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# Improved out-coupling efficiency from a green microcavity OLED with a narrow band emission source

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ABSTRACT

A highly efficient green microcavity organic light emitting diode was developed using a tetradentate cyclometalated platinum complex, PtN1N, with an intrinsically narrow emission spectral band (FWHM = 18 nm). Devices employing the narrow band emitter in MOLEDs consisting of a single pair of a high index dielectric, $Ta_2O_5$, and low index dielectric, $SiO_2$, exhibited a high peak external quantum efficiency of 33.7% compared to a standard OLED in the same device architecture with a peak external quantum efficiency of 25.6%. We have also found in our study that narrow band emission sources in tuned microcavity OLEDs exhibit larger enhancements in light out-coupling efficiency accompanied by small changes in color with respect to viewing angle compared to broad band emitters which is advantageous in display applications.



## 1. Introduction

Organic light emitting diodes (OLEDs) are a promising candidate for commercial applications in flat panel display technologies due to their low power consumption, low driving voltage, wide viewing angle, and high color gamut [1]. Significant improvements in the device efficiency of OLEDs has been realized through the development of new device architectures [2], efficient charge transporting materials [3], and efficient emissive materials spanning the visible spectrum [4]. In particular, the development of phosphorescent heavy metal complexes, which can harvest all of the electrogenerated excitons, has afforded near 100% electron-to-photon conversion efficiencies in select devices [5,6]. Despite such improvements, the external quantum efficiency remains limited to 20–30% for standard OLEDs on planar glass substrates since most of the generated photons do not contribute to the out-coupled optical power as a result of photon losses inside of the device [7]. These photon losses include surface plasmon polaritions (SPPs) [8], photon absorption at the metal electrode surface [9], and photons trapped by total internal reflection due to the mismatch of the refractive indices between the ITO anode (n~1.9) with glass (n~1.5) (waveguide modes) and the mismatch of refractive indices between glass and air (n~1) (substrate modes) [10]. Thus, care must be taken to improve the light out-coupling efficiency, or fraction of photons emitted from the device to total generated photons. Strategies for this include: using high index substrates ($n \geq 1.8$) [11], creating surface roughness at the glass/air interface [12], implementing an ordered microlens array [13], using a periodic two-dimensional (2D) photonic crystal [14], or through the design of a microcavity OLED (MOLED) [15]. MOLEDs are of particular interest due to their simple fabrication and their ability to be used in conjunction with the other aforementioned strategies [16]. A MOLED is formed by positioning the emissive layer (EML) between a highly reflective cathode and semi-reflective out-coupling mirror separated by a distance on the order of the wavelength of light emitted. Interference effects caused by the cavity redistribute the internal optical field and can change the spontaneous emission of the source inside of the cavity [17]. With an appropriate cavity design, a preferential propagation direction of the photons can be forced from the total internal reflection regime toward the extraction cone, resulting in an increase in light out-coupling efficiency [15–17]. Following this approach, significant improvements in efficiency as well as optical purity can be achieved with only a slight modification to the original device structure [15]. For example, one report from Wang et al. demonstrated an EQE as high as 40% with the addition of a $Ta_2O_5$ capping layer and a gold anode compared to ~25% using a standard OLED on a planar glass substrate with an ITO anode [15a].

It has been previously suggested that microcavity effects are stronger with narrow band emission sources since a larger fraction

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of the emission profile can be accelerated by the cavity [18]. For this reason, organic emitters with narrow emission spectral bands are desired for microcavity OLEDs. However, organic emitters typically exhibit large spectral emission bands with a full width at half maximum (FWHM) between 40 nm and 100 nm, which makes them less suitable for a MOLED design compared with sources that exhibit a narrow spectral emission band, such as inorganic emitters or colloidal quantum dots [19–21]. Recently, select rigid tetradentate Pt complexes were designed to exhibit extremely narrow emission bandwidths [22]. In this report, we employ one of these narrow band emitters, PtN1N, with a FWHM of 18 nm, into a MOLED structure. By tuning the optical cavity [23], a high forward viewing EQE of 33.7% was achieved compared with the reference OLED structure without a DBR which exhibited a peak EQE of 25.6%, which is an enhancement factor of 1.32. Furthermore, compared to a characteristically broad organic emitter in the same structures, PtN1N greatly outperformed the broad emitter in tuned MOLEDs, demonstrating both larger enhancement factors and smaller changes in color with respect to viewing angle. Such a development is a great advantage for many display applications.

## 2. Materials and methods

### 2.1. Materials

The hole injection material, 1,4,5,8,9,11-hexaazatriphenylene-hexacarbonitrile (HATCN), was purchased from Lumtec Corp., the hole transporting layer, N,N′-diphyenyl-N,N′-bis(1-naphthyl)-1,1′-biphenyl-4,4″-diamine (NPD), was purchased from Chemical Alta, and the materials di-[4-(*N*,*N*-di-tolyl-amino)-phenyl]cyclohexane (TAPC), 2,6-bis(*N*-carbazolyl)pyridine (26mCPy) [24], diphenyl-bis [4-(pyridine-3-yl)phenyl]silane (DPPS) [25], 1,3-bis(3,5-dipyrid-3-yl-phenyl)benzene (BmPyPB) [26], platinum(II)-2′-(H-pyrazol-1-yl)-9-(pyridine-2-yl)-9H-2,9′-bicarbazole (PtN1N) [22], and platinum(II)-2-(3-(3-(pyridine-2-yl)phenoxy)phenoxy)pyridine (PtOO3) [27] were prepared following previous literature reports.

### 2.2. Device design

Fig. 1 shows a schematic diagram of the microcavity OLED. The microcavity structure consists of a reflective aluminum cathode and a semi-reflective distributed Bragg reflector (DBR) or quarter wave stack (QWS) out-coupling mirror. The DBR consists of λ/4 optically thick repeat pairs of a high index of refraction material, $Ta_2O_5$ (n = 2.2), and a low index of refraction material, $SiO_2$ (n = 1.46). The reflectivity is tuned by varying the number of DBR pairs [28]. According to theoretical models, for MOLEDs where the optical cavity length is equal to the peak wavelength of the source emission (i.e. a second-order microcavity), it is predicted that an out-coupling mirror reflectivity on the order of 35–45% is ideal for light out-coupling enhancement [29]. However, the accuracy of the approximation depends on many factors such as the absorption of photons at the electrodes, self-absorption from the organic layers, the dispersion relation of the out-coupling mirror, and the spectral distribution of the source. In this study, we investigate a range out-coupling mirror reflectivities by varying the number of DBR pairs in a second order MOLED design from one to three $Ta_2O_5/SiO_2$ pairs with a reflectivity centered on the peak intrinsic emission wavelength of PtN1N. The absolute reflectance versus wavelength for the DBRs in this study were measured using a Varian Cary 5000 equipped with an integration sphere and are shown in Fig. 1b. The optical cavity length was altered by varying the thickness of the hole transporting layer, NPD, in the device structure of glass/DBR(z pairs)/ITO(53 nm)/HATCN(10 nm)/NPD(xnm)/TAPC(10 nm)/8% PtN1N:26mCPy (25 nm)/DPPS(10 nm)/BmPyPB(45 nm)/LiF(1 nm)/Al(100 nm), where x is the thickness of the NPD layer in nm, and z is the number of DBR pairs (0, 1, 2, or 3). The ITO thickness of 53 nm was optimized to achieve a peak reflectivity centered on the peak intrinsic emission wavelength of PtN1N (~490 nm). A 100 nm $SiO_2$ spacing layer was inserted between the ITO anode and $Ta_2O_5$ to extend the optical cavity closer to the intrinsic emission wavelengths without changing the electrical properties of the device.

### 2.3. Device fabrication and characterization

Thin films implementing the high-index of refraction material, $Ta_2O_5$, and the low-index of refraction material, $SiO_2$, were deposited alternatingly on glass substrates in a single chamber using an ion-beam sputtering technique. The last $Ta_2O_5$ layer was capped with a 100 nm $SiO_2$ spacer layer [30]. The DBR stack was then

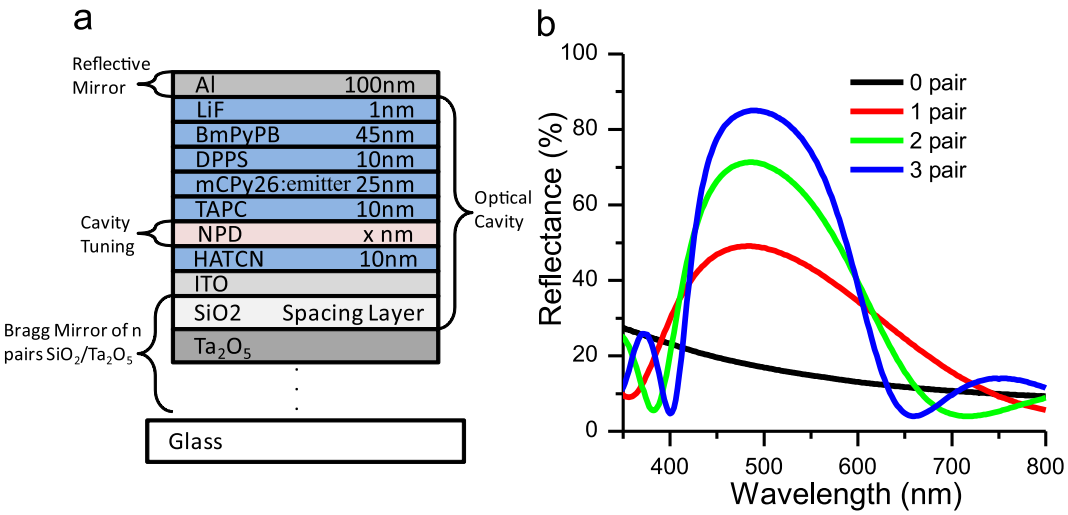


**Fig. 1.** (a) Schematic diagram of the microcavity OLED. The optical cavity is defined between the reflective aluminum cathode mirror and the Bragg mirror, composed of alternating quarter-wavelength thick high index materials, $Ta_2O_5$, and low index materials, $SiO_2$. Cavity tuning was achieved by varying the NPD layer. The emitters in this study were co-deposited with the host, 26mCPy. (b) The reflectance versus wavelength for thin film structures of glass/ITO(60 nm) (black), glass/$Ta_2O_5$(57 nm)/$SiO_2$(100 nm)/ITO(53 nm) (red), glass/$Ta_2O_5$(57 nm)/$SiO_2$(83 nm)/$Ta_2O_5$(57 nm)/$SiO_2$(100 nm)/ITO(53 nm) (green), and glass/$Ta_2O_5$(57 nm)/$SiO_2$(83 nm)/$Ta_2O_5$(57 nm)/$SiO_2$(83 nm)/$Ta_2O_5$(57 nm)/$SiO_2$(100 nm)/ITO(53 nm) (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)