Light out-coupling strategies in organic light emitting devices

Dalip Singh Mehta[1], and Kanchan Saxena[2]
[1]Laser Applications and Holography Lab., Instrument Design Development Centre
Indian Institute of Technology Delhi, Hauz Khas, New Delhi – 110016, India.
[2]Polymeric and Soft Materials Section, National Physical Laboratory,
Dr. K. S. Krishnan Road, New Delhi - 110012, India.
dsmehta@iddc.iitd.ac.in

Abstract: *In this paper we present various light out-coupling techniques that have been implemented to enhance the external efficiency of OLEDs. Various internal and external OLED device modification techniques have been reviewed and discussed. Some of the most efficient techniques, such as, substrate modification, use of micro-lens array, two-dimensional photonic crystal structure, nano-patterned and nano-porous films are reviewed, and discussed.*

Keywords: Organic light emitting devices; light out-coupling techniques; external efficiency.

Introduction

There has been considerable amount of research and development for the improvement of efficiency of organic light emitting diodes (OLEDs) because of their potential applications in general illumination, flat panel displays, automotive and outdoor lighting. Numerous efforts have been made to improve their external coupling efficiency ($\eta_{cp,\ ext}$) by means of improved device concepts, such as electrode modifications, synthesis of new organic materials and device fabrication[1-2]. The light generation mechanism in OLEDs is due to the radiative recombination of excitons on electrically excited organic molecules. Light is generated from thin organic emitting layer spontaneously in all the directions and propagates via various modes, that is, external modes (escape from the substrate surface), substrate-, and ITO/organic-waveguided modes due to total internal reflection (TIR)[3-7]. According to classical ray optics theory a large amount of generated light is lost in waveguided modes due to glass substrate and ITO/organic material which means that the majority of the light is either trapped inside the glass substrate and device, or emitted out from the edges of an OLED device. It is well known that the fraction of generated light escaping from the substrate, $\eta_{cp,\ ext}$ is[7]

$$\eta_{cp,ext} \approx \frac{1}{2n_{org}^2} \tag{1}$$

and the fraction of light trapped in the substrate $\eta_{cp,\ subs}$ and in the ITO/organic layers $\eta_{cp,\ org}$ are given by[7]

$$\eta_{cp,subs} = \cos\theta_{org,c1} - \cos\theta_{org,c2} \tag{2}$$

$$\eta_{cp,org} = \cos\theta_{org,c2} \tag{3}$$

where $\theta_{org,\ c1}$ and $\theta_{org,\ c2}$ are the critical angles between organic–air and organic-substrate, respectively. For the purpose of applications in general illumination and flat panel displays, light emitted from the substrate surface (external modes) is most useful which is only 20% of the total emitted light from the OLED device. Figure 1 shows the schematic diagram for typical OLED structure and the light propagation via various modes. According to classical Ray optics theory, the coupling efficiencies of the external, substrate, and the ITO/organic-waveguide modes are ~ 20%, ~30%, and ~50 % respectively[4-5]. In this paper we present various light out-coupling techniques that have been implemented to enhance the external efficiency of OLEDs. Various internal and external OLED device modification techniques are reviewed and discussed.

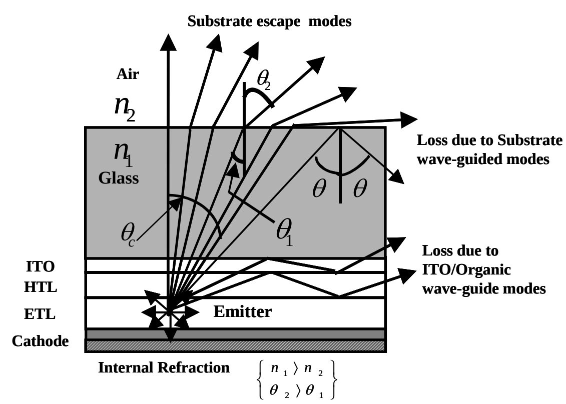

Figure 1. Schematic diagram illustrating light-loss due to wave-guided modes.

Light out-coupling techniques

Shaped substrate technique: To extract the substrate wave-guided light one of the simplest technique is the use of shaped substrate technique. Various substrate shaping techniques have been implemented for enhancing the external out-coupling efficiency of generated light[3, 7--9]. Gu et al[7] demonstrated a novel substrate structure that can increase the external out-coupling efficiency by a factor of 4 over that obtained with flat surface. It has also been reported that further efficiency improvement can be obtained by depositing a thin film of a low-loss, high-refractive-index dielectric material on glass substrate before ITO followed by mesa etching[7]. In an another approach, a spherically shaped patterns on the back side of the glass substrate were used for improvement of external out-coupling efficiency in OLEDs[8]. Figure 2 shows the extraction of substrate wave-guided modes using a spherically shaped backside substrate. A spherically shaped substrate acts as a refractive index matching material and it also acts as a lens. Due to these modifications the substrate-waveguided modes are coupled out from the substrate. A factor of 9.6 for emission intensity at normal viewing angle and 3.0 for total emission intensity was reported.

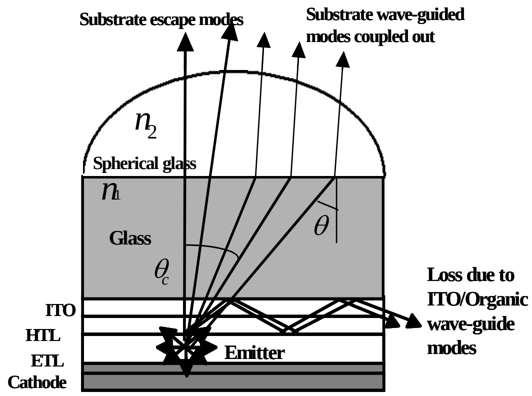

Figure 2 Schematic diagram illustrating spherically shaped substrate for coupling out the substrate-wave-guided modes.

Micro-lens arrays: Use of ordered and disordered micro-lens arrays on the backside of substrate surface have been demonstrated[10-12]. It was shown that the external out-coupling factor of the OLED devices increases by a factor of 1.5 and 1.8, respectively. With the incorporation of micro-lens arrays waveguiding loss in the substrate is suppressed remarkably and light is coupled out. Figure 3 shows the schematic diagram of OLED structure with ordered micro-lens arrays for improving the light out-coupling efficiency of OLED.

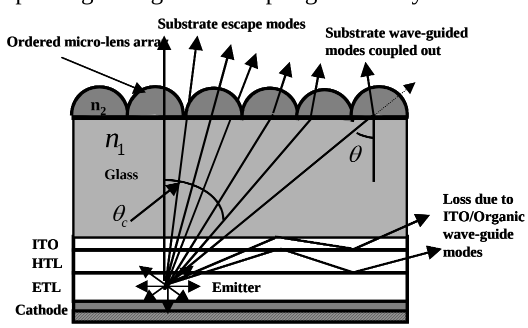

Figure 3 Use of micro-lenses for extracting substrate wave-guided modes.

More recently, Peng et al[11] have reported that with the use of an optimized micro-lens pattern, an increase of over 85% in the coupling efficiency of the OLED is expected theoretically and 70% was achieved experimentally, without detrimental effect to the electrical performance of the OLED. Further, a well designed micro-lens arrays may also act as beam shaping device[14].

Micro-cavity OLEDs: Several research groups have demonstrated the incorporation of well designed micro-cavities in OLEDs[16 - 20]. Micro-cavity OLEDs can improve upto twofold enhancement in luminance and cd/A. A typical micro-cavity OLED consists of a bottom mirror composed of dielectric distributed Bragg reflector (DBR) and a top metal mirror. In the presence of micro-cavity, due to field redistribution and the influence of cavity on the transition rate of molecular excited states, enhancement in forward direction emission is observed. Even week reflections in an OLED micro-cavity can influence device luminescence properties significantly. The micro-cavity determines the electric-field mode distribution, thereby modifying the exciton spontaneous life-time and hence the quantum efficiency. This intern can modify the spectral width, spectral peak, distribution of emission intensity, and directionality of emission of radiative dipoles in layered media. Because of the micro-cavity structure spectral narrowing, strongly directed and enhanced intensity is observed[17-18]. Such micro-cavity OLED have been found to be very much suitable for displays. More recently, a fivefold enhancement in luminance was achieved with cavity tandem devices having only two emitting units[21]. Fig. 4 shows the two-unit tandem micro-cavity OLED. A very high efficiency of 200 cd/A has been demonstrated with a phosphorescent cavity two-unit device. The optimized microcavity TOLED shows a current efficiency enhancement of 65% and a total out-coupling efficiency enhancement of 35%, compared with a conventional OLED. No color variation was observed in the forward 140° forward viewing cone.

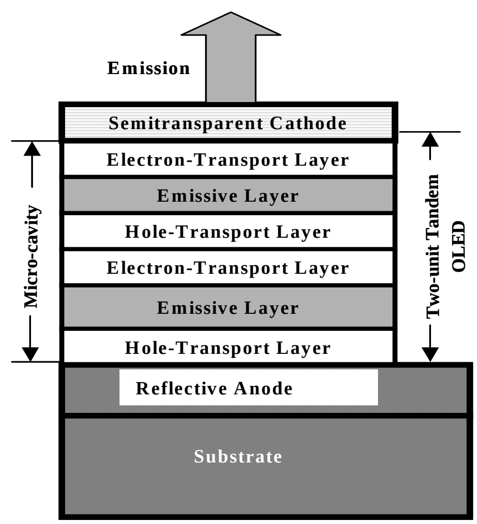

Fig. 4 Two-unit tandem micro-cavity OLED.

Two-dimensional photonic crystal structure: OLEDs with two-dimensional photonic crystal structure have been fabricated by several groups[22-24]. Photonic crystal (PC) is a periodic dielectric structure with the possibility to control light variously. When the period of a two-dimensional (2D) PC is equal to the cavity wavelength of the guided mode, the guided waves propagating to several in-plane directions are coupled to the radiation mode in the direction normal to the device surface since the Bragg diffraction condition is satisfied. Two-dimensional PC devices containing two-dimensional (2D) SiO_2 /SiN*x* photonic crystal (PC) layers have been studied and it has been demonstrated that incorporation of the PC layer in OLED device improved the light extraction efficiency by over 50% compared to the onventional OLED, without noticeable degradation in electrical characteristics, under typical operating conditions[22]. Figure 5 demonstrates the use of two-dimensional photonic crystal OLED for extracting ITO/Organic wave-guided modes. This improvement originates from the liberation of the photons trapped in the high-index guiding layers.

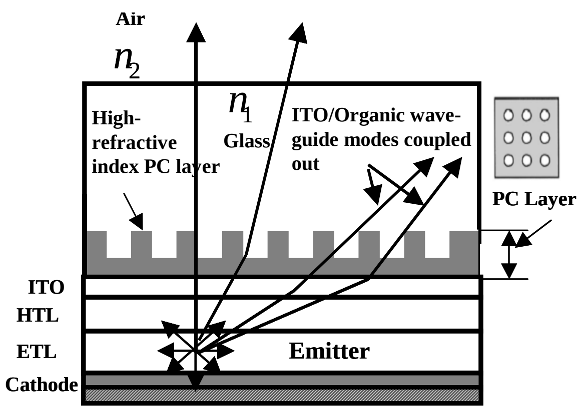

Figure 5. Use of two-dimensional photonic-Crystal structure for extracting the ITO/Organic wave-guided modes

*Nano-patterned and Nano-porous films***:** Various nano-patterning techniques have been developed recently, such as, conventional lithography, interfering lithography, electron-beam lithography, nano-contact printing, Dip-Pen lithography, and nano-imprinting.. To improve light extraction from organic light-emitting diodes a nano-pattern of 2D- nanohole array into the SiO2 film is carried out on top of ITO glass patterned with 3 mm stripes was developed[25]. A 2D nanohole array template was introduced onto a patterned ITO glass substrate by two-step irradiated hologram lithography and reactive ion etching, and then a 2D nanohole OLED array was prepared by following typical OLED fabrication procedures. Lee *et al*[26] introduced a nano-patterned photonic crystal into the glass substrate to improve the coupling efficiency. An enhancement factor of 1.5 over viewing angle of ±40° was achieved. The periodic modulation converts the guided waves in the high-refractive-index indium-tin-oxide/organic layers into external leaky waves. Finite-difference time-domain method was used to optimize the structural parameters of the photonic crystal pattern and to analyze the microcavity effect by the metallic cathode of the OLED. With the use of an optimized photonic crystal pattern, an increase of over 80% in the extraction efficiency of the OLED is expected theoretically. An increase in the extraction efficiency of over 50% was achieved experimentally, without detriment to the crucial electrical properties of the OLED. Nanoporous[27] alumina film was used to modify the optical wave propagation and coupling of light from the OLED. Experimental results showed an increase of over 50% in the coupling efficiency of the nanoporous device, without affecting the electrical properties of the OLED.

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