emitters have strongly affected the foundation of OLEDs in recent years. The required CIE coordinates for blue OLEDs are (x, y) $(0.15, 0.06)$ as defined by the National Television Standards Committee.⁸ As per the demand nowadays, different devices or a series of emitters with blue colors are introduced in OLEDs. Despite this, the device must have the highest external quantum efficiency (EQE), which will give future direction for the best applications in the field of lighting applications.⁹

2.1 Historical Background of OLEDs

Eosin was the first organic TADF material found in early 1960 that was able to emit light and this was the initial starting period of research in the field of OLED technology. Many other simple organic compounds with fluorescence were known but their low efficiency and color purity were the issues. In 1987, the first OLED was reported by Tang et al., which was the breakthrough in OLED technology.¹⁰ Since then, continuous research studies have been undertaken in the fields of academia and industry. In 1988, Kyushu University's research panel introduced a double heterojunction-based OLED.¹¹ Following the work in 1990, the first OLED based on polymer materials was introduced by scientist Burroughs from Cambridge University. Many years later, a commercial OLED was successfully developed by Pioneer and was applied to car audio systems.¹² In the middle of 2002, Phillips introduced the first commercial OLED to the market.¹³ AMOLEDs (active-matrix OLEDs) were the first full-color active-matrix device. It was the result of a commercial manufacturing partnership between Eastman Kodak and Sanyo Electric Company. In 2003, Kodak introduced the first AMOLED digital camera (LS633).¹⁴ In 2005, Sony announced the XEL-1, the first ever OLED TV (11").¹⁵ National Tsing-Hwa University, Taiwan was the first to demonstrate the sunlight-style OLED, which was introduced to the market in 2009.¹⁶ In the early 2011, LG announced their 55" OLED TV prototype, and in the same year, OSRAM developed the world's most efficient, flexible white OLED.¹⁷ Two years later, LG Chem started producing 320×320 mm OLED lighting panels (BMW's M4 GTS) with its OLED tail lights. In the same year, Samsung announced the galaxy S6 and the S6 Edge and also its R&D research panel introduced the first bendable devices.¹⁸ Even an immensely rollable TV was introduced by LG in 2020. Recently, people were fascinated by new inventive designs of foldable gadgets such as Samsung (Galaxy fold)

phones, foldable Lenovo laptops, smart iPhone devices, and Intel (ThinkPad XI Fold) devices, which have gained much attention from the market (Figure 3).¹⁹

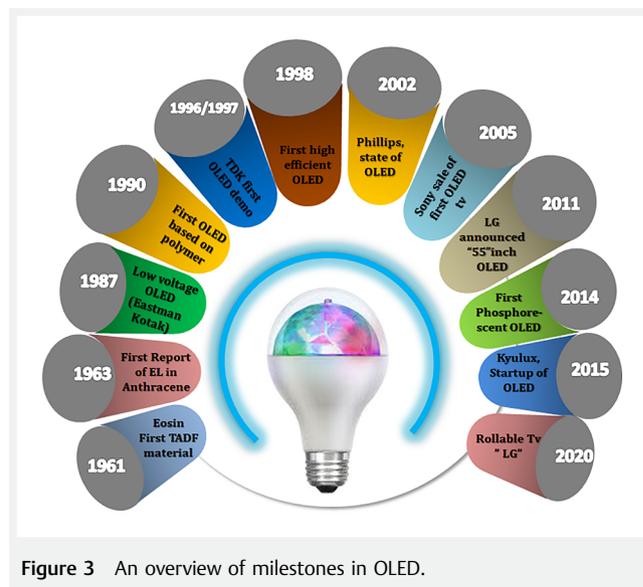


Figure 3 An overview of milestones in OLED.

2.1.1 International Status

To enhance the efficiency of OLEDs, tremendous work is going on at the international level in companies and academic research groups and they are doing work on their toes to reach new heights in OLED technology. As we know earlier in 2021, CYONARA launched cyBlueBooster as a blue emitter which has efficiency close to about 15%.²⁰ Within a short period of time, they assured the world to deliver a hyper-fluorescence yellow emitting material with a smart chip inside.²¹ The estimated income from OLED devices through the market in 2020 was 34.3 billion USD and it is believed that it will reach around 52 billion USD by 2023.²² Some of the major players in the OLED market are Samsung, LG Display Co. Ltd., Panasonic Corporation, and Tohoku Pioneer Corporation.²³ It has been seen that companies and academia both have been taking the same interest in OLED technology. For example, Cambridge Display Technology Inc., Dresden Microdisplay, and CYNORA GmbH (Karlsruhe Institute of Technology) are taking a prominent interest in the OLED technology.²⁴ As these universities have corroboration with companies, in 2007 the Sumitomo Chemical Group invested 285 million USD and CHIEL (which is now a part of Samsung) invested 260 million Euro on Novaled in 2013.²⁵ Other than investment, thousands of patents and papers have been reported up until 2019. This strong bond between academia and industry is increasing day by day and as a result, they organize regular meet-ups, workshops, and international conferences on OLED technology. Therefore, the investment from both sides led the OLED display technology to achieve

newer heights and hence proves the constant growth in the lighting field.

2.1.2 National Status

In the area of OLEDs, our nation was not previously focusing on targeted molecules and established device architectures to achieve highly efficient emitters. However, in the last 5 years, research has been conducted on a serious note in the OLED field. On this subject, a few research groups in India are working. To the best of our research knowledge, University of Delhi,²⁶ IISE Bangalore, NISER Bhubaneswar and J. Jayabharthi from Annamalai University²⁷ and J. Tagare²⁸ from NIT Rourkela have been involved in this topic with various luminogenic molecules with collaborating research in organic light-emitting device fabrication and characterization. The work reported in OLEDs was based on red, blue, and green OLEDs. As we discussed the scenario of OLEDs nationally and internationally, as compared with international development, India is somehow lacking in certain aspects. The reason behind this is less awareness about OLED technology, lack of communication between academia and industry, improper facilities, and most importantly lack of investment funding. So, here we briefly introduce the development of OLEDs which has been made to date. Our motto is to give a glance at OLEDs to create more awareness so that industry and academia can close the gap of communication between them. Here, we are only giving information regarding published works done by academia and industry to date to get an exact idea regarding their further research work in light technology. Besides this, we have only focused on the development of blue emitters known as the “next generation”.²⁹ As discussed earlier in the Introduction part, the materials play a crucial role in color purity and efficiency. If we talk about color purity, the blue color emitter is in great demand. As these types of devices have excellent color purity and a long lifetime as compared to other generations, so, here we are just sharing the progress of the blue OLED light-emitting devices in the past 10 years.

3 Progress of Blue Light Emitters in India

In 2014, Karthik et al. published their work on triplet–triplet fluorescence (TTF) pyrene-benzimidazole deep blue emitting dopants (PyPIC1–PyPIC5) (Figure 4) with different π linkers, for example, phenyl, thiophene, and triphenylamine. All the emitters displayed deep blue emissions due to the pronounced intramolecular charge transfer from the donor to the acceptor. The device fabricated by PyPIC2 as an emitter was capable enough to give blue light emission. In addition, it gives the maximum luminance of 714 cd/m², EQE 1.5%, CIE coordinates of (0.16, 0.05) at 100 cd/m² and 100% color saturation. All the dye probes showed a high

thermal decomposition at around $\geq 470^\circ\text{C}$, which indicates good thermal properties the emitters have.³⁰

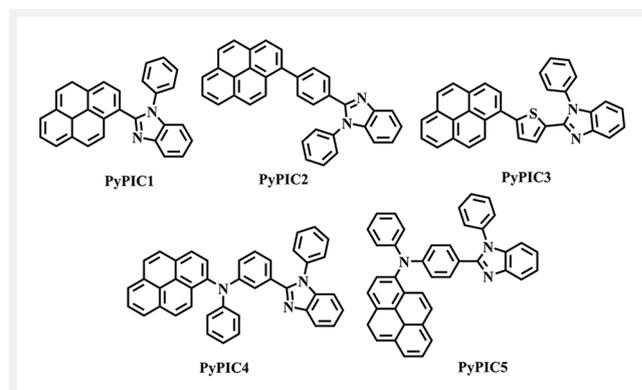


Figure 4 Pyrene-benzimidazole deep blue emitting dopants.

After 3 years in 2015, Kumar and Patil reported a potential application and synthesis of two-electron transporting blue emitting materials such as TPFDP SO₂ and TPFDBTO₂ (Figure 5). These two fluoranthene-based materials were capable enough to fulfill several requirements used in OLEDs just because of their suitable electronic structure. These materials exhibit excellent thermal stability with distinct decomposition due to their rigid backbone structure. Also, these devices have high glass transition temperatures, which improve the stability and durability of the device. As result, it has been observed that these devices give nearly five times better device performances as compared to their parent sulfide molecules. These molecules were used to fabricate the electroluminescent devices and displayed bright sky-blue color emissions at 460 and 454 nm with efficiencies of 0.50% and 0.61%, respectively.³¹

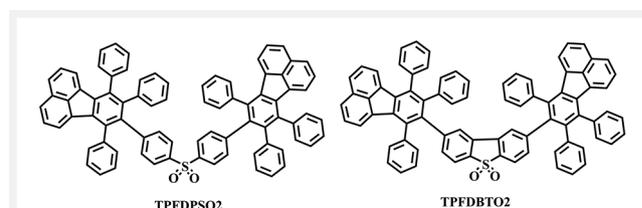


Figure 5 Blue emitting materials TPFDP SO₂ and TPFDBTO₂.

In the same year, Dahule et al. synthesized a DPQ (blue light-emitting 2,4-diphenylquinoline)-substituted blue light-emitting organic moieties such as OMe-DPQ, M-DPQ, and Br-DPQ (Figure 6). These developed molecules are in very low molecular weight, however, capable to improve the stability and operating lifetime of an OLED device. Electroluminescence behavior was studied for Br-DPQ phosphor. The resultant data characteristic curve revealed that EL begins at 400, which indicates the brightness of the OLED. The

brightness increases exponentially with applied AC voltage, and the turn-on voltage of the fabricated device was 11 V. So, the demonstrated compounds were capable enough to show a bright light blue emission in the wavelength range of 405–450 nm in the solid state. So, this phosphor can be used as a promising blue light material for electroluminescent devices.³²

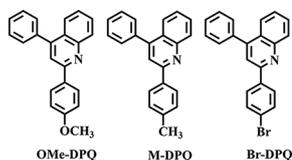


Figure 6 Organic phosphors OMe-DPQ, M-DPQ and Br-DPQ.

Again, the same group of Kumar gave their devotion to develop TPFDPs and TPFDBT fluoranthene molecules (Figure 7). Among the two, one of the molecules, TPFDPs, exhibited a high T_g of around 210 °C. The thermal stability of the compound was found to be up to 500 °C. Besides this, the synthesized molecule, TBADN, was fabricated on the device to reveal the various applications as an electron transporting layer. The EQEs of the electron transporting materials TPFDPs and TPFDBT were found to be 0.04% and 0.40%, respectively. Both the fluorophores showed blue emission maxima at 466 and 458 nm.³³

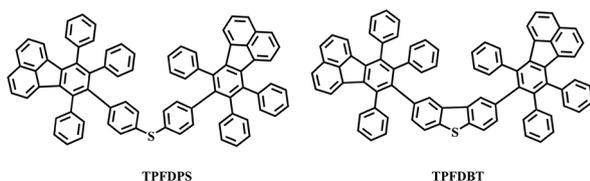
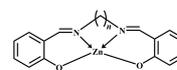


Figure 7 Fluoranthene TPFDPs and TPFDBT derivatives.

In addition to Zinc-based complexes, Nishal et al. developed five Schiff bases: Zn(salen), Zn(salpen), Zn(salbutene), Zn(salhexene), and Zn(salheptene) (Figure 8). These ligands exhibited excellent thermal stability and gave blue luminescence (430–450 nm), which can be easily used for making white light for display applications. But this material did not prove to be a good efficient device.³⁴

Blue polymeric OLEDs can be significantly used for primary color display applications and for white light illumination. But after the investigation, Gupta and his team concluded that only some of the diodes show low efficiency and the reason behind this was a large band gap as it involves high energy for the desired emission. By considering this fact, they reported the polyfluorene-based polymer poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)



$n=2$, Bis(salicylidene)ethylene-1,2-diaminotzinc(II) [Zn(salen)]
 $n=3$, Bis(salicylidene)propylene-1,3-diaminotzinc(II) [Zn(salpen)]
 $n=4$, Bis(salicylidene)butylene-1,4-diaminotzinc(II) [Zn(salbutene)]
 $n=6$, Bis(salicylidene)hexylene-1,6-diaminotzinc(II) [Zn(salhexene)]
 $n=7$, Bis(salicylidene)heptylene-1,7-diaminotzinc(II) [Zn(salheptene)]

Figure 8 Schiff base ligands such as Zn(salen), Zn(salpen), Zn(salbutene), Zn(salhexene) and Zn(salheptene).

and it was used as a blue emitter. The emissive layer of the device was made up of polyfluorene and the hole transport layer was fabricated by a titanium dioxide-based nanocomposite. It has been observed that if the TiO₂ concentration increases in the hole transport layer, a blue peak extends up to 430 nm and the turn-on voltage of the device also increases. So, the final optimized concentration for the titanium dioxide was 15 wt% for this proficient device. For the performances of TiO₂ with different concentrations see Tables 1 and 2.³⁵

Table 1 Doping % of TiO₂ in PEDOT:PSS derivative

Device	% of TiO ₂ in PEDOT:PSS
1	0
2	5
3	10
4	15
5	20

Table 2 Performance of the device

Device	Doping % of TiO ₂ in PEDOT:PSS	Operating voltage (V) @100 cd/m ³	Current efficiency (cd/A) @6 V
1	0	12.6	0.76
2	5	11.5	1.35
3	10	10.9	4.32
4	15	9.2	6.53
5	20	9.6	7.30

Lakshmanan et al. synthesized three fluorophores named ELC₁, ELC₂ and ELC₃ (Figure 9), which were used as electron transporting or electroluminescent materials. All three compounds have good photophysical and thermal properties. As per their UV spectra, the excitation band was found at 240 and 330 nm, and the photoluminescence spectra were observed at 385, 405, and 440 nm. Among these three, the fluorescence lifetimes of ELC₁ and ELC₂ were found to be around 0.35 and 1.55 and for ELC₃ it was 0.29. The calculated value was enhanced from 5.96 (C-1) to 6.08 (C-3) eV. Hence, it was confirmed that ELC₃ is more electron-donating in nature.³⁶ At the same time, Jadhav et al. successfully synthesized a novel phenanthroimidazole (PI)-substituted (Figure 10) de-

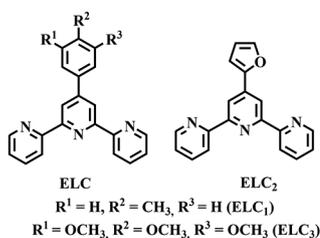


Figure 9 ELC₁, ELC₂, and ELC₃ fluorophores.

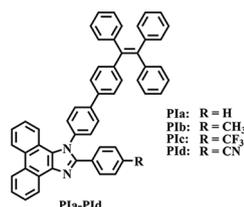


Figure 10 Phenanthroimidazole-substituted derivatives.

riative. As we all know that PI shows good thermal stability, they introduced a cyano group to PI to increase its thermal stability. The PI derivative exhibited very low emission in solution and a strong emission in the aggregated state because of the AIE (aggregation-induced emission). As per the mechanochromism, the colors observed for PI was blue and green. Also, the compounds performed very well as non-doped blue emitters PIc and PId in OLEDs, giving 3.9% and 4.0% EQEs, respectively.³⁷

The benzophenone moiety was represented as a prototype in the molecular system. Up until 2016, the molecule was only used in triplet-state chemistry. In the same year, Jhulki et al. designed three novel hosts: BP₂, BP₃, and BP₄ (Figure 11). These phosphorescent molecules contain benzophenone as an active triplet-sensitizing molecular component. They have the ability to use as a universal host material for blue phosphor, as the band gap observed for the molecules was 3.91–3.93 eV and also showed excellent triplet energies of 2.95–2.97 eV. Hence it has been proven that

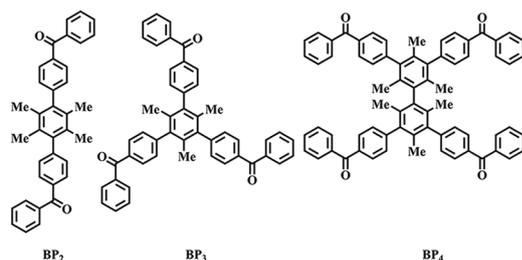


Figure 11 Host materials BP₂, BP₃ and BP₄.

they are an exceptional dopant. In addition, the efficiency obtained for the device was 17.0–19.2%, and the emission observed for blue light was at 389–410 nm. Among them, BP₂ was an excellent host and it was demonstrated as a proof by co-doping with the device.³⁸

Gandeepan et al. successfully produced blue TADF fluorescence emitters such as BPypC, BPypTC, BPyp2C, and BPyp3C (Figure 12). From the density functional theory (DFT) calculations, it was confirmed that the molecule showed their LUMOs on the benzopyridine moiety. Besides this, from the EL and photoluminescence (PL) properties, it was confirmed that BPyp3C acts as a very worthy TADF material. However, the energy gap value for BPypC observed was to be 0.29 eV and it decreased to 0.05 eV for BPyp3C. However, the maximum EQE of BPypC was 4.2% and it increased for BPyp3C at 23.9%. This signifies that the EQE of BPyp3C increased two times more than that of BPypC.³⁹

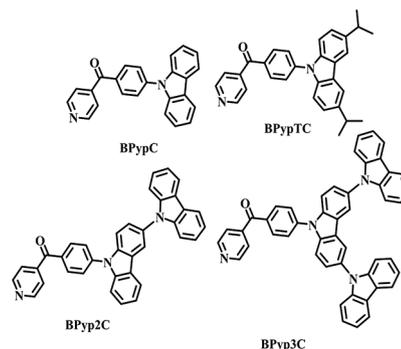


Figure 12 Fluorescence emitters BPypC, BPypTC, BPyp2C and BPyp3C.

Kumar et al. reported symmetrical and non-symmetrical fluoranthene derivatives (Figure 13) with different donor and acceptor moieties. These molecules showed a high PL quantum yield and exhibited deep blue emission in solution and in the solid state. The EL emission was observed from 477 to 490 nm for sky blue to bluish green because of different functional groups on the periphery of fluoranthene. The EQE achieved was 1.1–1.4% and the high luminance observed was $\geq 2000 \text{ cd/m}^2$.⁴⁰

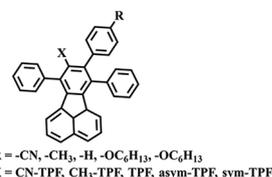


Figure 13 Fluoranthene derivatives.

Gupta et al. also introduced a new concept of D- π -A for blue emitters. They synthesized multiakynylbenzene-bridged triphenylene-based molecules (Figure 14) by incorporating spacers. All the compounds showed emission at 365 nm in solution under long UV irradiation. In addition, the molecules were reported to have good thermal stability, and good yield with high purity. They also fulfilled a criterion required for a good blue emitter but they did not have that much efficiency as compared to other blue emitters.⁴¹

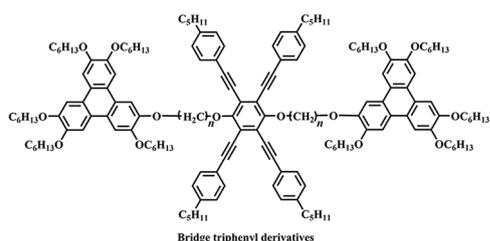


Figure 14 Multiakynylbenzene-bridged triphenylene-based molecules.

Rajamalli et al. synthesized two benzopyridine carbazole-based fluorescence molecules DCBPy and DTCBPy (Figure 15) made up of carbazole and 4-(*t*-butyl) carbazolyl groups, respectively. The molecules showed very low energy gaps of 0.03 and 0.04 eV and the PL value proves that they are TADF molecules. The EQE of the molecules named DCBPy and DTCBPy was reported to be 24.0% and 27.2%, respectively.⁴²

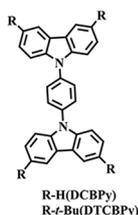


Figure 15 Fluorescence DCBPy and DTCBPy molecules.

Pathak et al. introduced a series of five-ring polycatenars (a–d) (Figure 16). All the reported molecules played a very important role as compared to the number of flexible trails in subsequent photophysical characterization. From all the reported compounds, the *p*-substituted moiety showed a columnar hexagonal phase, whereas the *m*-substituted one exhibited a reduced tendency to stabilize the mesophase. All three *p*-substituted compounds highly promoted *p*-*p* interaction. Besides this, one of the molecules is capable enough to have AIE in blue light. All these qualities made them promising molecules for application as emissive layers.⁴³

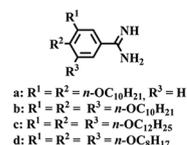


Figure 16 Polycatenar derivatives.

Again, in the same year, Pathak's group came up with a new concept and they developed stilbene derivatives (a–e) in a star shape (Figure 17). The compounds were made by linking dialkoxy styrene with benzene at the third and fifth positions and a single amide linkage at the first position of the central benzene ring exhibited gelation at a very low concentration in hexadecane. These star-shaped molecules are applied as blue emitting materials due to their emissive nature in solid and solution phases and a wide band gap value. The emission maxima observed for the molecule were in the range of 406–412 nm.⁴⁴

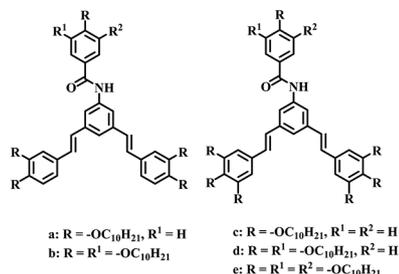


Figure 17 Dialkoxy styrene-based molecules (a–e).

Thanikachalam et al. synthesized compounds composed of donor-linker acceptors with phenyl and styryl as spacers. They are new and good enough to be utilized in non-doped OLEDs. These newly synthesized blue emissive materials exhibited excellent quantum efficiency (QE) and high thermal stability (HTS). The styryl spacer containing the TPA-MPS device exhibited the current efficiency at 1.73 cd/A, power efficiency (PE) at 1.46 lm/W, and provided 2.11% EQE with 4.6 V. Both the reported emitters TPA-MPI and TPA-MPS (Figure 18) acted as a potential blue candidate for OLEDs.⁴⁵

Although there have been many metal-based complexes, Urinda et al. synthesized Ir (II)-based N⁴N and C⁴N complexes (Figure 19). They aimed to provide different types of molecules which can have excellent relative effectiveness. They succeeded and proved that the molecules provided a fine emission wavelength as a blue phosphorescent. They even modified molecules by fitting the pyridine-tetrazole as an ancillary ligand and compared it with other nitrogen-rich cyclometalated ligands. The aftermath was deliberated on the basis of DFT/TDDFT (time-dependent DFT) calcula-

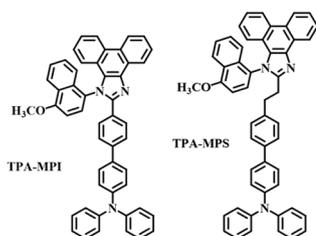


Figure 18 Emitters TPA-MPI and TPA-MPS.

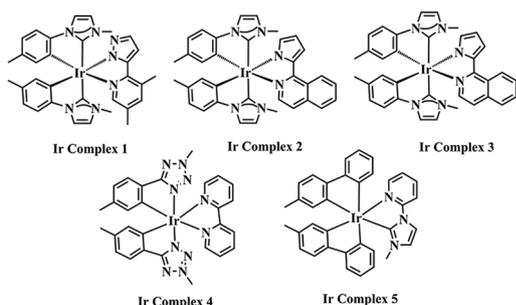


Figure 19 C^N (Ir Complex 1–3)-based and N^N (Ir Complex 4 and 5)-based cyclometalating ligands.

Table 3 Reported blue emitters with external quantum efficiency and λ_{\max}

Sample name	EQE (%)	λ_{\max} (nm)	Lifetime (ns)	Ref.
PyPIC2	1.5	–	–	30
TPFDPSO2	0.50	460	17	31
TPFDBTO2	0.61	450	16	31
OMe-DPQ, M-DPQ, Br-DPQ	–	near 450	–	32
TPFDPS	0.04	466	13	33
TPFDBT	0.40	458	14	33
Zn(salen) ($n = 1-7$)	–	430–450	–	34
ELC1	–	385	–	36
	–	405	–	36
ELC2	–	–	–	36
ELC3	–	608	–	36
Pic	3.9	–	–	37
Plid	4.0	–	–	37
BP ₂ -BP ₄	19.2–17.0	389–410	–	38
BPypc	4.2	–	–	39
BPyp3C	23.9	–	–	39
Fl. derivative	1.1–1.4	477–490	13, 13, 11, 9, 14	40
DCBPy	24	–	–	42
<i>t</i> -Bu (DTCBpy)	27.2	–	–	42
TPA-MPS	2.11	–	–	45
Ir Complex 5	14	–	–	46

tions, emission properties, and QE. The highest QE was reported for Ir Complex 5 and that was around 14%. Hence, the complexes added a guideline path to design better performing OLED materials.⁴⁶

As per the literature survey, the blue OLED device started with only 15.8% EQE in 2012 and reached to a record high EQE of almost 27.2% in 2016. The EQE and wavelength for the reported blue emitter are shown below in Table 3^{30–46} from the year 2010 to 2016.

In 2017, Valsange et al. demonstrated a small organic molecule named PY-II (Figure 20) which has a simple pyrene core. The resultant study provided that it has excellent solubility in simple organic solvents and has thermal stability up to 345 °C. The photoluminance attained for the molecule was 0.9 with bright blue emission close to 450 nm. In addition, the processed non-doped OLED device exhibited blue emission with CIE coordinates of 0.16 and 0.16. The PE reported was 0.17 lm·W⁻¹, with 0.41 cd/A current efficiency and 202 cd/m² maximum brightness.⁴⁷

Bishnoi et al. reported novel non-planar phenothiazine-5-oxides based on the donor, acceptor, and spacer concept compounds 2a–I (Figure 21). The synthesized compounds showed blue and blue-green emission in solution and in the solid state. The “push-pull” behavior of the donor and acceptor is proved by DFT and solvatochromic studies. In addition, the compounds also bear thermal stability in a range of 159–302 °C.⁴⁸

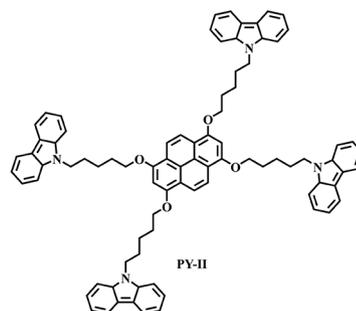


Figure 20 Small organic molecule PY-II.

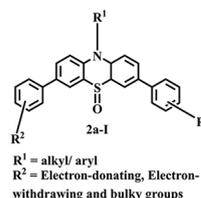


Figure 21 Non-planar phenothiazine-5-oxides.

Imide groups containing naphthalimide (NI) compounds (a–f) (Figure 22) are very well-known acceptor compounds. So, to develop multiple applications and to gain attention in the scientific community Gopikrishna et al. developed an NI compound. These molecules were reported as a member of newly synthesized AIE-active material compounds and exhibited emission in the blue region. In addition, the scientists also found their excellent response towards many other applications such as good biocompatibility and photostability, and also showed a good response in *in vitro* and *in vivo* studies to imaging of cells.⁴⁹

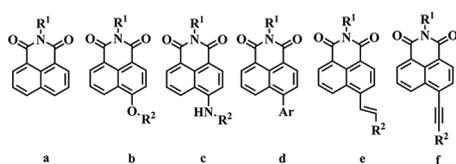


Figure 22 Naphthalimide compounds (a–f).

The new efficient deep blue emitter was reported in the same year, and the compounds named NPI-PITPA, MeNPI-PITPA, and OMENPI-PITPA were based on the concept of D–A. These molecules unveiled deep blue emissions as per the photophysical characterization. The compound NPI-PITPA exhibited an EQE of 4.60%, a current efficiency of 4.8 cd A⁻¹, and a PE of 4.2 lm·W⁻¹, for MeNPI-PITPA the EQE found was 4.70%, the current efficiency was 5.2 cd A⁻¹ and the PE was 5.1 lm·W⁻¹. The third emitter OMENPI-PITPA demonstrated an EQE of 4.90%, a current efficiency of 5.9 cd A⁻¹ and a PE of 5.1 lm·W⁻¹. In addition, the CIE coordinates observed for the materials were (0.15, 0.09) for NPI-PITPA, (0.15, 0.08) for MeNPI-PITPA and (0.15, 0.07) for OMENPI-PITPA at very low driving voltage. The materials showed blue emission at 338, 441, and 443 nm, respectively. Besides this, the maximum EQE of doping device based on OMENPI-PITPA was 19.0%. The materials were further doped with various molecules to check whether they give more true color or not, but the color found was not different from the original ones (Figure 23).⁵⁰

Joseph et al. reported one of the methods in which a cyano group was added to increase EL properties of moieties and they developed five probes (Figure 24). From all of them, the compound containing carbazole named triphenylamine units exhibited positive solvatochromism in the fluorescence spectra. From the PL, it was observed that the compound reflected blue emission and EQEs of 338 nm with 1.7% (CBza), 441 nm with 2.0% (CBzb), 404 nm with 2.9% (CBzc), 436 nm with 2.8% (CBzd) and 404 nm with 3.1% (CBze). The EQE expected was that the fluorene derivative having cyano substituents showed the best EL and the reason is the well-adjusted charge transport emissive layer.⁵¹

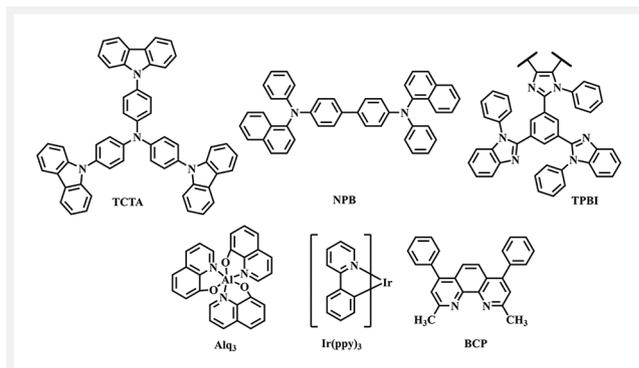


Figure 23 Materials used for fabrication of the developed blue OLEDs.

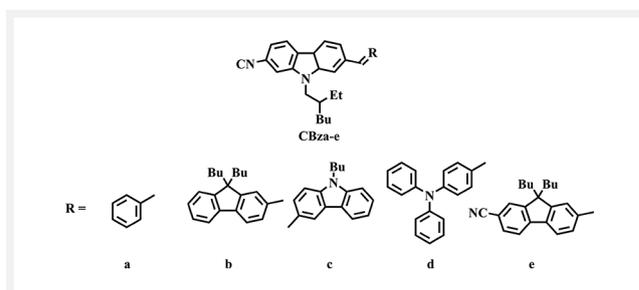


Figure 24 Cyano-functionalized carbazole moieties (CBZa-6).

In the same year, Konidena et al. succeeded in the synthesis of a modified hybridized local and charge transfer (HLCT) fluorescent TPA-based emitter (Figure 25). An OLED using this material showed an EQE of 6.5% with a CIEy value of 0.06. Besides this, the compound exhibited an emission at 432 nm.⁵²

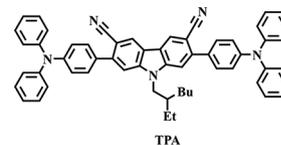
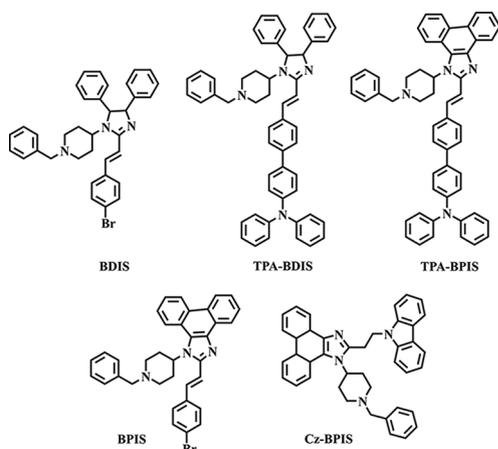


Figure 25 Fluorescent TPA-based emitter.

Thanikachalam et al. conducted a study on five new blue emissive D–π–A materials (Figure 26) to investigate non-doped OLEDs. Among them, TPA-BDIS displayed a QE of 1.98% along with CIE coordinates of (0.16, 0.09) and a narrow FWHM (full width at half-maximum) of 40 nm in the EL spectra. Thus, these values suggested that TPA-BDIS acts as a potential deep blue emitter. The EQE for Cz-BPIS observed was 2.61% and the radiative rate was 13.6 × 10⁻⁶·s⁻¹. Moreover, the current efficiency was 1.99 cd A⁻¹ and the PE was 1.63 lm·W⁻¹, and a strong emission was observed at 369 nm.⁵³

Figure 26 Blue emissive D- π -A materials

One year later in 2018, a one-pot four-component methodology was developed to synthesize coumarin-linked triazolyl-DHPM. The synthesized compound sufficiently showed fluorescence. All 10 synthesized compounds exhibited violet-blue light in the visible region. In addition, the compounds also demonstrated a high yield and the electronic structure was studied by DFT characterization. As per thermal analysis, the compounds bear stability up to the temperature range of 0–290 °C.⁵⁴ However, compared to other core molecules, this molecule is quite weak when it comes to efficiency. Bala et al. found an electron-deficient core (*s*-heptazine) for OLED development (Figure 27). This moiety exhibited AIE. Besides this, solid-state molecules showed sky-blue emissions. They were fabricated by using Hpz-C12 along with various hosts such as CBP with a 3% dopant concentration. The best CBP-containing device showed a PE of 0.3 lm·W⁻¹, a current efficiency of 0.4 cd/A, and an EQE of 1.6% along with CIE coordinates of (0.17, 0.08) at a brightness of 100 cd/m². Hence this device opened a new pathway to broaden the development of AIE-based blue light emitters.⁵⁵

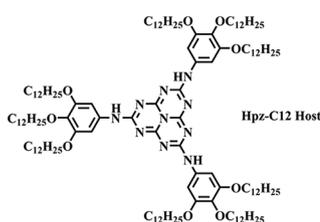


Figure 27 Hpz-3C12 host.

Ghate et al. published a work on organic phosphor OEt-DPQ (ethoxy) (Figure 28) using an acid-catalyzed process, which was further doped with polymethylmethacrylate at different wt% to check the expected results. The surface morphology and percentage comparison were assessed by scanning electron microscopy. It was found that the thermal stability is in the temperature range of 80–113.6 °C. The absorption band in UV was exhibited in the range of 260–340 nm, whereas PL was found at 432 nm. Thus, the PI value indicated the emission of blue light in the visible region. As per the chromaticity diagram, CIE coordinates were poisoned at (0.159, 0.019). Hence this emitter was found to be capable enough to be used as a blue emitter in OLED.⁵⁶

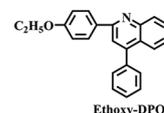


Figure 28 Organic phosphor OEt-DPQ.

Efforts have been devoted by Konidena et al. to report a star-shaped triazine–perylene conjugate (Figure 29). As solubility was an issue since starting for emitting materials, the triazine–perylene molecule (PerTz1) has good solubility due to its propeller shape. According to the DFT studies, it was observed a change in energy levels of HOMO and LUMO. Additionally, these star-shaped molecules exhibited bright greenish-blue fluorescence with high quantum yield. According to the data of luminance (L_{\max} 5,561 cd m⁻²), it was proved that the designed star-shaped molecules promote charge migration along with better charge recombination to improve efficiency. The EQE observed for the synthesized molecule was 2.57%.⁵⁷

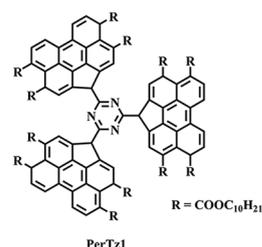


Figure 29 Star-shaped triazine–perylene conjugate (PerTz1).

Sharma et al. synthesized star-shaped TPE (Tx1) and TPAN (Tx2, Tx3) truxene molecules (Figure 30). The molecules were prepared via Suzuki and Sonogashira reactions. The reported TPE-substituted truxenes exhibited AIE behavior, whereas the TPAN-substituted truxene derivative showed an ACQ (aggregation caused quenching) effect in

THF as well as in water because of π - π stacking. Also, TPAN molecules displayed HTS as the 10% weight loss temperature is more than 400 °C. EL properties of truxenes were investigated in solution-processed and vacuum-deposited OLEDs. The reported non-doped OLED based on TPAN truxene moiety Tx3 showed λ_{max} of 360 nm, 3.8% EQE, and a maximum brightness of 7,000 cd/m².⁵⁸

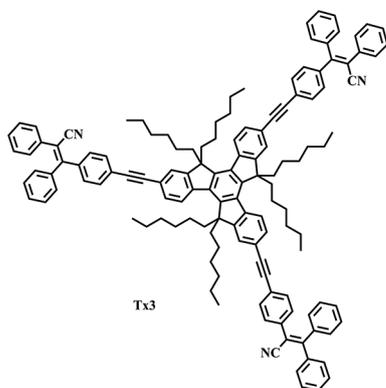


Figure 30 Star-shaped TPAN (Tx3) derivative.

Siddiqui et al. introduced a donor-acceptor derivative where acridone acts as an acceptor and carbazole acts as a donor (AcCBz) (Figure 31). The band gap ΔE_{ST} found was as low as 0.17 eV, which was favorable for TADF compounds. Furthermore, the emission exhibited at 465 nm and the compounds were found to be efficient for blue light TADF in OLEDs. The compounds were blended with poly-vinyl carbazole in a 1 : 7 (W/W) ratio to check the efficiency. The efficiency found for the compounds blended with poly-vinyl carbazole was very high compared to the plain molecule. The current efficiency found was 65 Cd·A⁻¹ at high luminance of 9,800 Cd/m² for the device. So, it was observed that the acridone-carbazole derivatives offered EL as an undoped TADF greenish blue emitter and a blue emitter when doped in PVK.⁵⁹

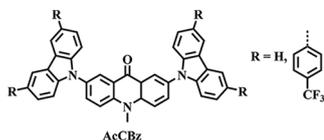


Figure 31 Greenish blue TADF emitter (AcCBz).

Tagare et al. reported two-star-shaped fluorescent PI fluorophores PIMCFTP and PIPCFTP (Figure 32) with a D- π -A structure. These two fluorophores exhibited an excellent transition temperature and HTS with decomposition temperature up to 377 °C. The doped device made up of these molecules exhibited bluish-green emission at 436 nm

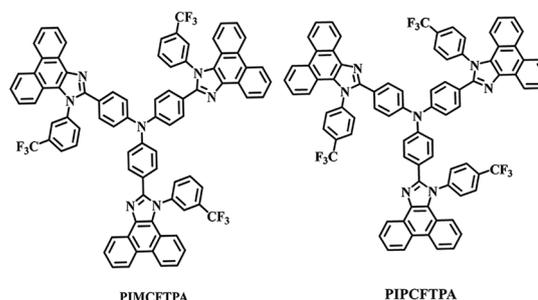


Figure 32 PI fluorophores PIMCFTP and PIPCFTP.

with high efficiency (current efficiency of 6.58 Cd/A, PE of 5.91 lm/W and 3.62% EQE at low turn-on voltage of 2.83 V).⁶⁰

Venkatramiah et al. introduced three carbazole-based molecules with the D- π -A structure (Figure 33). The compound exhibited excellent quantum yield with a different color. Among them, Cbz-Pth showed sky-blue color emission at 481 nm in the solid state. Besides this, the OLED was fabricated with the three-layer device using Cbz-Pth molecules. The fabricated molecule showed 4.1% EQE and a brightness close to about 73,915 cd/m².⁶¹

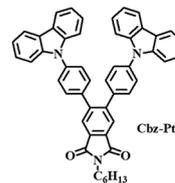


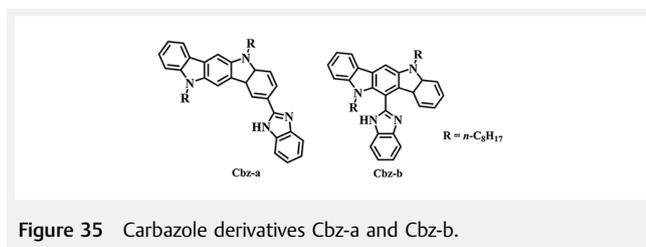
Figure 33 Cbz-Pth molecule.

Later in 2019, Manohara et al. gave their devotion to reporting cyanopyridine derivatives via Williamson ether synthesis. The molecules were further reacted with chalcone via an aldol condensation reaction to check the capacity of the molecule. All three synthesized fluorophores BZnCY, BZnCYBR, and BZnCYVY (Figure 34) revealed an absorption band close to the 274–355 nm region and also exhibited blue emission in the 412–438 nm range. The energy gap reported as per the CV result was between 1.37 and 2.12 eV. As per the collected data, the derivatives can be used in optoelectronic devices such as OLEDs.⁶²

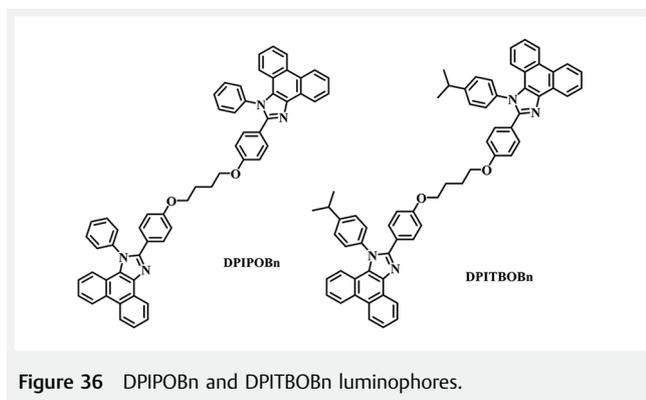


Figure 34 BZnCY, BZnCYBR and BZnCYVY fluorophores.

Kadam et al. introduced substituted indol carbazole derivatives Cbz-a and Cbz-b (Figure 35). As per the DFT studies, it was found that Cbz-a was more planar than Cbz-b. Both of the compounds showed significant change in color under long UV-light exposure and the absorption band was found near 353 nm.⁶³



In the same year, two new blue PI-based luminophores DPIPOBn and DPITBOBn (Figure 36) were reported and both luminophores emitted intense blue color in the solution and solid phase. Then, the synthesized compounds were fabricated in OLEDs to test whether they act as emissive materials or not. Each device exhibited emissions near around 380–395 nm under UV light. The CIE values reported were (x, y) (0.16, 0.09 or 0.10). The DPITBOBn-fabricated device demonstrated a PE of 0.5 lm/W, a current efficiency of 1.2 cd/A, and an EQE of 1.9%.⁶⁴



Kajjam et al. successfully synthesized novel TPI-based luminophores (TP 1–TP 4) (Figure 37). It was found that the designed molecules showed fluorescence in the range of 380–420 nm.⁶⁵

Jayabharthi et al. developed new blue-emitting bis-PI derivatives such as NPIBN, CNPIBP, and CNPIBN. These molecules exhibited high PL quantum yield (Φ_s/f : NPIBNO-0.75/0.68, CNPIBP-0.85/0.76 and CNPIBN-0.90/0.88). Besides this, the non-doped/doped device based on CNPIBN molecule displayed a maximum efficiency of 4.96/5.4%, a current efficiency of 7.46/7.56 cd A⁻¹ and a PE of 6.85/6.91 lm·W⁻¹ at low turn-on voltage (3.5/3.8 V). In addition, non-doped devices based on the (D- π -A) moiety (Figure 38), TPNCN-TPA

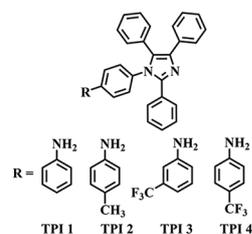


Figure 37 TPI-based luminophores.

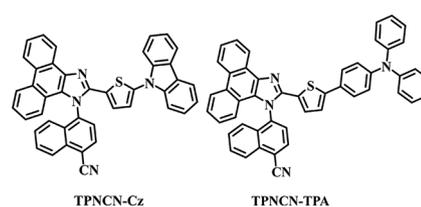


Figure 38 PI derivatives TPNCN-TPA and TPNCN-Cz.

and TPN-Cz, showed emission at 420 and 435 nm with internal quantum efficiency values of 10.1%, and 11.6%, respectively, which is attributed to the charge transfer component from cyano substitution. Further, η_{ex} 2.01%, η_{c} 3.89 Cd/A, η_{p} 3.15 lm/W and 2.32%, η_{c} 4.0 Cd/A, η_{p} 3.42 lm/W were observed for TPNCN-TPA and TPN-Cz, respectively.⁶⁶

Bala et al. introduced new compounds based on the TP-PA discotic moiety (Figure 39). The fabricated doped device (TP-PA8a) showed a QE of 2.1%, 1.2 lm·W⁻¹ power efficiency, and 2.0 cd A⁻¹ current efficiency. Among all the devices, it was found that the TP-PA8 acts as a potential candidate for application in semiconducting OLED materials.⁶⁷

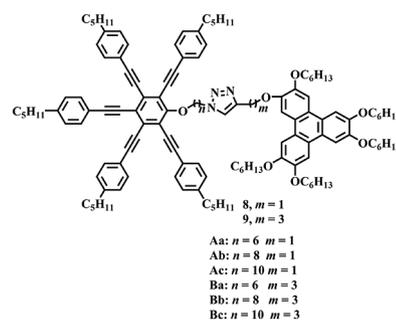


Figure 39 TP-PA discotic dimer.

Awasthi et al. synthesized an acridone-dinaphthylamine derivative (AcNpH) (Figure 40) to investigate its property as a blue TADF material. The synthesized compound showed fluorescence and the emission was observed in greenish blue light at 550 nm. The energy gap found was 0.3 eV and

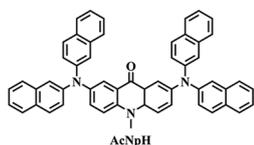


Figure 40 Acridone dinaphthylamine derivative (AcNpH).

the OLED based on the synthesized compound exhibited nearly 17,000 cd/m² at 25 mA/cm².⁶⁸

Once again in the same year, four more deep blue emitter compounds PNSPI, ANSPI, PSPINC and ASPINC (Figure 41) were reported. Among the four synthesized compounds, PSPINC-based non-doped devices showed blue emission at 476 nm. The ASPINC-based non-doped device exhibited excellent performances, such as current efficiency (η_c 12.13 cd/A), EQE (η_{ex} 6.79%), PE (η_p 5.98 lm·W⁻¹), and CIE (0.15, 0.17) at 3.15 V.⁶⁹

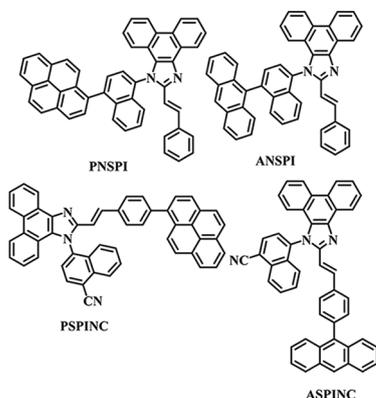


Figure 41 ANSPI, PNSPI, ASPINC and PSPINC moieties.

Mahadik et al. designed a series of quinoxaline derivatives (Figure 42). They synthesized nine 2,3-di(thiophene-2-yl) quinoxaline-based amine derivatives and characterized them by standard spectroscopic techniques. All the

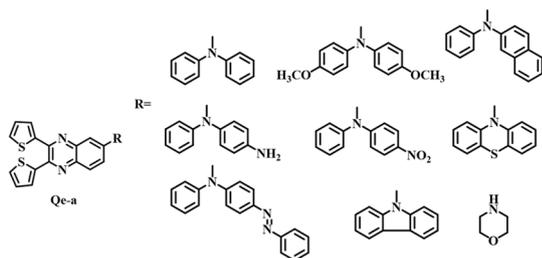


Figure 42 Quinoxaline molecules Qe-a.

molecules showed an absorption spectrum in the range of 390–461 nm. Among them, eight molecules Qe-a exhibited an emission maximum within 465–566 nm for yellow-blue light. In addition, the HOMO and LUMO values were found in the range of –4.90 to 5.70 eV and –3.10 to –3.36 eV, respectively.⁷⁰

For the pyrene-substituted oxadiazole moiety, Najare et al. developed a new molecule with proper hole and electron transfer (Figure 43). Differential scanning calorimetry and thermogravimetric analysis studies proved that the molecule has excellent stability for application in optoelectronics in the range of 204–366 °C. The estimated HOMO and LUMO values found for the compounds were in the range of –5.67411 to –8.27307 eV and –1.886383 to –5.93044 eV, respectively.⁷¹

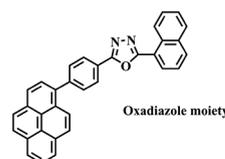


Figure 43 Pyrene-substituted oxadiazole moiety.

Ravindra et al. reported an AIE-based fluorescent imidazole molecule AIE moiety (Figure 44). It was found from powder X-ray diffraction that the mechanofluorochromic properties of the compound was reversible under an external force just because of a decrease in crystallinity. Due to this reason, the moiety revealed bright cyan-blue luminescence in the solid state with excellent QE. The absorption found for the molecule was at 365 nm under UV illumination. As per all the outcome results, it was proved that the molecule with good AIE was considered a promising candidate for OLEDs as well as latent fingerprints for visualization applications.⁷²

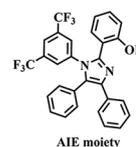


Figure 44 AIE-based fluorescent imidazole molecule (AIE moiety).

Three fluorophores were also published meanwhile (Figure 45) and all the emitters exhibited a deep blue emission with brilliant device efficiency. The maximum luminance (I_{max}) was found to be 994 cd/m² and emission was observed at 442 nm. The observed current efficiency was 2.6 cd/A, with a PE of 1.0 lm/W and an EQE of 3.2% at the brightness of 100 cd/m² for TBIMPTPA. These results verified

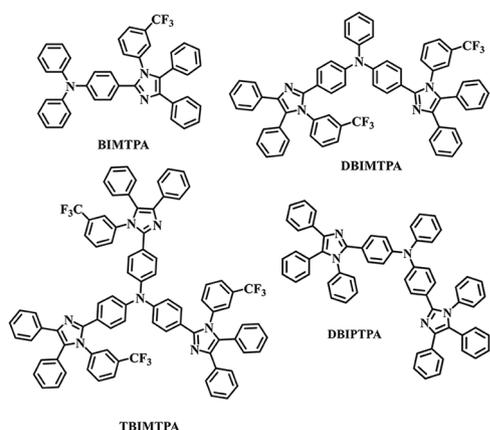


Figure 45 Fluorophore molecules BIMTPA, DBIMTPA, TBIMTPA and DBIPTPA.

that the molecules prepared from the concept of D–A are favorable for blue OLEDs.⁷³

Similarly, in 2020 three bright blue color bipolar fluorophores BIPTPA, DBIPTPA, and TBIPTPA were designed (Figure 45). The device based on DBIPTPA reflected exceptional electroluminescence performance among all three. The maximum luminance noted for the device was 495 cd/m², with an emission at 471 nm from the PL data and the EQE noted was 2.5% along with 0.8 cd/A current efficiency.⁷⁴

In the same year, Patil et al. published their work on a TADF-based IDFL molecule (Figure 46). The IDFL-2DPA molecule was further synthesized by attaching two diphenylamine (DPA) units. The reported molecule showed a large singlet–singlet energy gap of 0.45 eV for the TADF one. The fabricated IDFL-2DPA device showed an initial luminance L_{\max} of 48,900 cd/m² and exhibited an EQE of 5.7%. The emission observed was at 461 nm for the same molecule in THF solution.⁷⁵

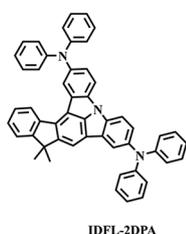


Figure 46 IDFL-2DPA probe.

Also, it was in the same year when Karuppusamy and Kannan developed three novel pyrazoline skeleton donor–acceptor molecules. Among them, the two compounds PP-OCH₃ and PP-Br (Figure 47) exhibited blue and sky-blue emissions, respectively. The absorption for PP-OCH₃ and

PP-Br at 416 nm and 439 nm, respectively, were confirmed by fluorescence spectrometry. The derivatives have excellent thermal stability as both compounds demonstrated thermal stability at 325 °C and 291 °C, respectively. Besides this, the HOMO and LUMO energy gap observed for PP-Br and PP-OCH₃ was 3.111 and 3.274 eV, respectively.⁷⁶

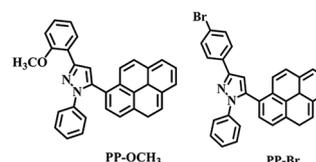


Figure 47 Pyrazoline skeletons PP-OCH₃ and PP-Br.

In 2021, two new blue emissive materials were designed (Figure 48). The synthesized molecules NSPI-DVP and CNSPI-DVP were capable enough to show AIE and free-of-concentration quenching in film. Both molecules showed excellent emission in the color range of blue and green. The fabricated non-doped device based on CNSPI-DVP unveiled blue emission at 427 nm with CIE coordinates of (x, y) (0.14, 0.13). However, the device showed excellent electroluminescence performance compared with NSPI-DVP with a superior EQE of 5.23%. The doped device fabricated by CNSPI-DVP improved the efficiency and EQE noted after doping was 9.81%, with a CE of 7.56 cd A⁻¹ and a PE of 6.81 lm · W⁻¹.⁷⁷

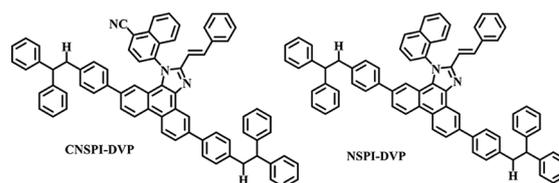


Figure 48 Blue emissive materials CNSPI-DVP and NSPI-DVP.

Dixit et al. came up with a huge stroke by developing seven different bipolar PI derivatives PI1–6 (Figure 49). The properties found for the reported molecules were satisfying in the case of high fluorescence quantum yield (> 90%). The compounds synthesized showed an emission maximum at 391 nm for PI1, 381–414 nm for compound PI2, 403–414 nm for compound PI3, and 396–429 nm for compound PI4. Besides that, the oxidation potential was found in the range of 0.96–1.57 V. In addition, the EQE found was about 3.2% for all compounds.⁷⁸

Sharma et al. designed luminogens having PI, carbazole, and cyano functional groups. The MIPCN and DPICN emitters (Figure 50) were polar and exhibited very good thermal stability. It was discovered that these compounds exhibited

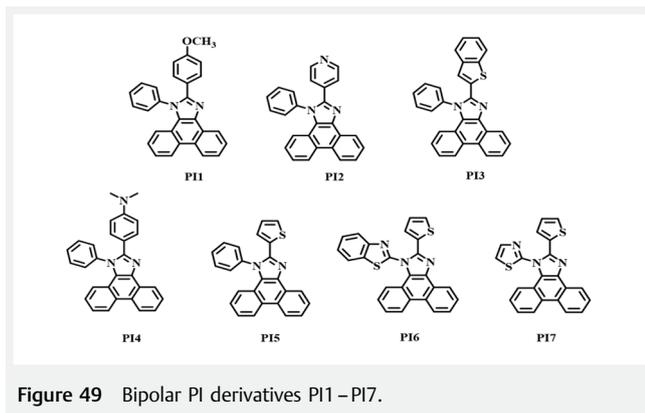


Figure 49 Bipolar PI derivatives P11–P17.

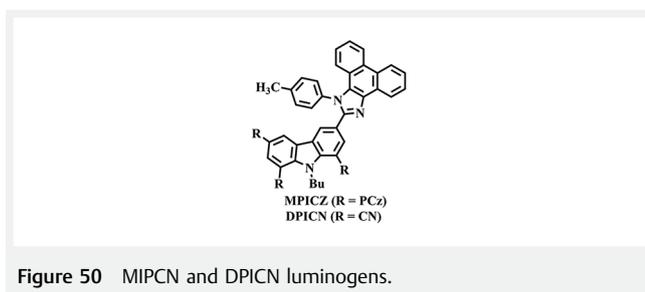


Figure 50 MIPCN and DPICN luminogens.

a very good blue shift in the presence of an acid. An OLED device based on MPICN showed the best performance among all. The device was capable of exhibiting a PE of 1.4 lm/W, a current efficiency of 3.2 cd/A and an increased EQE of 1.8% at 100 cd/m². Besides this, the violet bluish emission was found near 407–418 nm in the solid state.⁷⁹

Four imidazole derivatives BIPOCz, BIPTOCz, BITBOCz and BIFOCz were synthesized in the same year. The reported fluorophores show a PL quantum yield (PLQY) of 59%. Other than this, the CIE coordinates observed for y were less than 0.08. However, the BIPOCz molecule-based OLED device (Figure 51) exhibited an EQE of 1.9% along with CIE coordinates of (0.17, 0.07), and also showed emission near 367–460 nm (solid).⁸⁰

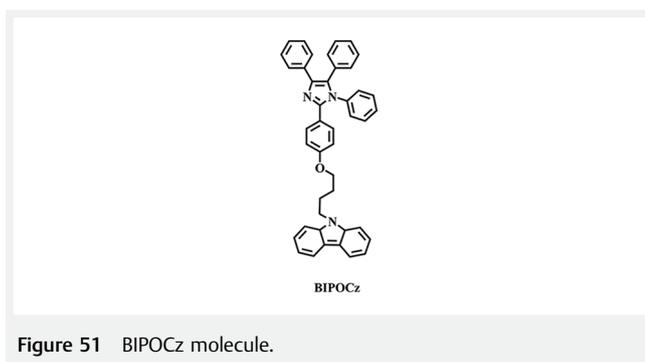


Figure 51 BIPOCz molecule.

Vasylieva et al. synthesized three novel conjugated organic TADF molecules with a D–A–D structure (Figure 52). The absorption band of the Conj-a TADF molecule was found in the range of 400–420 nm. But the fabricated device, Conj-a molecule, exhibited luminance of up to 22,900 cd/m². The EQE noted for the device was 5.2%.⁸¹

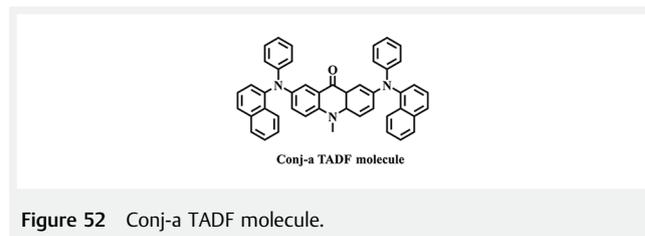


Figure 52 Conj-a TADF molecule.

Najare et al. synthesized three oxadiazole derivatives (Figure 53). All devices were studied in detail using optoelectronic properties. Among all the optoelectronic properties the synthesized moieties CHEM-a and CHEM-c have good thermal properties, which was confirmed by the glass transition temperature (T_g). The band gap value observed for these moieties was in the range of 2.70–3.11 eV with high Stokes shift values of 5018–9143 cm⁻¹. In addition, all the compounds exhibited excellent thermal stability and the temperature noted was more than 300 °C with 5% decomposition.⁸²

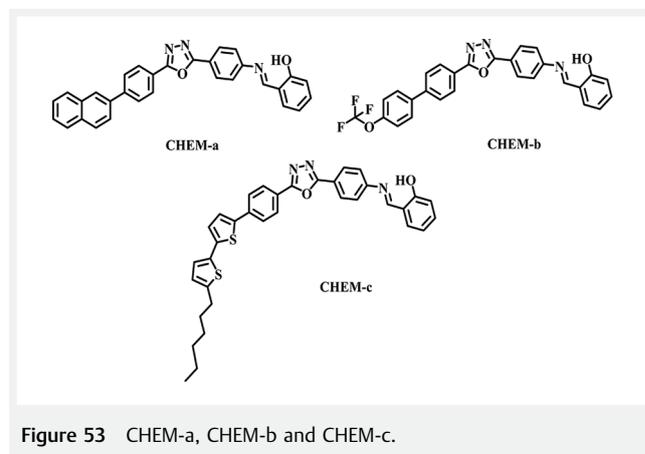


Figure 53 CHEM-a, CHEM-b and CHEM-c.

Kumar et al. synthesized fluorescent derivatives based on a core called coumarin thiophene fluorescent tags (CTFTs) (Figure 54). The PL properties of the CTFTa molecule (R = H, R¹ = Cl) showed a strong excitation at 407 nm. The bandgap of CTFTa is 3.04 eV and for CTFTb it is 3.29 eV.⁸³

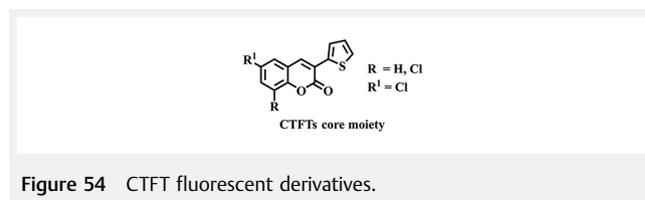


Figure 54 CTFT fluorescent derivatives.

In 2022, Bahadur et al. demonstrated two potential isomers BPy-pDTC and BPy-mDTC (Figure 55). Both of the TADF emitters exhibited more than 90% PLQY. BPy-pDTC-containing OLED devices provided a high EQE of 25% with a narrow emission of 456 nm. In addition, CIE coordinates noticed were (0.14, 0.13).⁸⁴

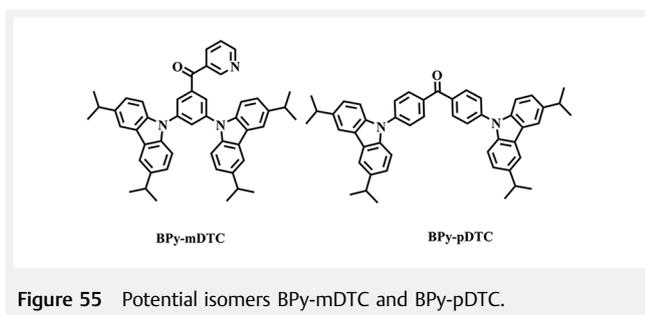


Figure 55 Potential isomers BPy-mDTC and BPy-pDTC.

Two new bipolar molecules 4-PIMCFTPA and 4-BICFTPA were reported (Figure 56). The doped device fabricated with 4-PIMCFTPA fluorophore exhibited a maximum PE of 0.3 lm/W with 1.7% EQE. The CIE coordinates detected were (0.17, 0.06).⁸⁵

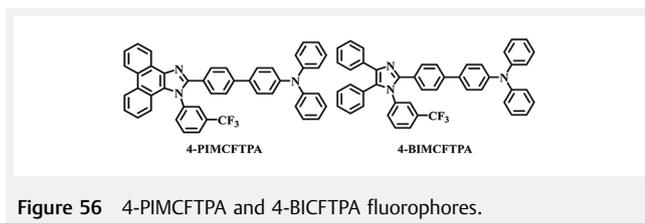


Figure 56 4-PIMCFTPA and 4-BICFTPA fluorophores.

Proper charge transfer was an issue for a long time and dipolar PI derivatives (PI-1, PI-2 and PI-3) properly optimize the charge balance. So, by changing the position and number of PI probes (Figure 57) Thomas et al. designed a molecule that can balance the intramolecular charge between molecules. From all three PI emitters, the device fabricated by using a molecule linked at the *p*-position of the C₂ phenyl ring (PI-2) showed CIE values of (0.16, 0.08) with an EQE of 1.4% and a CE of 1.0 Cd/A. PI-1 and PI-3 showed EQEs of 1.0% and 0.7%, CEs of 0.6 and 0.6 Cd/A and CIEs of 0.17, 0.09 and 0.17, 0.11, respectively.⁸⁶

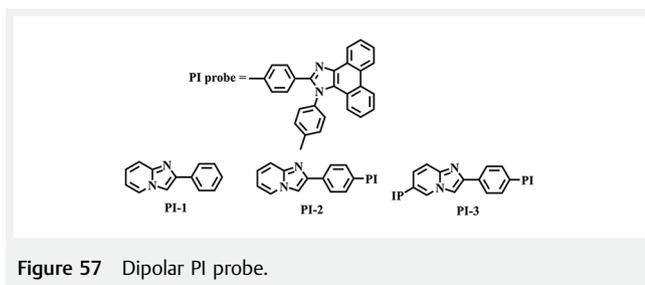


Figure 57 Dipolar PI probe.

Very recently, three core acceptors PHBISN, PTBISN, and m-CFBISN were reported (Figure 58). All compounds synthesized have a wide energy band gap of more than 3 eV. The molecule PTBISN was fabricated in OLEDs and exhibited an EQE of 1.5%. The CIE coordinates observed for the same device were (0.15, 0.08). The *y* value exactly matched with the standard value defined by the National Television System Committee.⁸⁷

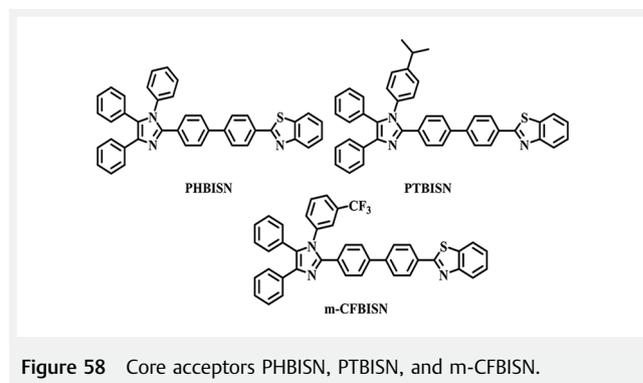


Figure 58 Core acceptors PHBISN, PTBISN, and m-CFBISN.

In the year 2022, a few of the best blue OLED emitting molecules with outstanding photoluminance and electroluminescence properties are reported from India. By seeing this kind of development in blue OLEDs, particularly in India, and as per the experts from the display industry, the next 15 years for the blue OLEDs will be bullish. Also, this significant device will be the next player of light technology and it will have great influence directly on improving the economic growth of India. Here are the significant results of a number of molecules reported from the year 2017 to 2022 (Table 4). This table includes lifetime, EQE and blue light emission values.

4 Present Scenario of Blue OLEDs

In this work, the current status of blue light emitting material design is discussed which includes various emission molecules based on fluorescence, phosphorescence, TADF, and HLCT. The majority of the blue materials are facing lifetime issues as compared to the red and green devices. But the molecules made based on TTF and hyper-fluorescence are harvested to prevent the buildup of the efficiency of the blue materials. The extension of TADF and HLCT by incorporating the above phenomenon is a new milestone for blue emitters. Moreover, the TTF-based blue materials have low efficiency compared to the phosphorescence and TADF-based materials as these materials show satisfactory efficiency and electroluminescence spectrum. If suitable materials are chosen for the design of the device, Ph-OLEDs can be used as the best blue OLED material for device fabrication. Here, we gathered all the information from the materials that have already

Table 4 Performance of blue emitting materials and λ_{max}

Name	EQE (%)	λ_{max} (nm)	Lifetime (ns)	Ref.
NPI-PITPA	4.60	338	–	50
MeNPI-PITPA	4.70	441	–	50
OMeNPI-PITPA	4.90	443	–	50
CBza	1.7	400	–	51
CBzb	2.0	400	–	51
CBzc	2.9	404	–	51
CBzd	2.8	436	–	51
CBze	3.1	404	–	51
Flue. TPA	6.5	432	1.33, 3.23	52
TPA-BDIS	2.61	369	–	53
HP ₂ -3C ₁₂	1.6	450	–	55
OEt-DpQ	–	432	–	56
PerTz1	2.57	–	–	57
TPAN(Tx3)	3.8	389–410	–	58
AcCBz	–	465	11.5	59
PIMCFTPA	3.62	436	1.70	60
CBz-Pth	4.1	481	Solution: 11.2 Film: 10	61
BZnCy, BZnCyBR, BZnCyVY	–	412–438	–	62
DPITBOBn	1.9	–	–	64
TP1-TP14	–	380–420	–	65
TPNCN-Cz	11.6	435	4.3	66
TPNCN-TPA	10.1	420	5.4	66
TP-PA	2.1	454	4.10	67
AcNpH	–	550	Air: 11.7 In N ₂ : 18.6	68
PSPINC	–	476	–	69
ASPINC	6.79	430–450	–	69
Qe-a	–	465–566	–	70
TBIMTA	3.2	442	–	73
DBIPTPA	2.5	471	–	74
IDFL-2DPA	5.7	461	13.5	75
PPOCH ₃	–	416	2.33	76
PPBr	–	439	1.74	76
NSPI-DVP	5.23	427	–	77
CNSPI-DVP	9.81	427	–	77
PI4	3.2	429	ACN solvent: 2.08	78
MPICN	1.8	407–418	9.53	79
BIPOCz	1.9	367–460	–	80
Conj.-a	5.4	400–420	15.3–15.8	81
CTFTa	–	407	–	83
BPy-pDTC	25	456	–	84
4-PIMCFTPA	1.7	439	–	85
PTBISN	1.5	429	–	87

been published and made an effort to cover all the blue light-emitting molecules reported so far in India.

Several groups are working on blue-emitting materials to achieve the most efficient molecules that can provide the best OLEDs. It is expected that it may reduce energy consumption in human day-to-day life. Few efficient groups from India are working to achieve the milestone of the OLEDs and among them J. Jayabharathi and her team from Annamalai University have established solution-processed blue light-emitting OLED materials based on phenanthroquinone using a boronic ester moiety. The group reported the molecule TPN-Cz with an EQE of 11.6%. Similar to this work, Sivakumar and his team from NIT Rourkela are also working in the same direction to develop efficient pure blue light materials. As per literature analysis in this work, we found that a few molecules such as 9,10-phenanthroquinone-based moiety and carbazole-based heterocyclic derivatives are reaching the ultimate level for blue OLED development. Another research group from IISC Bangalore, P. Rajamalli and colleagues, is also working on TADF materials.⁸⁸ Further, there are other applications found to be used for plant growth under artificial light generation by implementing OLEDs (effective white light creation). At present, Vasilo-poulou and colleagues are working on a pure blue fluorescent device.⁸⁹ They have synthesized a heterocyclic molecule-based TADF material for pure blue light emission. The EQE reported for this molecule is 41.2% and it is the highest reported to date. For more progress in the blue emitters, other groups also have worked on this, for example, Adachi et al. and J. Y. Lee and group are continuously evolving new blue OLED materials; however, India is somehow still lacking behind in OLED production expansion and working collaboratively with industry and academia at national and international levels.^{11,90} There is a positive impact found by current research work that the devices made to increase efficiency are not far away from internationally manufactured blue OLED devices. In addition, it will boost the implementation of highly efficient blue lighting devices to bring India at the top level.

5 Conclusions and Outlook

In conclusion, the development of blue OLEDs is going on ever since 1987. Subsequently, we can see the feathers adding year by year in OLED technology. The factors basically responsible for blue emitting materials are bright color and efficiency. They might be simple organic molecules or metal-based complexes. Among them, blue light-emitting materials are fast emerging. As an overview of the 12 years, the development in OLEDs has yet another season for even better blue light-emitting devices. For more inventions in blue OLEDs, there are more strategies for further improvement like the usage of a well-ordered structure with a proper en-

ergy band gap and emission at a lower wavelength. Recognizing the importance of OLEDs in upcoming years will be for more size-based OLEDs like small-size, mid-size and large-size devices. In addition, as per the article on the display daily market in the next year, OLEDs will consume 50% penetration and today the production of OLED devices has increased from 40% to 45% (647 billion dollars). Hence, it proves that in the future smart device manufacturing companies will focus on OLED devices with extra smart features with very good efficiency.

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Conflict of Interest

The authors declare no conflicts of interest.

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