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ScienceDirect
Organic Electronics 7 (2006) 490–494
Organic Electronics
www.elsevier.com/locate/orgel

Using a low-index host layer to increase emission from organic light-emitting diode structures

L.H. Smith, W.L. Barnes *

School of Physics, University of Exeter, Exeter, EX4 4QL, UK

Received 22 March 2006; received in revised form 29 June 2006; accepted 7 July 2006
Available online 15 August 2006

Abstract

The out-coupling efficiency of organic light-emitting diodes (OLEDs) may be significantly increased by use of a low-index host material for the organic emitters. We report on modelling undertaken for substrate-emitting and top-emitting OLED structures and show that up to a 2.5 fold increase in out-coupling efficiency, over that for structures containing a standard emissive layer, may be achieved in both cases. The relationship between radiation efficiency and refractive index varies for each type of structure and this is discussed, as is the nature of the electromagnetic (EM) modes supported.

PACS: 85.60.Jb; 72.80.Le

Keywords: Organic light-emitting diode (OLED); Out-coupling efficiency; Refractive index

1. Introduction

Since their introduction in 1987 [1] much work has been undertaken concerning organic light-emitting diodes (OLEDs), with a large amount of this work centring on the efficiency of such devices. Research into improving efficiency may be split into two main branches, optical efficiency and electrical efficiency. Both of these factors must be considered if one is to construct an efficient device. Much of the work into efficiency has concentrated on the electrical aspect, with huge advances being made. These have included improvements to hole and electron injection [2–4], and the introduction of phosphorescent materials [5,6]. However, there is still much scope for further improvements particularly by way of optical out-coupling efficiency – the amount of light produced within a device which escapes as radiation. Most of the light generated within an OLED, typically about 80%, is trapped, and if this could be recovered the overall device efficiency could be significantly enhanced. To date, a number of methods have been investigated with this aim in mind [7–12]. Here we examine how reducing the refractive index of the organic host layer may improve the efficiency with which light is extracted from the device.

The refractive index of a typical organic emissive material is approximately 1.7 (dielectric permittivity, $\varepsilon = 2.89$) within the optical regime. A simple ray model can be used to demonstrate that the pro-

* Corresponding author. Tel.: +44 (0) 1392 264104; fax: +44 (0) 1392 264111.
E-mail address: w.l.barnes@ex.ac.uk (W.L. Barnes).

1566-1199/$ - see front matter
doi:10.1016/j.orgel.2006.07.001

portion of light lost to these waveguide modes may be reduced by using an emissive layer whose refractive index is less than 1.7. For example, considering a structure consisting of air and an organic layer, with a refractive index of 1.7, only light emitted within the cone of ±36° relative to a surface normal may be radiated into air. However, if the index of the organic is reduced to 1.5, the radiation cone increases to ±42°. These escape cones correspond to 40% and 47%, respectively, of the total power dissipated by the emitter.

Different materials whose refractive indices are less than 1.7 are now being used as hosts for organic emitters. A host is a non-emissive material in which emissive organic molecules may be placed. An example of such a host is polystyrene (PS) which is non-polar and produces a high quality film [13]; the ratio of host to emissive molecules used by Yang et al. [13] was 83:17% by weight. The refractive index of PS is 1.58 within the visible spectrum and thus acts to reduce the power dissipated by the emitter into waveguide modes.

Low-index materials may also be used for other OLED layers. For example, Tsutsui et al. [12] used an aerogel layer placed between the indium-tin-oxide (ITO) and silica layers of a substrate-emitting OLED. Aerogel has a very low refractive index of 1.03, and is almost transparent. Within an OLED, this layer decreases the amount of power that is lost to waveguide modes within the thick silica substrate, and as a result the fraction of the total power radiated is increased.

Here we investigate the use of low-index host materials within two types of OLED, substrate- and top-emitters. We focus on the optical out-coupling efficiency and demonstrate the dependence of this efficiency on the index of the host layer.

2. Method

The structures considered for this study are illustrated in Fig. 1. Fig. 1(a) shows a substrate-emitting OLED consisting of an aluminium (Al) cathode, a host layer containing the organic emitters, an ITO anode and a thick silica substrate. The Al cathode is considered to be optically thick for the purposes of the modelling. Fig. 1(b) displays a top-emitting structure consisting of a composite silver (Ag)/ITO anode, a host layer containing the organic emitters, and a composite Ag/ITO cathode. In this structure the Ag part of the anode is taken to be optically thick.

We have considered host materials with refractive indices in the range of $n = 1.0 \rightarrow 1.76$, which corresponds to dielectric permittivities off $\varepsilon = 1.0 \rightarrow 3.1$. By way of example, the emitters placed within the host material are taken to be the first generation *fac-tris*(2-phenylpyridine) iridium-cored dendrimer (Ir–Gl) [14]. For each of the cases studied here the emission spectrum of Ir–Gl has been accounted for, with the results weighted accordingly. The index of the host material is assumed to be dispersionless over the emission range (∼450–700 nm). When Ir–Gl is used as an emissive organic material within an OLED it is often mixed with another material, for example 4,4′-bis(*N*-carbazole) biphenyl 3 (CBP). The index of Ir–Gl and CBP mixed 20:80% by weight [14] at the peak emission wavelength of 518 nm is 1.76 ($\varepsilon = 3.1$). We have chosen to represent the dielectric permittivities of Al, Ag and ITO by polynomial functions [15].

To model the structures we make use of a classical technique which calculates the power lost by an emissive dipole in a planar multilayered structure

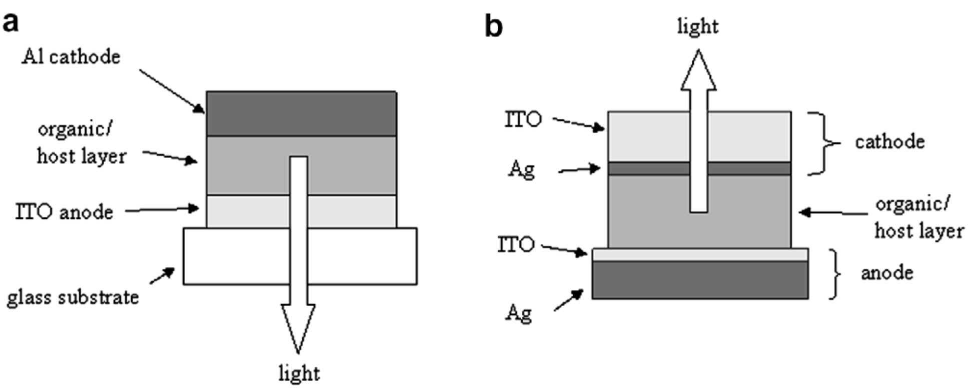

Fig. 1. Schematics of the (a) substrate-emitting and (b) top-emitting OLED structures investigated.

[16–18]. The emitters are considered as forced, damped, electric-dipole oscillators. The dipole field is represented by a sum of plane waves, each wave being characterised by a different in-plane wavevector, k_x, where k_x is the component of the wavevector parallel to the interfaces. The model allows the modes of a given structure to be identified and provides information as to the strength of coupling between the emitter and these modes [16–18]. It can also be used to calculate the percentage of the total power dissipated that may emerge from a structure as useful far-field radiation. This radiated percentage is often referred to as the out-coupling efficiency.

3. Results

For a number of host layer ε values within the range of $1.0 \rightarrow 3.1$, the maximum possible out-coupling efficiency has been calculated for the structures shown in Fig. 1. The optimum dimensions of both the organic and ITO layers, for each ε value, have been determined to the nearest 5 nm, and the radiation from this optimised structure calculated. Plots showing these results are displayed in Fig. 2.

Considering first the substrate-emitters, it may be seen that the power radiated increases significantly as the host layer ε value is reduced. It is apparent from the plot that there are two different regimes. The first, with the organic emissive host layer having $\varepsilon_{org} = 1.0 \rightarrow 2.1$, describes host layers with $\varepsilon_{air} \leqslant \varepsilon_{org} < \varepsilon_{silica}$.

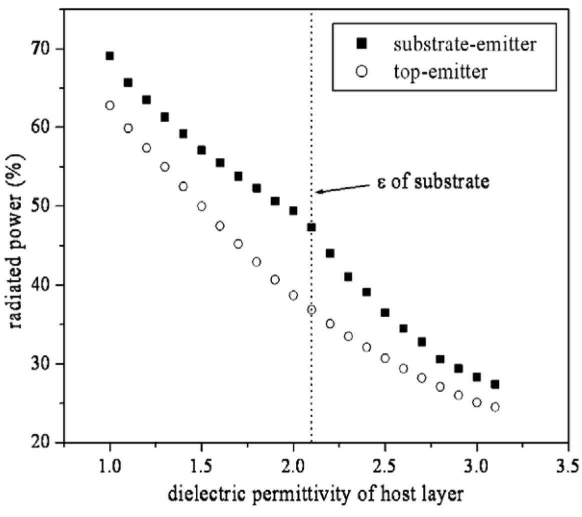

Fig. 2. A plot showing the percentage of the total power radiated (the optical out-coupling efficiency) for the substrate-emitting (■) and top-emitting (○) OLED structures.

The second regime, with $\varepsilon_{org} = 2.1 \rightarrow 3.1$, describes host layers with $\varepsilon_{org} > \varepsilon_{silica}$.

If the host material has $\varepsilon = 1.0$ then the amount of power radiated from the structure reaches 69.1%. With a value of $\varepsilon = 2.0$ this is reduced to 49.4%, and for $\varepsilon = 3.1$ only 27.4% of the power is radiated from the structure. This dramatically demonstrates the potential of lower index host layers to improve optical out-coupling.

In contrast, the data for top-emitters displays only one regime, with the radiated power decreasing as the dielectric permittivity of the host material is increased. It is the lack of a silica layer which leads to this result; the organic host layer is now always of a lower dielectric permittivity than the other structure layers above it (Ag and ITO). In this case, if the host material has $\varepsilon = 1.0$ then the power radiated form the structure may be 62.7%, falling to 38.7% for $\varepsilon = 2.0\%$ and 24.5% for $\varepsilon = 3.1$.

The structure dimensions required for maximum radiation for each different ε value vary greatly. As the ε value of the host material increases, the cavity thickness decreases. For example, for the substrate-emitting structure, at $\varepsilon = 1.0$ the combined organic/ITO cavity thickness is 385 nm. However, at $\varepsilon = 2.0$ this thickness is 275 nm, and at $\varepsilon = 3.0$ it is only 225 nm. This behaviour is expected as higher ε – valued materials increase the effective cavity width [19]. A cavity consisting of materials with high ε values has a lower cut-off thickness for waveguide modes than a cavity comprising low ε – valued materials. For the top-emitting structures the trend is the same. The combined organic/Ag/ITO cavity thickness for a host layer value of $\varepsilon = 1.0$ is 360 nm. For $\varepsilon = 2.0$ this is 195 nm and for $\varepsilon = 3.0$ it is 170 nm.

In order to gain an understanding of the nature of the modes supported by structures incorporating host layers with differing ε values, it is instructive to examine dispersion diagrams calculated for these structures. Such dispersion diagrams may be produced using the oscillating dipole model [16–18] and display the power dissipated by the emitter as a function of both k_x and angular frequency, ω. Figs. 3(a) and (b) show such plots for ε values of 1.06 and 3.0 respectively for the substrate-emitting structure. The value of $\varepsilon = 1.06$ is equivalent to that of aerogel, a material which might in future perhaps be used as a host. The value $\varepsilon = 3.0$ represents a typical value for organic emitters. It is evident from the plots (Figs. 3(a) and (b)) that the two substrate-emitting systems are very different in nature.

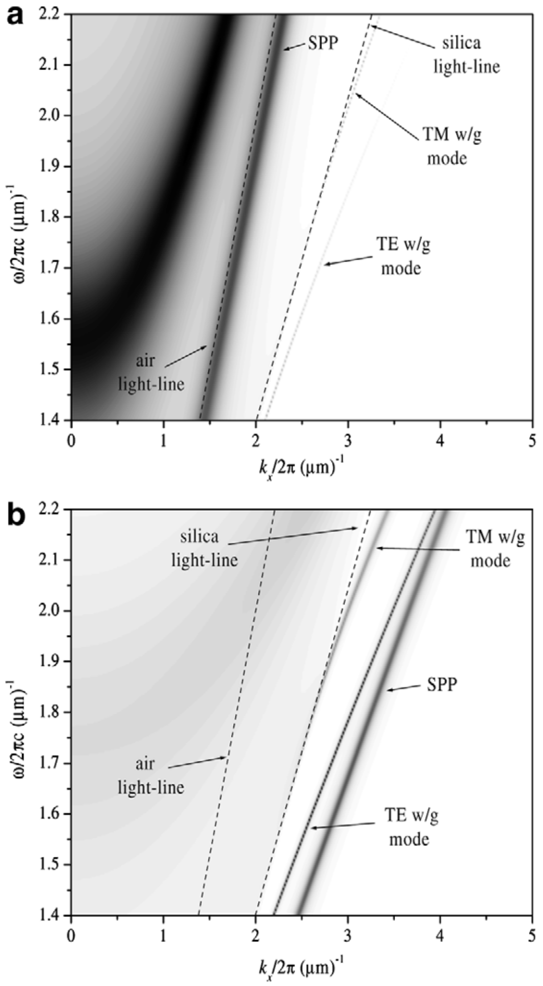

Fig. 3. Dispersion diagrams for the substrate-emitting OLED structure shown in Fig. 1(a) for ϵ values of the host material of: (a) 1.06 and (b) 3.0.

Although both structures support two waveguide modes and one surface plasmon-polariton (SPP) mode the dispersion of these modes varies, and crucially so does the strength with which the emitter couples to them. From Fig. 3(a), showing the modes for a system containing a host with $\varepsilon = 1.06$, the vast majority of the dissipated power lies within the air light-line. The strong feature within this region is a leaky waveguide mode and much of the power lost to this mode emerges from the structure as radiation. The SPP mode in this case is close to the air light-line and will lie just to the right of the host layer light-line. It is the only guided mode within the structure to which a significant amount of power is lost. The two waveguide modes, one TE- and one TM-polarised, are very weak in nature. This is because the k_x values of the photons emitted in the organic layer are low enough that they are not reflected by the silica/ITO interface, thus preventing the formation of a cavity. It may also be noted that for the same reason, a negligible amount of power is trapped within the silica layer.

The reasons for a drop in radiated power when a higher ε – valued material is used may be observed from Fig. 3(b). Using a host with $\varepsilon = 3.0$ leads to sharper, stronger guided modes which account for much of the dissipated power. This means that less power is lost to the left of the light-line than for the structure modelled in Fig. 3(a). A considerable fraction of power is also trapped within the silica substrate in this case as some light produced within the organic layer has k_x values too high to escape this layer.

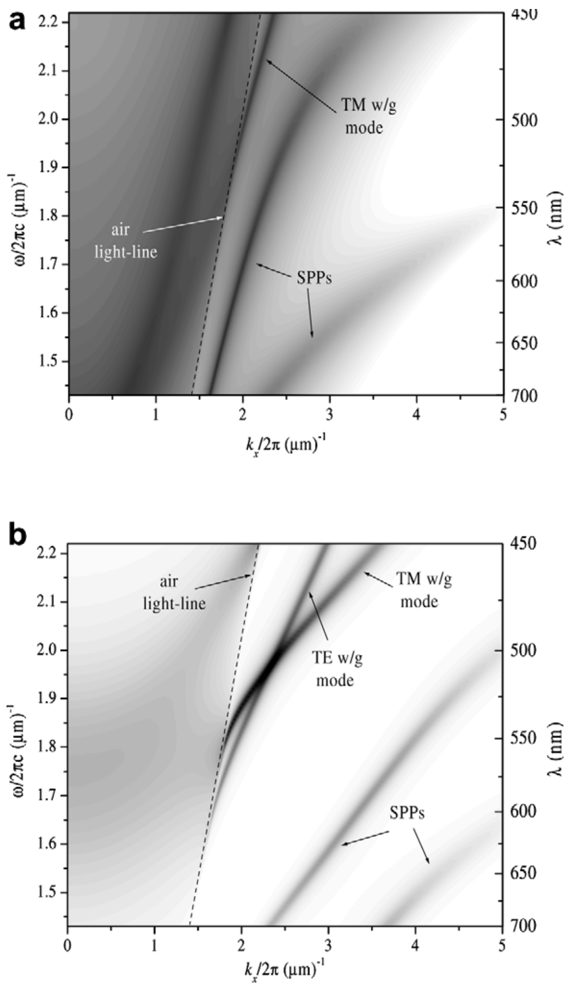

Fig. 4. Dispersion diagrams for the top-emitting OLED structure shown in Fig. 1(b) for ϵ values of the host material of: (a) 1.06 and (b) 3.0. Note that for (a) the z-axis is on a log scale to allow the highest k_x valued SPP mode to be seen.

Fig. 4 shows similar dispersion diagrams but for the top-emitting structure, with (a) and (b) corresponding to host layer ε values of 1.06 and 3.0 respectively. As for the substrate-emitting system, these plots differ greatly from one another. Both structures support two SPP modes which are coupled with respect to the thin Ag cathode layer and are both also influenced by the Ag anode interface. From Fig. 4(a), when $\varepsilon = 1.06$, it may be seen that there is one TM waveguide mode close to the air light-line and another leaky mode within the light-line. It is this leaky mode which provides most of the far-field radiation from this structure and yields the relatively high out-coupling efficiency. When $\varepsilon = 3.0$, Fig. 4(b), both of these modes lie to the right of the light-line and hence are trapped modes. This leads to a lower out-coupling efficiency for this structure.

4. Conclusions

We have investigated the effects of using a low-index material as a host for organic emitters within an OLED. We have considered two types of structure, substrate- and top-emitting OLEDs. For the substrate-emitting structure it was shown that the out-coupling efficiency may be enhanced by up to 2.5 times its value for a standard organic emissive layer by use of a lower index host material. The relationship between radiation and ε is clearly divided into two regimes. For the top-emitting structure a similar 2.6 fold increase in out-coupling efficiency may also be achieved by use of a host material.

This modelling clearly indicates the desirability of keeping the refractive index of the emissive layer as low as possible. This poses a significant materials challenge since none of the emitting materials to date have the low index required. As a result emissive molecules would probably need to be dispersed in a low index host. However, there is then the competing requirement of having a high enough loading of the emissive guest to achieve the desired electrical characteristics. If this problem could be overcome then this material has the potential to increase the efficiency of OLEDs by more than a factor of two over the efficiency of current devices.

Acknowledgements

The authors would like to thank both the EPSRC (through the DTI-link Project XTRAOLED) and CDT for financial support. This work was also supported by “Surface Plasmon Photonics”, an EC funded STREP Project, FP6 NMP4-CT-2003-505699.

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