Closing the Reliability Gap between Blue and Green Phosphorescent Organic Light-emitting Devices using the Double-sided Polariton-enhanced Purcell Effect

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Abstract

Short operational lifetime of blue phosphorescent organic light-emitting diodes (PHOLEDs) is one of the greatest challenges in organic electronics. The polariton-enhanced Purcell (PEP) effect has recently been introduced to extend the lifetime of blue PHOLEDs. Here, we introduce the polariton-enhanced Purcell effect from both the anode and cathode contacts to achieve the 10X absolute device lifetime enhancement in tandem blue PEP-PHOLEDs. With color saturation due to microcavity effects, we show that tandem blue PEP-PHOLEDs achieve a lifetime of 1800 ± 100h, effectively closing the gap between the lifetime of efficient green and deep-blue PHOLEDs.

Author Keywords

OLEDs; blue PHOLED lifetime; tandem OLED; Purcell effect; plasmonics; exciton-polaritons; radiation engineering

1. Objective and Background

Stable, efficient blue organic light-emitting diodes (OLEDs) are a missing piece among the colors used in OLED displays and lighting. In the past 20 years, OLEDs have reached 100% internal quantum efficiency (IQE) by harvesting triplet emission, achieving the full utilization of electrically generated excitons. Featuring unity IQE, phosphorescent OLEDs (PHOLED) and sensitized fluorescent OLEDs (SF-OLED) are among the most promising next-generation, energy-saving light source candidates. However, utilizing triplets slows down the radiative decay processes to microseconds from compared with nanoseconds in fluorescent OLEDs. This results in a high triplet density in the device that triggers a high probability for destructive bimolecular annihilation (1). A challenge preventing the application of unity-efficiency blue OLEDs is thus their intrinsic instability brought about by high triplet density.

Recently, we have shown that the Purcell effect enhanced by the surface plasmon-exciton-polaritons (PEPs)(2) or surface plasmon polaritons (SPPs)(3) can improve the device stability by increasing the optical density of states, thereby increasing their radiative decay rates. This, in turn reduces the triplet density in the diode emission zone. These surface evanescent modes increase the Purcell factor (PF) by extending the coupling strength to the high-wavevector (k) region while exponentially increasing the radiative coupling strength by reducing the distance between the emitting molecule and the dielectric/metal interfaces that carry the surface modes. PEPs, the strongly coupled quasiparticle between SPPs and the excitons in the dielectric material, can increase the PF and allow energy transfer to the organic excitons from lossy plasmons. Zhao *et al*.[1] have showed that the electron-transporting layer (ETL) material, BPyTP2, increases device lifetime by 5.3X by strong coupling of the blue emission to the Ag cathode.

2. Results

In this study, we demonstrate tandem blue PHOLEDs that combine PEPs generated at the cathode using BPyTP2 as well as at the anode using the hole-transporting layer (HTL) material, BCFN. Polaritons on both the ETL and HTL enable the Purcell effect to significantly increase blue PHOLED stability compared to one-sided devices reported previously(2). Figure 1a shows the structure of the full-cavity tandem OLED. We refer to devices using the weak-cavity, Al cathodes as control, **C**; the half cavity using Ag cathode as **H**; the full cavity using Ag cathode and anode as **F**. The single-stack devices are labeled as **C**, **H**, **F**, and the corresponding tandem devices are **CT**, **HT** and **FT**. Except for the cathode and anode structures, the organic layers are identical for both the single-stack and tandem devices. Figure 1b shows the reflectance of 20nm BCFN on top of 20 nm Al, indicating the formation of PEP. The lower polariton (LP) branch resonates in the blue visible region, increasing the PF to 4 near the HTL side. See the simulated PF for isotropic emitting dipole orientations in Fig. 1c.

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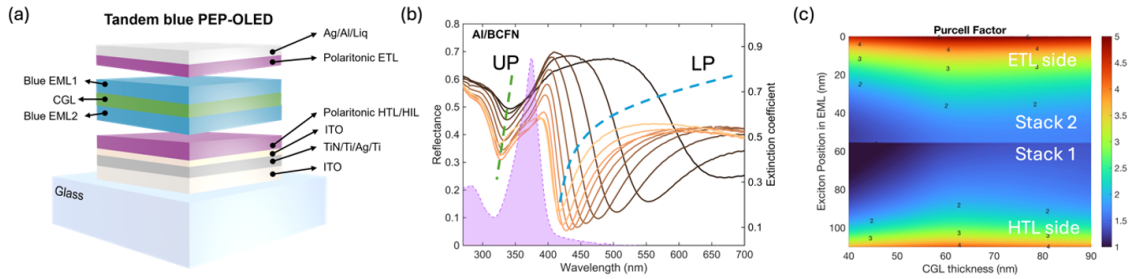

Figure 1. (a) Device architecture of full-cavity, tandem blue PEP-PHOLED. (b) Left: Reflectance of BCFN/Al. Right: Extinction coefficient of BCFN. (c) Simulated PF_{iso} vs. exciton position in EML. Charge generation layer (CGL) thickness varies as a measure of cavity length.

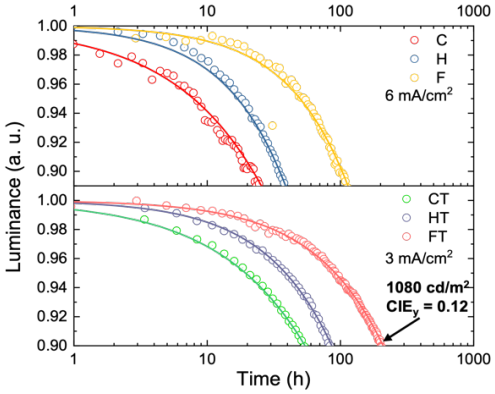

Figure 2. Device lifetime for single-element C, H, F and tandem CT, HT, FT aged at the similar photon exitance. This photon exitance is equivalent to an initial luminance of 1080 cd/m^2 for a deep blue color of CIEy = 0.12.

A tandem device **CT** using the emitting phosphor, PtON-TBBI(4), doubles the forward-viewing EQE up to 36.8% compared to single stack devices **C** and **H**, indicating that the charge generation layer (CGL) does not introduce losses. For the same photon exitance, the tandem structure has half the current density of the single-stack devices. The full cavity tandem PHOLED **FT** using double-sided PEP enhancements achieves 10X lifetime enhancement compared to a weak cavity, **C**, reaching 830 ± 30 h at an initial luminance of 500 cd/m^2. The tandem PEP-PHOLED **FT** has a Commission Internationale de l'Éclairage (CIE) y-coordinate of to CIEy = 0.12 compared to **C** with CIEy = 0.21. This is a deep blue color that is nearly suitable for displays.

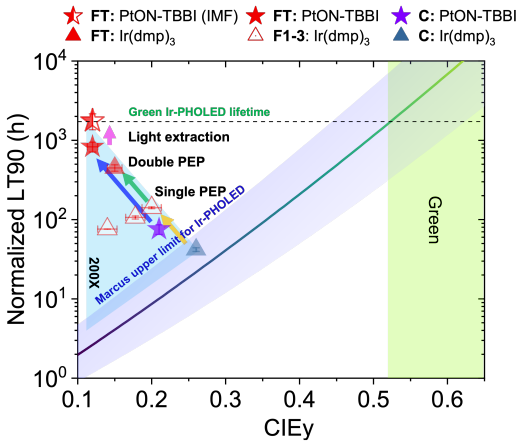

Figure 3. Eliminating the blue-green lifetime gap. Purple shaded area is the estimated intrinsic Ir-complex-based device lifetime using Marcus theory from ref. [4]. Greem shaded area is the green Ir-PHOLED area. Yellow and green arrows show the lifetime enhancement from Ir(dmp)$_3$ control device, single-sided PEP-PHOLED to double-sided PEP-PHOLED. Blue arrow shows the parallel enhancement for Pt-based PHOLED. Pink arrow shows the enhancement from the substrate light extraction using index-matching fluid. A 200X increase from conventional deep blue Ir-PHOLED eliminates the gap between blue-green lifetimes.

3. Impacts

Energy-driven, intrinsic electrochemical degradation due to the triplet annihilation leads to a 10^3 -10^4 lifetime gap between blue and green PHOLEDs(5). Figure 3 shows that the polariton-enhanced Purcell effect in the tandem devices, along with the decrease in current density, corresponds to 50X device lifetime increase compared to the weak cavity, single-stack PHOLEDs with the same chromaticity and photon excitance. This effect is double that from previously reported single-sided, single element

Ir-based PEP-PHOLEDs. The stability enhancement and color saturation is similar for Pt-complex-based devices, showing this method is general applicable to a range of phosphorescent emitters. Furthermore,using substrate outcoupling by applying index-matching fluid, we achieved another 2.1X device lifetime increase, reaching 200X lifetime increase compared to previously reported Ir-complex based blue PHOLEDs, which is comparable to the state-of-the-art green PHOLED lifetimes. The tandem PEP-PHOLED design is compatible with the established OLED fabrication process and can be adapted to either top- or bottom-emitting devices, paving the way for the application of blue PHOLEDs in all-phosphorescent, power-efficient displays.

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