Characterization of the radiation properties of quantum dots from the radiation field of an LED

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We present a study of some of the active optical properties of bottom emitting LEDs with CdSe/ZnS quantum dots used as emitters. The emission pattern is analyzed to extract deeper information about the emitter's properties, which is accessed by manufacturing LEDs with destructive interference patterns.

1 Introduction

Since the theoretical conception, manufacturing, and colloidal suspension of quantum dots (QDs) in the 80s [1-3], significant progress has been made in researching their practical applications.

In this work we put the focus on the examination and comprehension of two active optical properties of QD-LEDs, that are crucial in enhancing the performance of such devices, namely the emission zone and emitter orientation.

The analysis of the emission zone (EMZ) provides insight into the location of the exciton recombination along the transversal direction of the emissive layer. Additionally, the examination of the emitter's orientation provides information about the proportion of radiative emissions that exit the device.

2 Access of the optical properties

Previous research on OLEDs has demonstrated that devices intentionally designed to have destructive interference conditions between the radiation reflected from the cathode and the radiation directly emitted outside the device offer insights into the two optical properties mentioned above, i.e., EMZ and emitter's orientation [4-5].

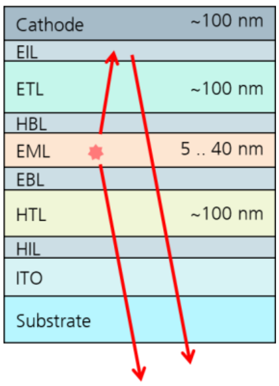

Fig. 1 *Typical OLED structure, composed by the following layers: a metallic reflective cathode and a transparent anode, which is typically composed of indium tin oxide (ITO). Additionally, two carrier injection layers, electron (EIL) and hole (HIL) injection layers, respectively, two charge carrier transport layers, ETL for electrons and HTL for holes, and the emissive layer (EML) are present. In addition, the figure shows two interfering beams.*

To satisfy the interference conditions, the distance between the emitter and mirror is manipulated by altering the thickness of the ETL. By achieving the destructive interference condition, it becomes possible to differentiate between the TE polarized radiation emanating from distinct points along the EML, see fig. 2. As a result, the shape of the EMZ can be determined.

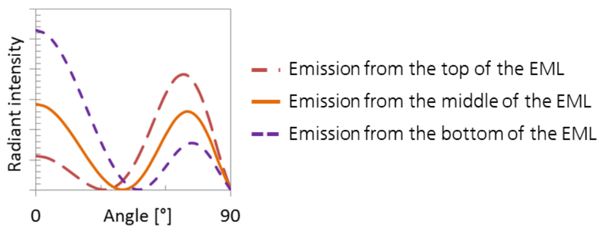

Fig. 2 *Simulation of TE polarized radiation emitted from three distinct isolated points positioned at different locations along the EML, from the top (red), from the middle (orange) and from the bottom (purple) points of the EML.*

Furthermore, we categorized the emitters into three groups based on the polarization they emit: parallel TE, parallel TM and perpendicular TM emitters. The ratio of emitters in each group determines the amount of extractable light. Radiation from all three emitter types is observed when the distance between EML and mirror generates destructive interferences, see fig. 3. Analyzing the emission pattern at this point reveals the ratio of parallel and perpendicular emitters, being $|p|_{\parallel}^2 : |p|_{\perp}^2 = 2:1$ the ratio for the case of isotropic emitters.

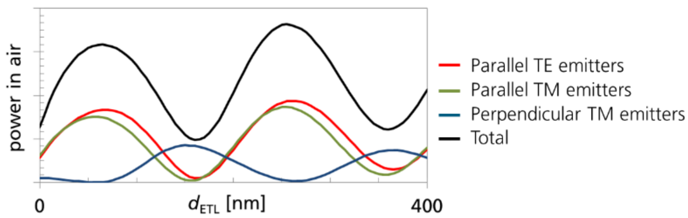

Fig. 3 *Simulation of the radiation emitted by each emitter type, parallel TE emitters in red, parallel TM emitters in green, and perpendicular TM emitters in blue. The total radiation emitted by all emitter types is depicted in black.*

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3 Results

Based on the proven good results obtained with OLEDs, we applied the same methodology to QD-LEDs. Due to the spin coating process used to layer the QDs, it was not feasible to stack as many layers as in the OLED case. The device structure remained the same except for the number of layers on top of the QDs, which was reduced to only the transport layer and an electrode (see Fig. 5). We used CdSe/ZnS QDs with an emission centered at λ=628 nm as our emitters.

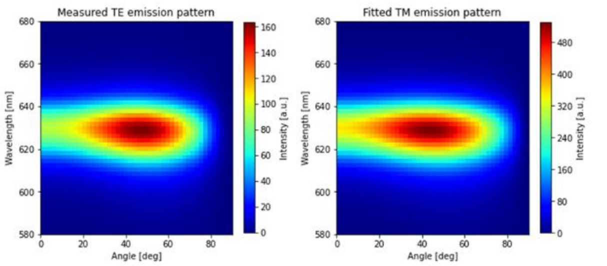

Fig. 4 *Measured TE (left) and TM (right) emission patterns from our QD-LED.*

We measured separately the TE and TM emitted radiation patterns (see fig. 4). By fitting our simulated TE radiation pattern with the measured pattern and using a third-order Lagrange polynomial to describe EMZ as a fitting parameter, we obtained the following expression:

$$I(z) = 1 + 0.51 * z + 0.45\left(\frac{1}{2}(3 * x^2 - 1)\right) \quad (1)$$

Where z indicates the transversal coordinate and is defined from -1 to +1, being -1 the lower extreme of the EML and +1 the top one. Figure 5 illustrates the appearance of the EMZ.

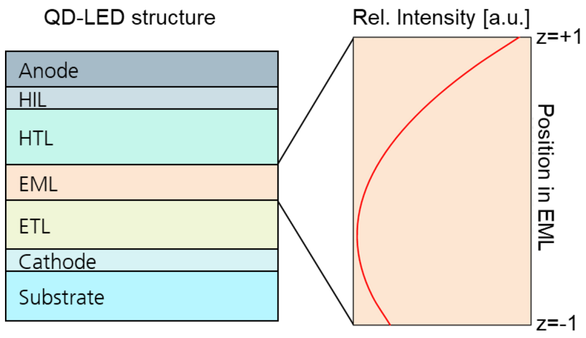

Fig. 5 *Structure of the QD-LED utilized in our research (left) and shape of the EMZ we acquired from the fit (right).*

Furthermore, we analyzed the TM-measured emission pattern to obtain information about the orientation of the emitters. This was accomplished by fitting the experimentally obtained values with the simulated ones, leaving the orientation of the emitters as the fitting parameter. From this fit we obtained the following ratio between the parallel and perpendicular emitters: $|p|^2_{\perp} : |p|^2_{\parallel} = 2 : 0.8$

4 Conclusions

We have implemented a previously established method for characterizing organic LEDs to analyze QD-LEDs.

Although we did not observe the expected destructive interference in the TE emission pattern, we were able to obtain a reasonable description of the EMZ. Our analysis suggests that radiative recombination occurs unevenly along the EML, with the highest frequency of this process occurring at the interface between the HTL and the EML. This is consistent with the well-known fact that holes have lower mobility than electrons in such a system [6].

Moreover, we were able to obtain a reasonable value for the ratio of the emitter's orientation, which suggests that the emitters are nearly isotropic, as we had expected.

The challenges presented in the preparation of QD-LEDs, such as the non-homogeneity resulting from using spin coating for the layer manufacture instead of thermal deposition and the narrow intrinsic emission spectrum from the QDs, have made it difficult to observe the minimum in the TE pattern that corresponds to destructive interference. Achieving greater precision in the production of layer thicknesses may help to overcome these challenges in future research.

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