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Characterization of Light-Extraction Efficiency for WOLEDs with Light-Out-Coupling Layer

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Abstract

We studied the light-extraction efficiencies of white OLEDs (WOLEDs) with a light-out-coupling (LOC) layer by simulations and experiments. The light-extraction efficiencies estimated by the simulation were confirmed to agree well with those measured by the experiments.

Moreover, we successfully obtained the high light-extraction efficiency of 69%.

1. Introduction

Recently, organic light-emitting diodes (OLEDs) have been developed extensively as next generation solid-state-lighting technology because of their potential advantages, such as being mercury free, thin, light weight and surface emission. However, further improvement of their efficiency is necessary to compete with other lighting sources such as light-emitting diodes (LEDs).

The external quantum efficiency (EQE) of OLEDs, is expressed as

$$EQE = \eta_{CB}\eta_{EF}\eta_{R}\eta_{OC} = \eta_{IQE}\eta_{OC} \qquad (1)$$

where, η_{CB} is the charge balance efficiency, η_{EF} is the exciton formation factor, η_{R} is the effective radiation efficiency, and η_{OC} is the light-extraction efficiency [1]. The product of η_{CB}, $\eta_{EF,}$ and η_{R} is expressed as the internal quantum efficiency (IQE), or η_{IQE} in the equation. The η_{EF} is unity in the case of phosphorescent emitters [2]. The η_{R} depends on the intrinsic radiation efficiency and exciton annihilation caused by accumulated excitons and carriers.

To achieve higher EQE in phosphorescent OLEDs, it is necessary to improve η_{CB} and η_{R}. Thus, each energy loss mechanism and room for improvement must be thoroughly investigated. Improving η_{OC} is also important for enhancing EQE. Simulation methods for the design of a white OLED (WOLED) structure with a light-out-coupling (LOC) layer are indispensable to improve η_{OC}. However, as far as we know, there have been no reports in which experimental and simulation values of η_{OC} of WOLED with LOC layers were compared.

We previously reported that the η_{OC} of green OLEDs with LOC layers estimated by simulation was in good agreement with that estimated by experiments [3]. In this study, we compared the light-extraction efficiencies of WOLEDs with a LOC layer estimated by simulations and determined by experiments.

2. Experiments and Results

The WOLEDs with LOC layers were prepared by the following method. We used a high refractive index glass substrate (n=1.81 at 546nm) with patterned indium tin oxide (ITO) film. A hole injection layer (HIL) and a hole transport layer (HTL) were formed by spin coating. An emitting layer (EML) was fabricated by one-step coating using a “self-layered technique” [4]. This EML layer was composed of host materials and three kinds of dopants such as red, blue and green.

A hole blocking layer (HBL), an electron transporting layer (ETL) and a cathode were formed by vacuum deposition. The silver cathode layer was patterned using shadow mask to define an emitting area of 4.52cm^2.

After the cathode formation, the devices were encapsulated using UV-epoxy resin and a glass lid with desiccant.

The LOC layer, which was composed of epoxy resin with high refractive index as a base material and fine particles, was fabricated on the back side on the structure.

Luminous efficacy of OLEDs was obtained by an integration of spectral and angular resolved measurements performed with a calibrated self-made spectrogoniometer.

Schematic structures of three OLEDs for the evaluation of η_{OC} were shown in Fig1. Type A is a bare WOLED for the evaluating the external mode. Type B is a WOLED attached to a high refractive index hemispherical lens (n = 1.89 at 546 nm) for evaluating the sum of external and substrate modes, which corresponds to almost all the amount of emitted photons from the emitter in the OLED. Type C is a WOLED with a LOC layer.

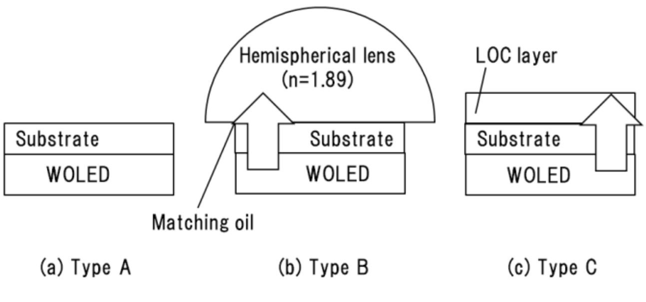

Fig.1. Schematics of WOLED structure for evaluation of light-extraction. (a)Type A is bare WOLEDs. (b) Type B is OLEDs with hemispherical lens. (c) Type C is OLEDs with LOC layer.

The spectra of the total flux of samples were measured with an integrating sphere. During the measurement, substrate edges were covered with a black sheet to avoid the influence of the light confined in the substrate. Current density was set to 1.1 mA /cm^2.

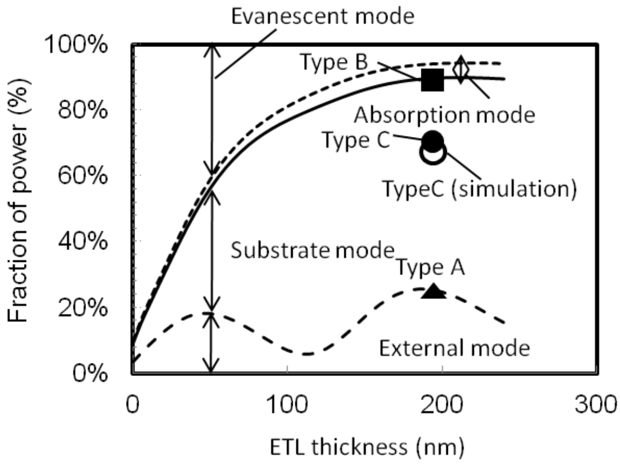

Fig.2. Fraction of transmitted radiation intensities of evanescent, absorption, substrate and external modes as a function of ETL thickness in WOLEDs calculated from simulation. The measured η_{OC} of WOLEDs were also plotted in figure: Type A (closed triangle), Type B (closed square), Type C (closed circle) and simulated Type C (open circle).

We employed two types of optical simulation tools: one based on the optical mode distribution of dipole emission including near-field and far-field optical phenomena in OLEDs and the other based on ray tracing. The η_{OC} of OLEDs without LOC layer was estimated by the simulation of the optical mode. While, the η_{OC} of OLEDs with a LOC layer was estimated by the coupling analysis of both simulations.

Electric dipole energy is classified in radiation energy (external, substrate, waveguide and absorption modes) and non-radiation energy (evanescent mode). In this paper, when all radiation energy and non-radiation energy are extracted out from OLED, η_{OC} is defined as 100%. To increase η_{OC}, decrease of evanescent mode is needed and evanescent mode is associated with ETL thickness.

Figure 2 shows the calculated fraction of optical modes contributing the total transmitted radiation for the WOLED as a function of ETL thickness. As the ETL thickness is increased, the evanescent mode is transferred to external and substrate modes. The light of the external mode is emitted into the air from the OLEDs. The light of the substrate mode is trapped in the substrate due to total reflection at the substrate/air interface. The light of the absorption mode is equivalent to absorption loss of ITO and Ag. Substrate , absorption, waveguide and external modes are total emitted power in the OLED. The evanescent mode includes direct coupling of the near-field with surface plasmon-polariton and lossy surface waves on the metal cathode. The waveguide mode is negligible (below 0.1 %), since the OLEDs were formed on high refractive index glass substrates (n=1.8) and therefore difference in the refractive index between the substrate and the emission layer is small. To maximize η_{OC}, it is necessary to set ETL thickness so that evanescent mode becomes minimum. Therefore, the ETL thickness was set to 190 nm.

The measured η_{OC} of WOLEDs were also plotted in Fig. 2: Type A (closed triangle), Type B (closed square), Type C (closed circle) and simulated value of Type C (open circle).

The η_{OC} of Type A, Type B and Type C was 25%, 90% and 69%, respectively. The simulated value of Type C exhibited η_{OC} of 68%, so calculated values were in good agreement with experimental ones. The reasons of high efficiency of η_{OC} are as follows, decrease of evanescent mode by thickening the ETL, and constitution optimization of LOC layers.

Table 1. Characteristics of WOLEDs calculated from experiments.

	Type A	Type B	Type C
Luminous efficacy	1	3.52	2.77
Absolute light quantity	1	3.48	2.71
η_{OC} (%)	25	90	69

Table1 shows the luminous efficacy, absolute light quantity and η_{OC} from measurements of integrating the sphere.

Luminous efficacy and absolute light quantity were normalized by the WOLEDs of Type A. Luminous efficacy and absolute light quantity of Type C are 2.7-2.8 times that of Type A. The WOLEDs with LOC layers showed superior characteristics.

3. Conclusions

We demonstrated that the η_{OC} of WOLEDs with LOC layers estimated by simulation was in good agreement with that measured by the experiment for the first time. We successfully obtained the high η_{OC} of 69% for WOLEDs with LOC layers. To our knowledge, this is the highest that has ever been reported for WOLEDs with LOC layers.

References

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