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Effect of External Micro-cavitycoupled with Surface Plasmon on the Performance of Organic LightEmitting Devices

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ABSTRACT
Luminescent properties have been improved by introducingan external micro-cavity effect in an organic light emitting device with multi-cathode structure. Angular dependence of the emission intensity and emission spectra were evaluated and it was clarified that the external micro-cavity coupled with surface plasmonis useful for the improvement of the color purity of the emission and out-coupling efficiency compared with an internal micro-cavity effect. In results, color coordinates of the green emission approaches to BT.2020 color standard and an external quantum efficiency becomes higher by a factor of 1.3. The relationship between the external micro-cavity effect and surface plasmon coupling will be discussed from a viewpoint of optical analysis.
Keywords: *Organic light-emitting diode, Light extraction efficiency, Micro cavity effect, Surface plasmon*

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I. INTRODUCTION

Organic light-emitting devices (OLEDs) are expected as a high performance flat panel display because of first response, wide viewing angle, excellent image quality and low power consumption. In addition, possibilities of flexible and transparent displays are attractive in the next generation information display market. The internal quantum efficiency of OLED has approaches to 100 % using multi-stacked thin film structure and phosphorescent materials [1]. However, the external quantum efficiency (EQE) remains about 20% due to the poor light extraction efficiency [2]. In 2012, international standard called BT.2020 was announced in an ultra-high definition 8K-TV, in which wide color gamut is recommended in order to realize high color reproducibility. The technical development for filling these demands these days has been reportedin the field of OLEDs [3]. However, it is difficult to satisfy these color requirements in the present OLED technology. One of methods may be an internal micro-cavity effect, which is often used for an enhancement of the forward directional emission intensity by the control of optical interference phenomenon in multi-stacked thin film layers [4, 5]. In this paper, we propose an external micro-cavity coupled with surface palsmon in the cathode for an improvement of color purity as well as the emission efficiency. The relationship between the external micro-cavity and surface plasmon resonance will be discussedfrom the experimental results and theoretical analysis.

II. EXPERIMENTALMETHODE

Figure 1 (b) shows a normal device structure, which consists of an indium-tin-oxide (ITO) bottom electrode, a Poly(3,4)-ethylendioxythiophene - polystyrenesulfonate (PEDOT:PSS) hole-injection layer, Bis[(1-naphthyl)-N-phenyl]benzidine (NPB) hole-transporting layer, a 4,4’-N,N’-dicarbazole-biphenyl (CBP) emissive layer (EML) doped with $Ir(ppy)_3$ emitting guest, a 2-(4-Biphenylyl)-5-(4-tert-butylphenyl-1,3,4-oxadiazole) (Bu-PBD) electron transporting layer (ETL) and an aluminum cathode. Figure 1 (a) is a proposed device structure with external micro-cavity layers, in which the cathode has three layers consisting of semi-transparent MgAg film, ITO optical buffer layer (OBL) and high reflective silver film. In other words, we call it “Multi-cathode (MLC) structure”. Each layer was prepared by physical deposition process such as vacuum evaporation, rf-sputtering and spin-coating techniques.
Optical phenomena in an OLED is verycomplicate because of the thin film stacked structure with an order of one wavelength. Optical energy in OLED consists of propagation wave and evanescent wave, which are generally divided into external, substrate, waveguide and surface-plasmon (SP) modes[6]. However, the sum of external and substrate modes is only less than half even if the device is carefully designed because of large losses induced by waveguide lights and SP. For the enhancement of light extraction, it is necessary to suppress the surface plasmon loss (SP-loss) and then to change the waveguide mode into the substrate and external modes. In order to optimize

the device structure, optical analysis of the device structure was carried out on a basis of wave optics including near-field optics by using an original simulation software.

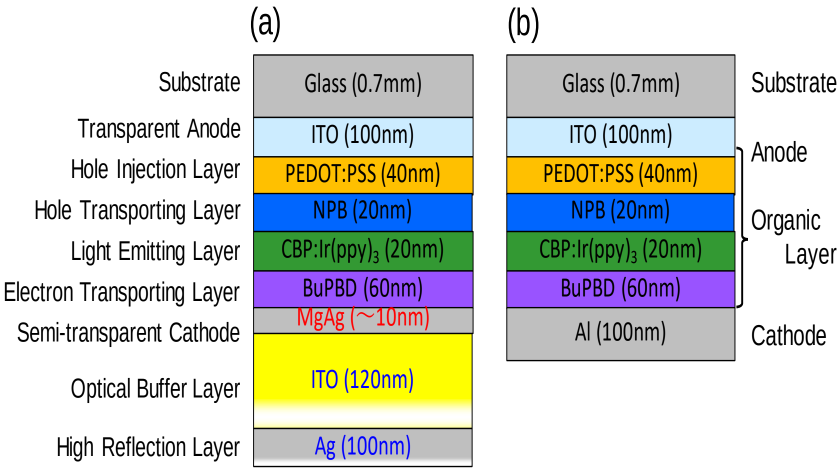


Fig.1 Device structures of green light emitting OLEDs with (a) multi-cathode structure and (b) normal structure.

III. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Effect of internal micro-cavity in the normal device structures

Figure 2 (a) shows a variation of emission spectra with the film thickness of ETL (d_{ETL}) in the normal structure. The intensity and peak wavelength (W_p) in the emission spectra significantly changes with d_{ETL} because of an internal micro-cavity effect, in which the distance between cathode and emission site is one of critical factors to determine the optical interference phenomenon. Emission site is generally located near the interface between EML and ETL because an electron-mobility is larger than hole-mobility in CBP host material. Figure 2 (b) shows emission properties such as luminance, W_p and CIE color coordinates (x, y) as a function of d_{ETL}. Luminance takes a maximum at 50 nm in $d_{ETL}$and$W_p$greatlyshift up to 545 nm from 515 nm at 60～70 nm in d_{ETL}. It is noted that the color purity of the green emission becomes gradually poor as d_{ETL} increases, judging from the change in CIE-x,y. From these results, optimum thickness of ETL is supposed to be around 50 nm.

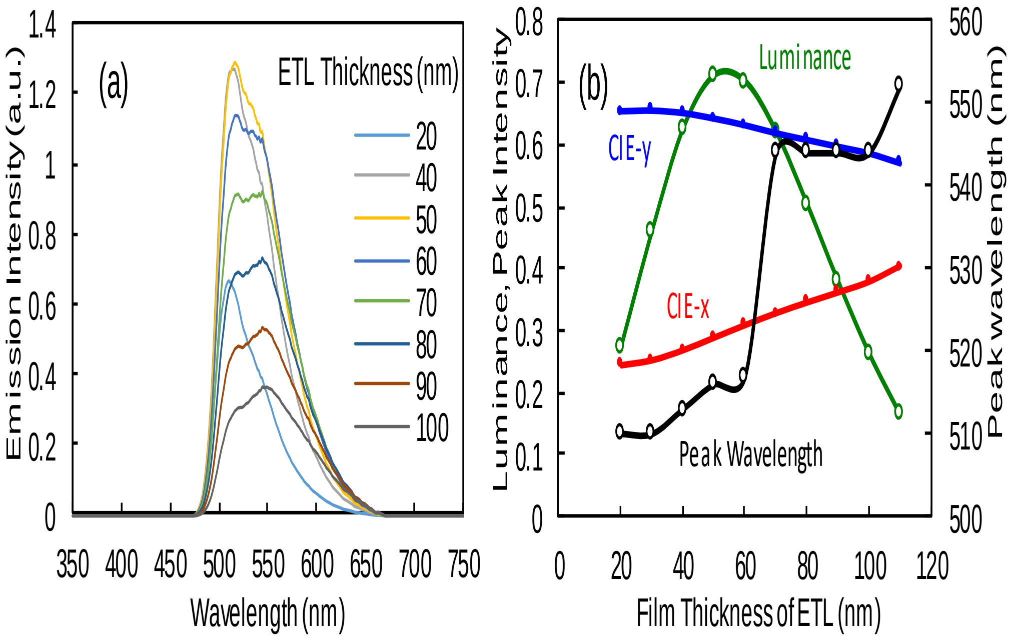
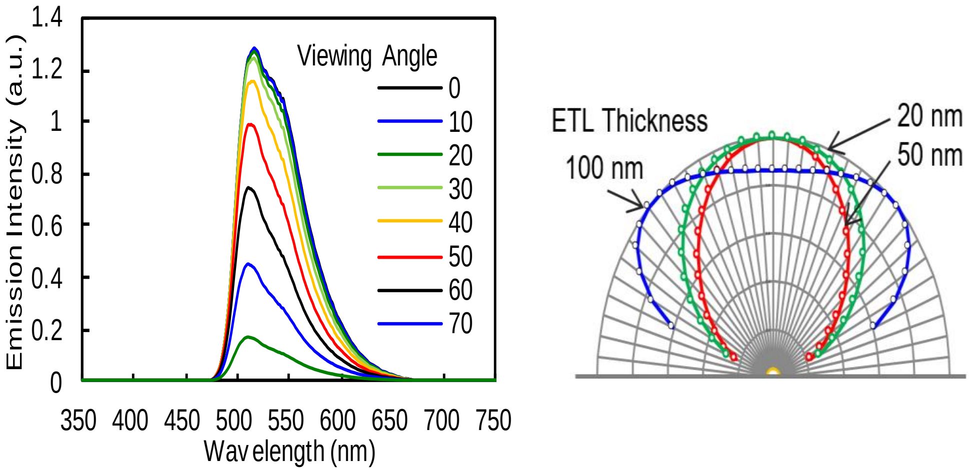


Fig.2 ETL thickness dependence of the emission spectra in the devices with normal structure.
(a) Variation of the emission spectra with the film thickness of ETL

(b) Luminance, CIE color coordinate (x,y) and peak wavelength of the emission spectra with the film thickness of ETL.

Figure 3 shows an angular dependence of the emission spectra in the OLED with 50 nm in d_{ETL} and intensity distribution at 20, 50 and 100 nm in d_{ETL}. Emission spectrum is almost unchanged with viewing angle, which is one of the requirements in an information display.Angular dependence of the emission intensity is nearly Lambertian distribution at 20 nm and 50 nm in d_{ETL}.But the emission intensity in a slant direction is dominant in the device with 100 nm in d_{ETL}.



(a) Emission spectra (b) Emission intensity distribution

Fig.3 Viewing angle dependence of the emission spectra and intensity in the normal devices.
(a) Emission spectra in an OLED with d_{ETL} of 50 nm.
(b) Emission intensity in three devices with different d_{ETL}.

3.2Effect Of External Micro-Cavity In The Multi-Cathode Device Structure

Figure 4 (a) shows a variation of emission spectra with the film thickness of OBL (d_{OBL}) in the MLC structure. Film thickness $d_{ETL}$is kept constant at 50 nm in this experiment. Peak intensity and W_p strongly depend on d_{OBL} because of the external micro-cavity effect, in which the distance between MgAg and Ag layers is a critical factor for the optical interference phenomenon. Figure 4 (b) shows emission properties such as luminance, Wp and CIE-x and y as a function of d_{OBL}. Luminance takes a maximum around 140 nm in d_{OBL}. $W_p$greatlyshiftdown to 500 nm from 560 nm at 90 nm in d_{OBL}, which results in the improvement of color purity of the green emission as shown in the change of CIE-x,y.

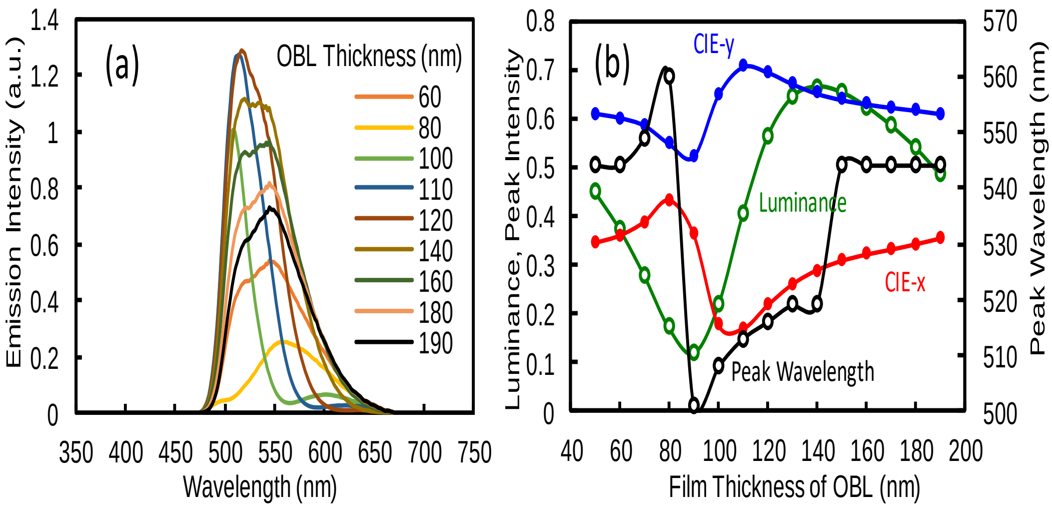
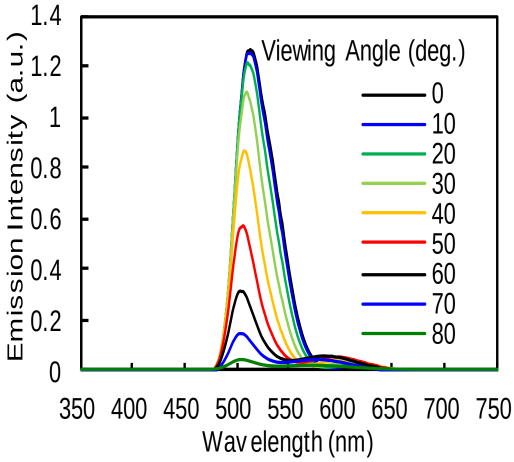


Fig.4 Dependence of emission spectra and intensity on the film thickness of optical buffer layer d_{OBL} in the MLC structure.

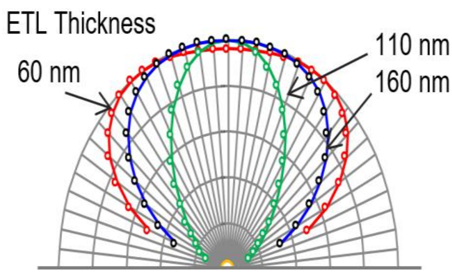
(a) Variation of the emission spectra with the film thickness of OBL.

(b) Luminance, CIE color coordinate (x,y) and peak wavelength of the emission spectra with the film thickness of OBL.

Figure 5 shows an angular dependence of the emission spectra in the MLC structure with 110 nm in d_{OBL} and intensity distribution at 60, 110 and 160 nm in d_{OBL}. Emission spectra becomes sharp compared with that of the normal structure as already shown in Fig. 3(a). Especially, the half-width in the spectrum is much narrower by introducing an external micro-cavity effect. Figure 6 shows CIE 1931 color diagram (x,y) containingthree triangles of color gamut in the standard of BT.2020, NTSC and sRGB, respectively. Emission color coordinates of the device with MLC structureis (0.161, 0.685) as indicated by open circles. Color purity of the green emission is significantly improvedby introducing the external micro-cavity and approaches to the green emission point in BT.2020 standard.



(a) Emission spectra



(b) Emission intensity distribution

Fig.5 Viewing angle dependence of the emission spectra and intensity in the MLC devices.
(a) Emission spectra in an OLED with d_{OBL} of 110 nm.
(b) Emission intensity in three devices with different d_{OBL}.

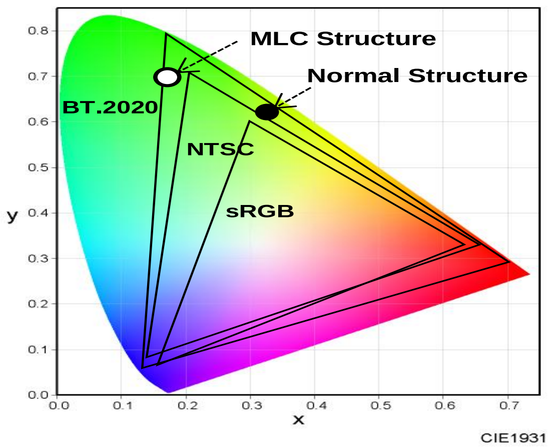


Fig.6 Color coordinates of the green emission in the devices with normal and MCL structures. Three triangles are color gamut in the standard of BT.2020, NTSC and sRGB, respectively.

3.3Optical analysis of the external micro-cavity effect

The radiant energy in an organic device originates in the dipolar oscillation of an organic molecule. In results, optical energy from the dipole consixts of a propagation wave and an evanescent wave. The former is further divided into external, substrate and waveguide modes, and the latter is mainly direct coupling of near-field with surface plasmon resonance on the metal cathode. Figure 7shows power spectra of the dipole emission in the devices with normal and MLC structure. In these graphs, optical energy densities of horizontaland vertical dipoles are plotted as a function of in-plane wave vector (k_h)normalized by the wave-vector in the air, so the horizontal axis is actually equal to refractive index of each material used in the device.

In the case of the normal structure, we can observe a strong surface plasmon pole at 2.02 ink_h. In contrast, plasmon pole almost disappears and waveguide TM modeat 1.62 becomes dominant in theMLC structure. Small plasmon peak around 2.3 ink_h does not originate in the MgAgcathode but the rear Ag reflector. This result indicates that the evanescent wave from the dipole emission is successfully converted to the waveguide mode as a propagation wave by employing the multi-stacked cathode. Increased waveguide mode is directly coupled with an external micro-cavity effect in the multi-cathode. It is considered that the interaction between two kinds of SP-coupling on both sides of MgAg layer is responsible for the reduction of SP-loss in the cathode [7]. Table 1 summarizes the relative power ratio of each optical mode witch is obtained by integrating the power spectra in the range of each mode. When we used the MLC structure, the SP mode decreases to 18.6 % from 42.1 % and instead the waveguide mode increases to 25.4 % from 16.1 %, which seems to beproof of direct coupling of SP loss with the micro-cavity structure. Moreover, the external mode and substrate modes are increasing with the increase in the propagation mode.

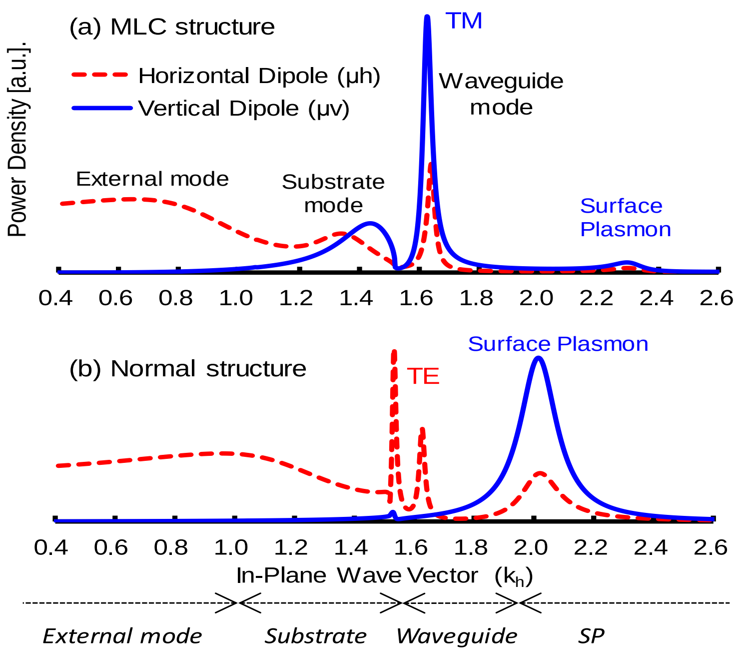


Fig.7 Optical power spectra of dipole emissionsin the devices with normal and MLC structure as a function of in-plane wave vector.

Table 1. Optical power ratio among external, substrate, waveguide and surface plasmon mode in the devices with and without external micro-cavity effect.

Optical mode	MLC structure	Normal structure
External	25.6 %	21.3 %
Substrate	30.4 %	20.5 %
Waveguide	25.4 %	16.1 %
Surface plasmon	18.6 %	42.1 %

Figure 8 shows the dependence of external quantum efficiency (EQE) on the luminance in the devices. Maximum values of EQEin a low luminance region are 17.8% and 23.1% in the normal and MLC structure, respectively.The efficiency becomes higher by a factor of 1.3 by introducing external micro-cavity in the MLC structure. Approximately 56% of optical power in the dipole emission can be utilized as external and substrate modes, since the substrate mode can be easily extracted out by using external out-coupling layer such as high refractive index glass, micro-lens array and light scattering layer[8].

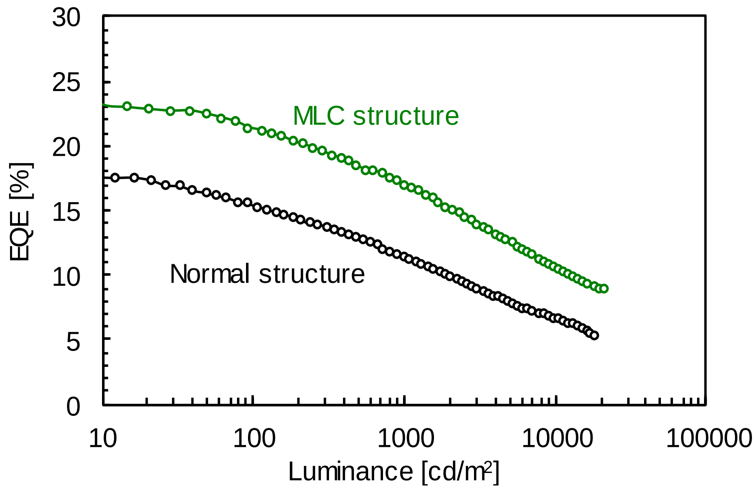


Fig.8 External quantum efficiency (EQE) vs. luminance characteristics in green light emitting OLEDs with normal and MLC structure.

IV. Conclusion

The effect of external micro-cavity on the emission propertieshas been investigated in the green light emitting OLED. It was clarified that the MLC structure increases the power ratio of the waveguide mode resulting in the enhancement of micro-cavity effect on the luminescent properties. The emission spectra becomes sharp so the color purity of the green emission is greatly improved. In addition, the external quantum efficiency is increased by a factor of 1.3, which originates in the reduction of SP loss accompanied with increased propagation mode. This optical technique is useful for the improvement of the emission color and efficiency without sacrificing an electrical property.

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