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Optical Control of Surface Plasmon Coupling in Organic Light Emitting Devices with Nanosized Multi-cathode Structure

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Abstract **-** Light extraction efficiency of organic light-emitting devices has improved by using a nanosized multi-cathode structure consisting of semi-transparent metal and an optical compensation layer. From the detail optical calculation based on the multi-scale analysis including near-field optics, it was found that surface plasmon loss in the metal cathode is suppressed to less than 10% due to long range and short range surface plasmon coupling on both sides of metal cathode. Not less than 90% of optical power in the dipole emission can be successfully utilized as propagation light. Light extraction efficiency in a phosphorescent device has improved about twice in a nanosized multi-cathode structure.

Keywords**:** Light-emitting device, Organic material, Surface plasmon, Optical simulation.

1. Introduction

Organic light-emitting devices (OLED) are now widely recognized as a potential application for high quality flat panel displays and general lighting. The internal quantum efficiency of OLED has been achieved near 100% using phosphorescent materials with proper management of singlet and triplet excitons. However, the external quantum efficiency (EQE) of conventional devices remains 20～25% because of poor light extraction efficiency. One of the reasons is quite a large losses induced by surface plasmon polariton which is direct interaction between a metal cathode and evanescent wave in near-field of vertical dipole emission, as previously reported by K.A.Netz (1998). In results, optical energy of propagation wave is restricted only a half of total emission energy. It is clear that the light out-coupling behaviour significantly changes with not only optical constants of materials but also the device structure including substrate, electrode and passivation layers, as shown by A.Mikami (2011). We have recently found that a multi-cathode (MLC) structure consisting of semi-transparent metal, an optical compensation layer and high reflection metal makes it possible to achieve more than 50% in out-coupling efficiency by the combination of high refractive index layer, as shown by A.Mikami (2012). The objective of this research is the control of surface plasmon (SP) in OLEDs. This paper will discuss mainly the reason why SP coupling can be suppressed by employing a nanosized cathode structure.

2. Experimental Methodes

2. 1. Device Structure and Sample Preparation

Figure 1 shows a basic device structure of green phosphorescent OLED used in this experiment. The device basically consists of an indium-tin-oxide (ITO) bottom electrode, a Poly(3,4)-ethylendioxy thiophene - 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 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 semi-transparent MgAg cathode. In addition, an optical compensation (OC) layer was deposited by thermal evaporation in order to control the SP coupling on the back-side of thin metal cathode. Transmittance of OC layer is more than 90%, and its refractive index is between 1.5 and 2.2.

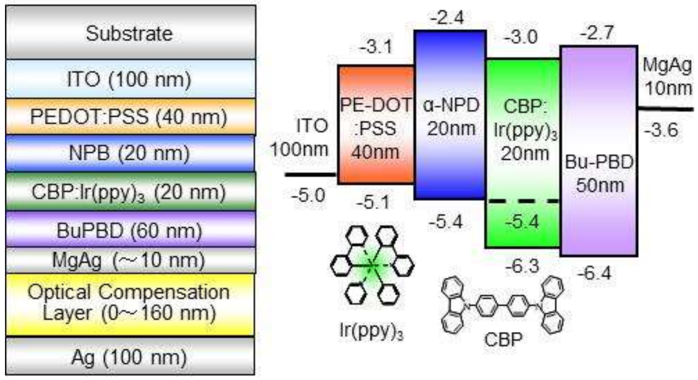

Fig. 1. Device structure and its potential energy level of phosphorescent OLED with a multi-cathode structure. The cathode consists of semi-transparent metal, an optical compensation layer and high reflection metal.

2. 1. Optical Analysis

Optical energy in OLED is generally divided into a propagation wave and an evanescent wave. The former consists of external, substrate and waveguide modes, and the latter is direct coupling of near-field with surface plasmon polariton and lossy surface waves on the metal cathode. These optical modes can be drawn by using in-plane wave-vector as shown in Fig.2. From the bottom side, the external mode will be treated by classical ray-optics. In the case of substrate mode, we have to take into account a multiple internal reflection in the thick layer. So wave-optics of incoherent light will be suitable for this mode. Waveguide mode should be calculated by electro-magnetic optics of coherent light. SP is directly related to the near-field optics. Because wide range of optics is deeply involved, we used multi-scale optical analysis for the optimization of multi-stacked OLED structure. An optical power spectrum of dipole emission including near-field and far-field optical phenomena was calculated by using original simulation software named “FROLED”. For the enhancement of light extraction, the way of using a substrate propagation mode is much practical to take the light out of the device by using high refractive index layer and micro-lens array. However, the sum of external and substrate modes is only less than half of total optical energy even if the device is carefully designed because of large losses induced by waveguide lights and SP. To solve this problem, it is required to suppress the SP loss and then to convert electromagnetic energy propagating as a waveguide mode into the substrate mode, eventually outside the device as an external mode.

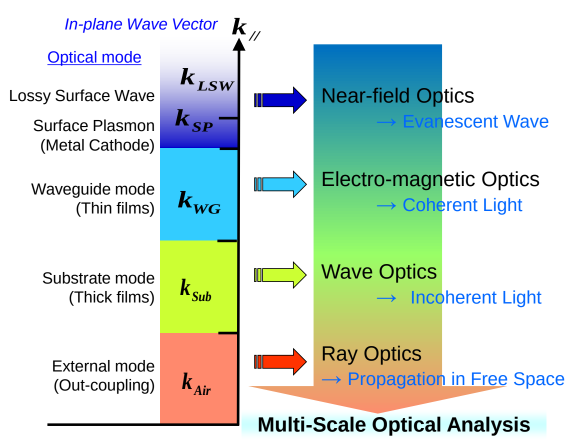

Fig. 2. Relationship between optical modes in OLED and optical theories in terms of in-plane wave-vector. Since OLED includes wide range of wave-vector, a multi-scale model is a powerful tool for solving various optical processes produced inside OLED.

3. Experimental Results

3. 1. Control of Surface Plasmon Coupling

We tried to visualize behaviour of SP coupling in three kinds of device structures based on a multi-scale optical analysis. Figure 3 shows [A] power spectra, [B] imaging of optical power density distribution in the devices and [C] device structure with different cathode and substrate; (a) normal cathode and (b), (c) multi-cathode structures. Refractive index (n_s) of the glass is (a) (b) 1.52 and (c) 1.80, respectively. Since SP loss mainly originates in vertical dipole, power density distribution was calculated only by exciting the vertical dipole moment. In the case of a reference device with normal cathode, the emission from the vertical dipole usually comes out in the direction of slant. Almost all the excitation power is lost and disappears in a short life time as SP in the cathode. In contrast, a strong forward emission can be observed as well as waveguide mode in a multi-cathode structure. When the high refractive-index glass is used, waveguide mode is directly coupled with substrate mode. The intensity of pointing vector in the glass increases from 36% to 59% and 87%.

As for the power spectrum, a strong SP pole appears at 2.02 in normalized k-space in the reference device. However, it almost disappears and waveguide TM mode becomes dominant in multi-cathode. A small peak at k_h=2.3 is another SP pole originating in a high reflection Ag layer because dipole and mirror is still only 120 nm away. In results, SP loss decreases to only 12% of the total power. If we use a glass of 1.8 in refractive-index, waveguide loss almost disappears. Actually, TM or TE waveguide lines disappear in the power spectrum. The substrate mode becomes 60%. In results, about 90% of optical energy exists as propagation wave.

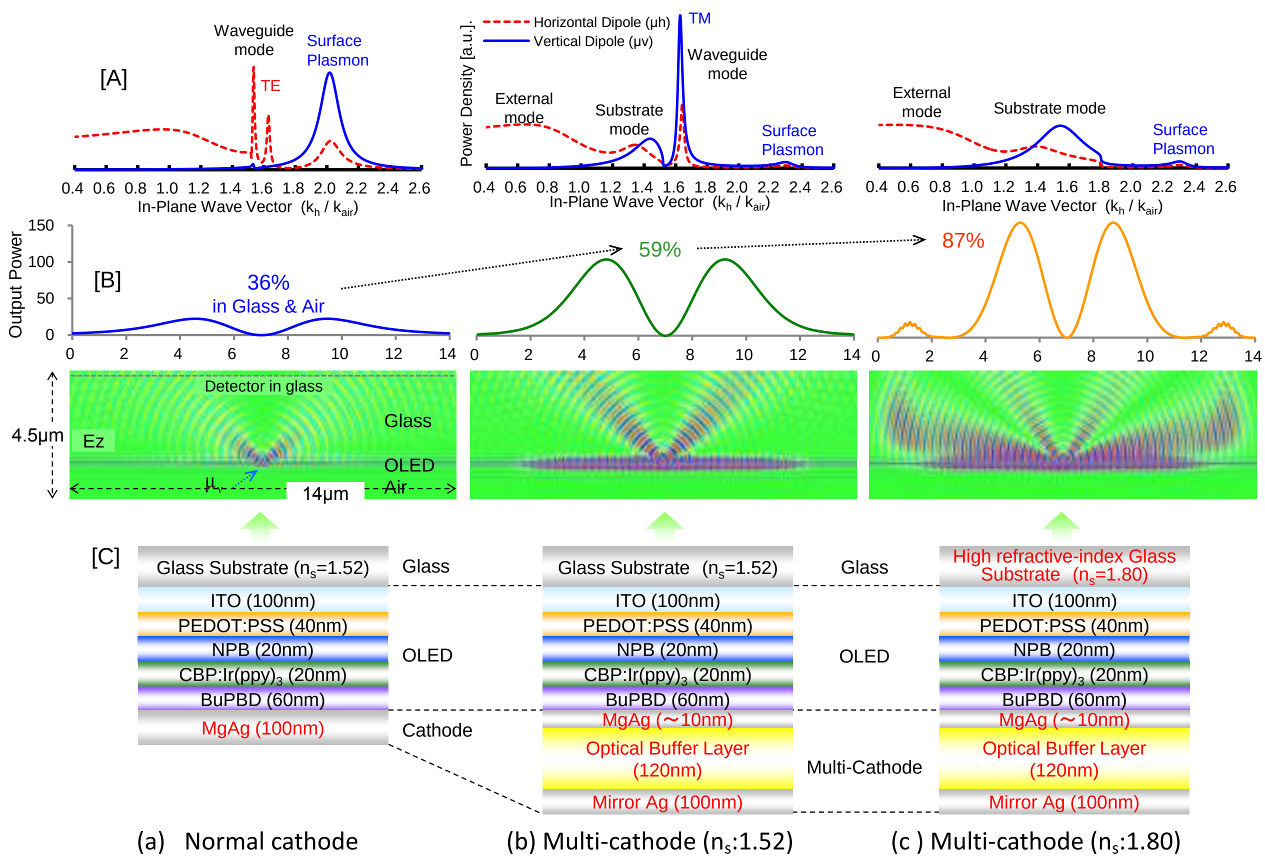

Fig 3. Optical power spectra (power density vs. in-plane wave-vector), imaging of power intensity distribution and device structure with different cathode structure and refractive-index of glass substrate.

Figure 4 shows a variation of power spectra with the thickness of MgAg layer (d_{MgAg}) in the wave-vector range which SP resonance is observed. Refractive index and the thickness of OC layer were kept constant of 1.8 and 120 nm, respectively. When d_{MgAg} is 100 nm, a strong SP pole appears at 2.02 as well as reference cathode structure. However, when d_{MgAg} is less than 60nm, the SP pole is divided to two peaks, which is corresponding to long range SP mode (LRSP) in the lower wave-vector and short range SP mode (SRSP) in the higher wave-vector, respectively. As d_{MgAg} is further decreased less than 20 nm, LRSP is combined with waveguide mode and is changed into propagation light. On the other hand, SRSP disappears in order to exceed the limit of resonance wave-vector in SP coupling. As a result, almost all of the evanescent wave can be successfully converted to propagation wave.

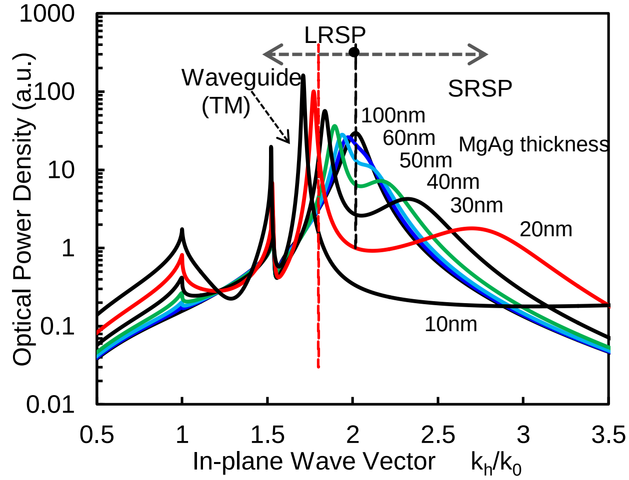

Fig 4. Variation of optical power spectra with the thickness of MgAg layer. Long range (LRSP) and short range (SRSP) surface plasmon tend to sift to an opposite direction as the MgAg thickness is decreased.

3. 2. Device Performance

We have experimentally confirmed the effect of MLC structure by using phosphorescent green OLED shown in Fig.1. Figure 5 shows a comparison of external quantum efficiency (EQE) of OLEDs with MLC structure and reference cathode. Half sphere lens and micro-lens array were used in order to extract the light out of the glass in the case of MLC structure. The maximum efficiencies in EQE are 64% in MLC with a half lens, 46% in MLC with micro-lens and 23% in the reference device, respectively. EQE has improved about twice in MLC structure.

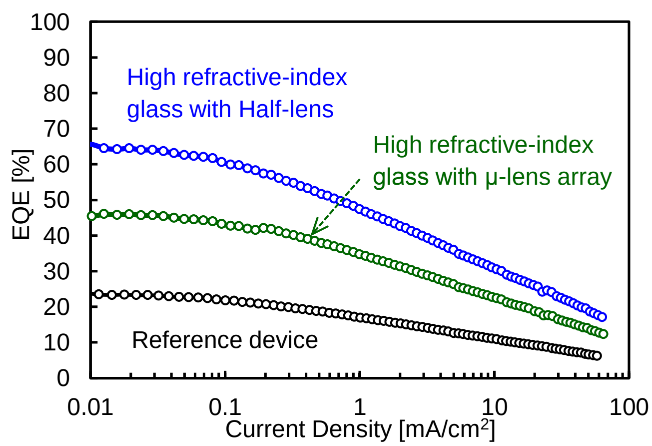

Fig 5. External quantum efficiency vs. current density characteristics in OLEDs with MLC and normal cathode.

4. Conclusion

The effect of the OC-layer on the suppression of the SP-loss was investigated in OLED with a nanosized MLC structure. In results, huge loss due to SP coupling with metal cathode was converted to propagation wave in waveguide and substrate mode. These phenomena can be explained by the change of wave vector in SP-coupling induced by the interaction of two SP mode (LRSP and SRSP) between both interfaces of MgAg layer. We would like to emphasize that this technique is effective for the conventional bottom or top emission type OLED. In addition, we would like to emphasize that multi-scale optical analysis is useful for the optical design of high efficiency OLED application.

References

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