Improved light emission from OLEDs for lighting

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ABSTRACT

Organic light emitting diodes (OLEDs) are now widely used in smart phones and some lighting products are already commercially available. Key parameters towards the success of OLEDs for lighting are efficiency, lifetime and cost. As several phosphorescent materials have an internal efficiency that is close to unity, the most important factor in the efficiency is the coupling of photons from the OLED to air. The design of the stack and the addition of scattering structures to avoid total internal reflection are essential.

INTRODUCTION

The OLED technology can provide thin, homogeneous white light sources on glass or on plastic. Current lighting panels are produced by Philips, Osram, Lumiotec, AcuityBrands and LG Chem and have areas in the order of 100 cm^2, but larger panels are under development. The brightness of these commercially available devices is very homogenous and of the order of a few thousand Cd/m^2 while the efficiency ranges between 30 and 80 lm/W. As there is not yet any mass production of OLED lighting devices, the cost remains high, but this may change in the future.

The light generation mechanism in an OLED consists of two steps: first a hole and an electron which are injected from the anode and the cathode recombine in the organic layer and form an exciton; when the exciton recombines a photon can be emitted. Thanks to the introduction of hole and electron blocking layers in the OLED stack, practically equal amounts of holes and electrons are injected from the electrodes and almost all injected electrons and holes combine to form excitons. The main limitation in the efficiency arises from the fact that not all excitons yield photons that are emitted into air, because there is competition from other processes: non-radiative decay of excitons; absorption of light in the OLED device (metal cathode, organic layers, transparent electrode); total internal reflection and waveguiding in the OLED substrate [1].

Prototypes with internal efficiencies of over 100 lm/W have been demonstrated by different research groups. This means that there is strong motivation to increase the extraction of light from the OLED stack into air. In this contribution, we will look into some opportunities to increase the light output.

APPROXIMATION BY GEOMETRICAL OPTICS

The OLED stack in which the light is generated has a relatively high refractive index of 1.8, which is larger than that of glass (1.5). When light is generated isotropically inside a planar plate with such a high refractive index, only 17% of the light has an angle of incidence below the critical angle (34^{o}) and can be emitted into air. All the rest (83%) will be reflected back and forth between the top and bottom surfaces of the plate until reaching the side of the plate or will be absorbed. There are several ways to improve the efficiency of the light extraction. The outcoupling of the light can be increased to practically 100 % by placing the emitters in a sphere of the same refractive index (and adding an anti-reflection coating at the surface), but this is not a practical solution, because materials with such a high refractive index are expensive and a lot of material is needed if only the center of the sphere is used. This is the configuration that is used to find record efficiencies [2].

An intermediate solution is to add small structures on the planar plate as illustrated in Fig. 1. Now the angle of propagation in the plate changes after reflection on the structures and (possibly after a few reflections) the light will be able to exit the high index plate. If all materials would be perfectly transparent, the total emission would still be 100%, but this is not the case, because the metallic cathode and the organic layers themselves all have some optical absorption. As a result the optical outcoupling will always be less than 100%. As the high index materials are expensive, the OLED is usually deposited on a substrate with a lower refractive index, which will also guide part of the light.

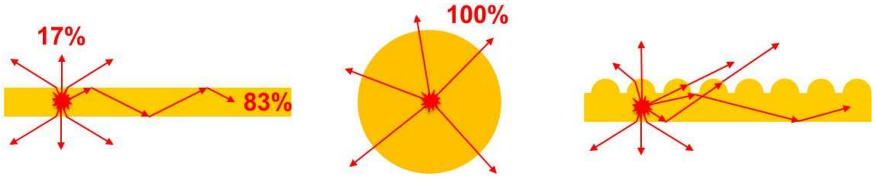

Figure 1. Outcoupling from a material with a high refractive index (n=1.8). Left: from a planar structure; middle: from the center of a sphere; right: from a structured surface.

DIPOLE RADIATION AND INTERFERENCE EFFECTS

Because the conductivity of the organic layers is small, the layers in an OLED usually have thicknesses in the order of a few hundred nm, which is comparable to the wavelength of light. The emission of a photon by exciton recombination occurs through an electrical dipole transition. The emission of light can be simulated by the classical theory of an elementary electrical dipole antenna in the OLED stack. The orientation of the electrical dipole antenna and the distance between the antenna and the reflecting cathode are important parameters that determine the emission pattern and the outcoupling efficiency. The emission from one particular dipole transition is coherent and the electric fields of waves that have reflected at different surfaces have to be added coherently, which leads to interference effects. On the other hand, different excitons decay in a non-coherent way and the intensity contributions (not the electric field contributions) have to be summed.

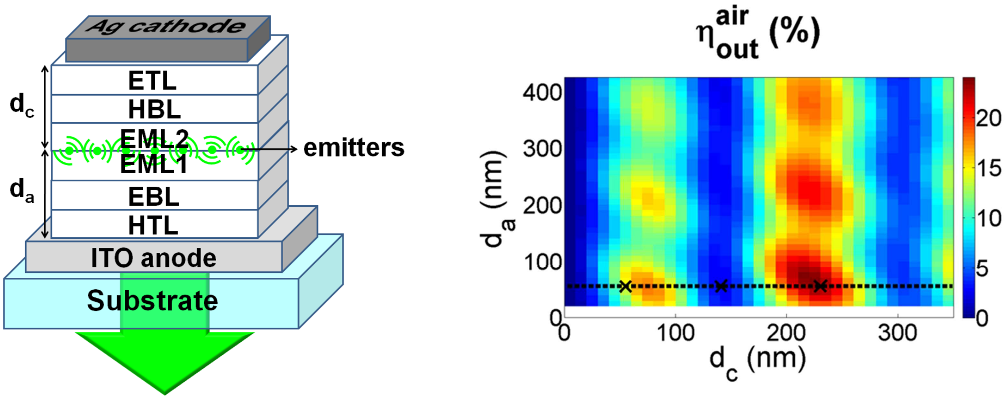

Figure 2. Left: planar structure of an OLED, indicating the location of the dipole emitters. Right: outcoupling efficiency in air as a function of the distance between the emitters and the cathode and anode.

The integrated power emitted by an electrical dipole antenna depends on the optical environment of that antenna. For the decay of an exciton, this implies that the probability for radiative decay depends on the location of the dipole and the structure of the OLED, as illustrated in Fig. 2. In addition, there may be an intrinsic non-radiative decay channel due to quenching sites. The value of radiative and non-radiative contributions can be separated by measuring the decay rate of the same molecule in the same organic layer that is placed in a different stack with different interference effects [3, 4].

Some planar luminescent molecules tend to orient mainly parallel with the substrate when they are deposited in vacuum and the electrical dipole that governs the emission is then also parallel to the substrate. Dipole antennas emit more radiation perpendicular to the axis of the dipole and therefore dipoles that are oriented parallel with the substrate emit more efficiently to air [5]. The decay rate also depends on the orientation of the dipole antennas and this has been observed experimentally [6].

Some organic materials that consist of long or planar molecules that are oriented during deposition have anisotropic optical properties [7]. Such materials have birefringent properties and this also has an impact on the emission pattern of electrical dipole antennas [8].

INCREASED OUTCOUPLING BY REFRACTION AND DIFFRACTION

As explained in the introduction, adding some structure to the OLED stack or the substrate is beneficial in order to avoid repeated total internal reflection. The simplest solution is to use a substrate that has scattering particles in the bulk or roughness on the opposite side of the OLED, as this does not interfere with the requirements for the deposition of the OLED. In this approach it is important that the roughness or the scattering can modify the angle of the rays sufficiently during one pass, otherwise the emission will be mainly at grazing angles with the substrate. It helps when the substrate has a higher refractive index, because in this case, most of the light is able to reach the substrate, and is not totally internally reflected within the OLED stack.

In order to reduce the light trapped inside the OLED stack, some structure has to be added within - or in the range of the evanescent field of – the OLED stack. One difficulty is that structures that can scatter light may disturb the electrical operation of the OLED and introduce shorts with increased electrical current and faster aging.

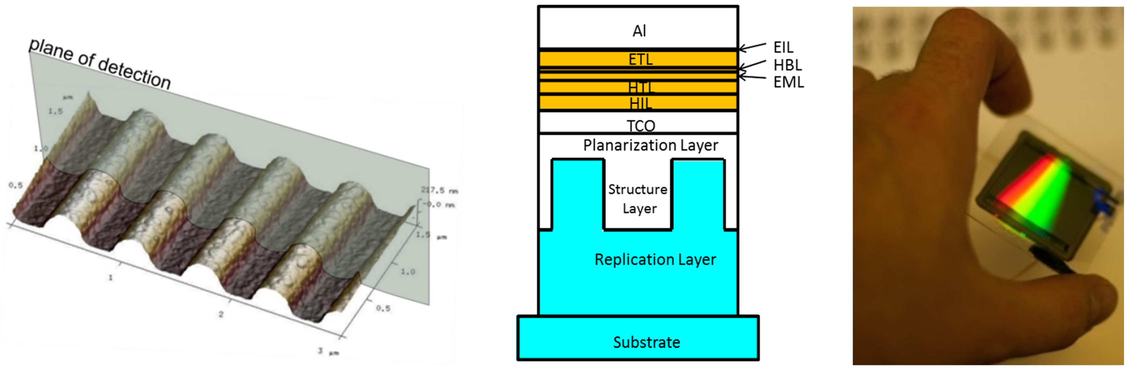

Figure 3. OLED deposited on a substrate with a structured layer. Left: AFM picture of the structured layer; Middle: OLED device deposited on the structured layer after planarization; Right: photograph showing diffraction of reflected light.

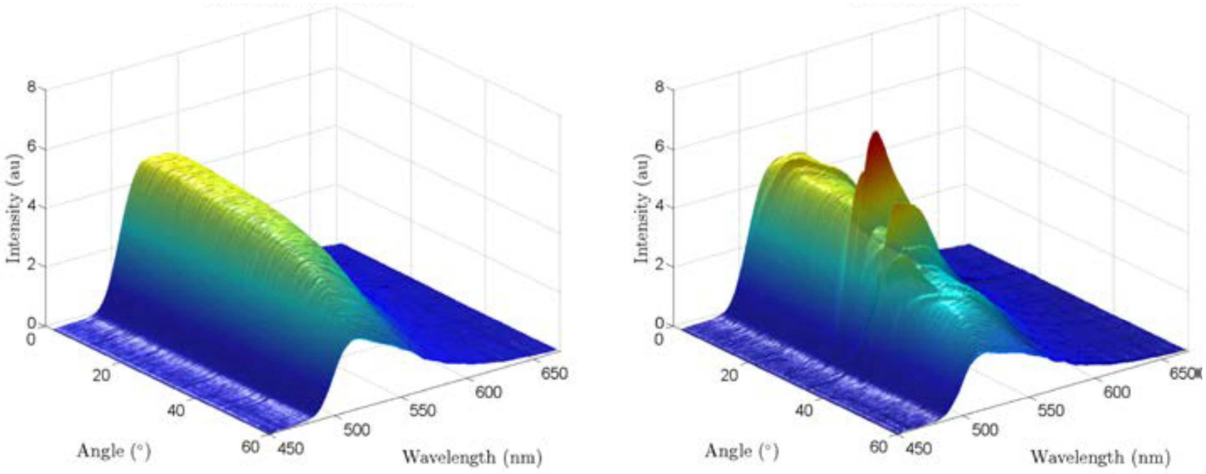

Figure 4. Emission intensity as a function of the emission angle and wavelength. Left: reference for a planar OLED device; Right: measurement for the device with a nanostructure below the OLED.

The approach illustrated in Fig. 3 uses a planarization layer and a structure with a periodicity of 600 nm which is sufficiently small to couple modes that are normally trapped inside the organic stack (with the higher refractive index) into air. Fig. 4 shows that the structure leads to additional emission that is visible in air, with different colors exiting at different angles [9].

CONCLUSIONS

OLEDs are extremely thin and can emit homogeneous bright white emission. Large area devices, high efficiencies and long lifetimes have been demonstrated, the cost is still a factor that limits a breakthrough to the consumer market. Light outcoupling remains one of the most important research topics to increase the light output and the efficiency. The use of anisotropic emitters and structured devices has a lot of potential to improve the quality of OLED devices.

Acknowledgements

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