Design of OLED glass patterns for enhanced outcoupling efficiency and good colour stability

Japan Advanced Institute of Science and Technology (JAIST)[1], IMRA America Inc.[2], °Savanna Lloyd[1], Tatsuya Tanigawa[2] and Hideyuki Murata[1]

E-mail: murata-h@jaist.ac.jp

Organic light emitting diodes (OLEDs) have been able to achieve almost 100% internal quantum efficiency (IQE, η_{IQE}), thanks to the development of active phosphorescent emitter materials. However, these devices still suffer from very low external quantum efficiency (EQE, η_{EQE}) due to the limitation of low light outcoupling efficiency (η_{OUT}), where

$$\eta_{EQE} = \eta_{IQE}\,\eta_{OUT}$$

For a typical bottom emitting OLED structure, only about 20% of light can escape into the forward viewing direction [1-2] due to light losses at 3 main interfaces; at the air/substrate [1, 2, 3-5] and substrate/organic interface [1, 2] (as a result of total internal reflection due to differences in refractive index) and at the organic/metal [3] interface. Of specific interest, previous works employed at the substrate/air interface to reduce substrate waveguided modes include for example; microlens [2, 3] and nanolens arrays [4], and nanoporous polymer films [5]. Associated with such outcoupling structures, strong view angle dependence (colour shifting) may present itself [6] while those intended to suppress view angle dependence, however, do not affect the outcoupling efficiency [5, 7].

In this work, based on our previously fabricated OLEDs with patterned glass substrates via Yb-doped fiber laser (FCPA µJewel DX-0540, IMRA America, Inc.) [8], we can optimize such patterns for maximum outcoupling efficiency while suppressing viewing angle dependence (colour shifting).

Good agreement in outcoupling efficiency trends between simulation and experimental data was first established by using the OLED simulation programme (Setfos 4.2, Fluxim). This was done by replicating existing patterns into the simulation via XYZ binary translation of the patterns using the 3-D Laser Scanning Microscope (VN-8000, Keyence). In order to optimize the dimensions of such patterns for local maximum outcoupling efficiency, their manual design became necessary to individually manipulate each parameter in a systematic fashion. Such parameters include, diameter, depth, shape of holes (conical, cylindrical) and edge-to-edge (EE) distance of hexagonally packed holes.

Coupling the 'Scattering' and 'Mode Analysis' modules of the simulation, Figure 1 shows the results of 256 combinations between diameter and depth where the EE distance and shape of holes were all maintained at 1µm and cylindrical, respectively. The contour plot shows that once the diameter ranges between 3-5µm, maximum outcoupling can be maintained for an even wider range of depth (2.5-11µm). The best combination between diameter (5µm)

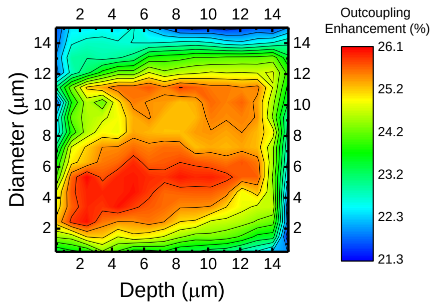

Figure 1. Contour plot generated among 256 combinations of diameter and depth for patterns arranged hexagonally with a cylindrical type shape and edge to edge distance of 1µm.

and depth (2µm) were then kept constant while first varying the EE distance, then shape, for which the maximum outcoupling efficiency was achieved at 1.5µm with conically shaped holes respectively. These optimal dimensions yielded a maximum outcoupling efficiency of 38.93%. Interestingly, the simulation suggested that further increases in outcoupling efficiency up to 79.1% is possible by adding nanometer sized surface roughness to the micrometer sized patterns, in the areas that were originally flat. We attribute this significant enhancement to the synergetic effect of combining the micro- and nanometer structures, similarly to the biomoth's eye nanostructure. Additionally, suppression of the view angle dependence of the optimized patterned device (inclusive of rough surface) was suggested via peak shifting of the electroluminescent spectra.

Finally, we have confirmed the simulation results with the experimental results in which the patterned devices showed an enhanced EQE and a suppressed shift in view angle dependence compared to the reference device.

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