Optical Interference Effects by Metal Cathode in Organic Light-Emitting Diodes *

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The dependence of light intensities of organic light-emitting diodes (OLEDs) on the distance of emission zone to metal cathode is investigated numerically. The investigation is based on the half-space optical model that accounts for optical interference effects of metal cathode. We find that light intensities of OLEDs are functions of the distance of emission zone from the metal cathode because of the effect of interference of the metal cathode. This interference leads to an optimal location of emission zone in OLEDs for the maximum of light intensities. Optimal locations of emission zone are numerically shown in various emitting colour OLEDs with different metal cathodes and these results are expected to give insight into the preparation of high efficiency full colour or white light OLEDs.

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Organic light-emitting diodes (OLEDs) show promising applications in practical electroluminescent devices such as flat-panel displays.[1–4] As a result, there have been many attempts to optimize their efficiency, including electrode modification, improved organic material synthesis, and ingenious device construction. In general, these devices typically comprise a thin layer of organic emitting material sandwiched between a metal cathode and transparent anode. Electrons and holes injected from the related contacts recombine in the emitting layer to form emissive excitons. Because these excitons are optically close to the highly reflective metal cathode, the optical emission properties of OLEDs are strongly modified by the optical interference effect.[5–7] Therefore, optimal efficiency of OLEDs can also be achieved by design of optical structure of devices. The optical microcavity with two parallel reflectors in OLEDs has the effect of narrowing the spectrum and enhancing the emission intensity.[8–10] In the conventional structure of OLEDs with one reflector, however, we can also change the spectrum and the emission intensity by adjusting the emission zone.[11–14] However, the optical interference by metal cathode is quite different for various emitting colour and metal cathodes (such as Ag, Ca, Mg, etc.), which have not been studied systematically.

In this Letter, the dependence of light intensity of OLEDs on the location of emission zone by the optical interference of metal cathode was numerically investigated for various emitting colour and metal cathodes. It is found that the light-intensity maximum occurs at a certain location of emission zone in OLEDs due to the optical interference for different emissive wavelengths and metal cathodes. However, these optimal locations are quite dependent on the wavelengths of the emitting light and the metal cathode. These dependences were often ignored in previous preparation of devices of OLEDs. Therefore the present numerical results can be used to instruct the structure design of electroluminescent devices for high efficiency.

First we introduce the optical schematic of OLEDs from the optical point of view, as shown in Fig. 1. For simplicity, we treat the OLED as a device with four optical layers. They are the metal layer, organic layer including layers of electron transport layer (ETL), emission layer (EML), hole transport layer (HTL) and indium-tin-oxide (ITO) for their similar optical refractive index (1.75–1.95), glass layer with refractive index (1.46) and air with refractive index (1.0). Also, we ignore the absorption of ITO and organic layers.

The emission of the recombination excitons is modelled by oscillating dipoles in front of a mirror in this paper.[15,7] These dipoles are embedded inside the

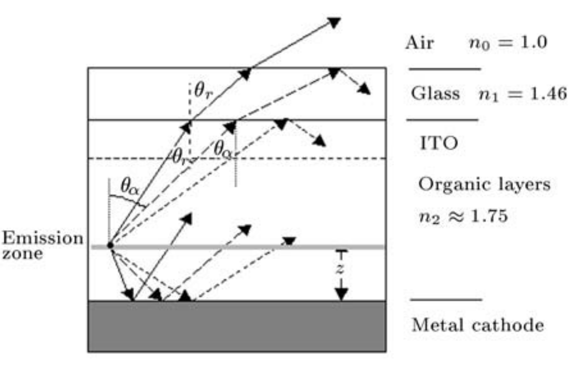

Fig. 1. Optical structure of the organic light-emitting diode.

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EML half space at a distance z from the metal cathode and are chosen to be isotropic for OLEDs based on a small-molecule organic material. The metal occupies the other half space. In the calculation, the transfer mixture formalism is used if the optical constant of all the layers and the emission zone are known.

In Fig. 1, for a sheet of dipoles at distance z from the cathode-reflector, the internal emission intensity can be expressed as

$$I(\theta) \propto |1 + r_s \exp(-2i\delta)|^2 + |1 + r_p \exp(-2i\delta)|^2, \tag{1}$$

$$\delta = 2\pi nz \cos\theta/\lambda, \tag{2}$$

where θ is the emission angle, r_s and r_p are the Fresnel reflection coefficients for the s and p polarization, δ is the phase and n is the refractive index of the organic material. The photons generated in the organic layer can only escape from the glass surface within a certain solid angle because of the total internal reflection by the interfaces between glass and air, ITO and glass. Outside the cone, the residual photons will be trapped in the layers of ITO and glass,[16] as shown in Fig. 1. The solid angle is approximately expressed by $\theta_{cr} = \arcsin(n_a/n_{org})$, where n_a and n_{org} are the refractive indices of air and the organic layers. The calculated emission intensity was integrated over the surface-escape cone. In Eq. (1), we just consider the wide-angle interference by metal cathode and ignore the multiple-beam interference effect between the ITO and the metal cathode because the optical reflection on the interfaces among glass, ITO, and HTL was quite small.

In order to obtain the emission intensity outside the glass layer, we account for the Fresnel transmittance. From Fig. 1, the transmitted intensity $I_T(\theta_T)$ is related to the incident intensity $I_I(\theta_I)$ by

$$I_T(\theta_T) = I_I(\theta_I)T(\theta_I)\frac{\cos\theta_I}{\cos\theta_T}, \tag{3}$$

where θ_I and θ_T are related by Snell's law

$$n_I \sin\theta_I = n_T \sin\theta_T,$$
$$T = \frac{1}{2}(T_s + T_p),$$
$$T_{s(p)} = \frac{n_T \cos\theta_T}{n_I \cos\theta_I} t^2_{s(p)},$$

with $t_{s(p)}$ being the Fresnel transmission coefficients for s- and p-polarizations.

In order to calculate the light intensity of OLEDs using the above optical model, the refractive index of the organic material is approximately chosen to be 1.75 and the complex refractive indices of the metals Ag, Ca, Mg, and Al are $(0.13 + 2.8i)$, $(0.28 + 1.97i)$, $(0.28 + 4.7i)$, and $(0.73 + 5.92i)$, respectively.[17] In our numerical simulation, for simplicity, the emission zone of OLEDs was considered as a sheet of the light-emitting molecule and we assume that charge mobility and injection rates remain unchanged for various locations of sheet of the light-emitting molecule.

Figure 2 shows the relative intensity of the OLEDs versus the distance between the light-emitting molecule and the Mg metal cathode at the wavelength 540 nm. The 540-nm wavelength of the emitting light was chosen in numerical simulation because it is similar to the spectrum peak of the green-light-emitting material, tris(8-hydroxyquinoline) aluminium (Alq). It is clear that the first maximum and minimum of light intensity occur at 65 nm and 150 nm. Thus, the position of the emission zone with the distance of 65 nm from the metal cathode can be considered as an optimal one for the high light intensity. This behaviour results from the optical interference of the metal cathode. The light intensity of OLEDs begins to grow beyond the distance of 150 nm. However, it is of little practical use because of high turn-on voltage for the devices. Figure 3 shows the optical outcoupling efficiency corresponding to Fig. 2. The solid and dashed lines show the light output efficiency coupled into the glass layer and air, respectively. For the latter, the efficiency has the maximum and minimum in the positions of 51 nm and 150 nm, which is also caused by the effect of optical interference of metal cathode. Figures 2 and 3 present an optimum location of the emission zone of OLEDs for high light intensity and efficiency.

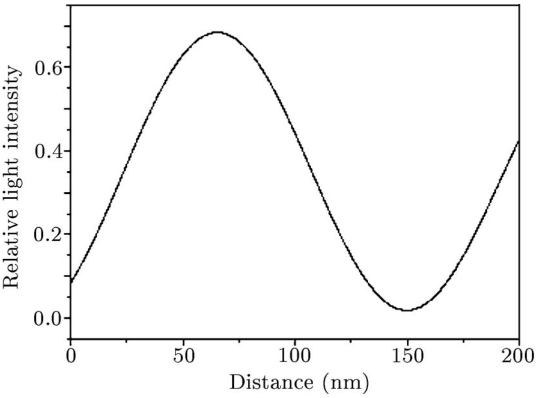

Fig. 2. Relative light intensity versus the distance between the cathode and the light-emitting molecule. The first peak of the solid line is located at 65 nm with Mg cathode and the central wavelength of 540 nm.

Figure 4 shows the surface emission patterns as a function of distances of the light-emitting molecules from the metal cathode. One of the advantages of OLEDs is the wide angle of the surface light emission such as Lambertian. However, our numerical results in Fig. 4 shows that the surface emission patterns of Lambertian are changed by the location of emission zone in OLEDs. In Fig. 4, the solid, dashed, dotted, dashed-dotted, and dashed-dotted-dotted lines show the surface emission patterns with distances of 40, 50, 60, 70, and 80 nm, respectively. It can be found that the surface emission patterns of Lambertian are approximately kept in 40, 50, and 60 nm, but broken for the case of 70 and 80 nm.

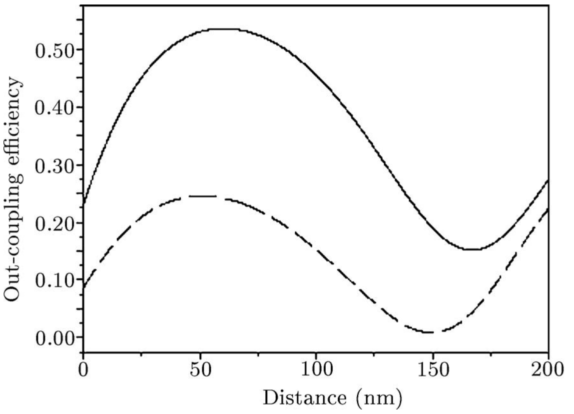

Fig. 3. Out-coupling efficiency versus the distance between the cathode and the light-emitting molecule. The solid and dashed lines represent the efficiency in the layers of glass and air, respectively. The first peaks of the solid line and the dashed line are located at 60 nm and 51 nm with the Mg cathode and the central wavelength of 540 nm.

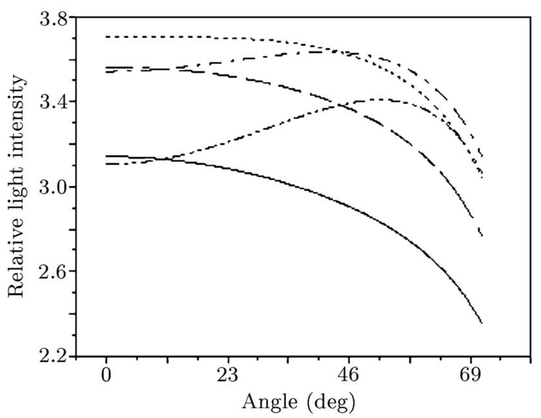

Fig. 4. Surface emission patterns with different distances of the light-emitting molecule from the cathode. The solid, dashed, dotted, dashed-dotted, and dashed-dotted-dotted lines represent the distance of 40, 50, 60, 70, and 80 nm, respectively, with the Mg cathode and the central wavelength of 540 nm.

Figure 5 shows the relative light intensity as the function of location of emission zone for the wavelength of 460, 540, and 640 nm, which can be used to represent the cases of blue-, green-, and red-light emission of OLEDs. The wavelengths of 460 nm and 640 nm show the peak spectrum of the blue- and red-light emitting material such as 9,10-di-(2-naphthyl) anthracene(AND) and 4-(dicyanomethylene)-2-(t-butyl)6-methyl-4H-pyran (DCJTB). It is shown that the locations of emission zone optimized for the maximum of light intensity at wavelengths 460, 540, and 640 nm are 56, 65, and 81 nm, respectively. Because these results come from the effect of optical interference, the shorter the wavelength of light emission OLEDs, the shorter the optimal distance of the light-emitting molecule from the metal cathode for the maximum of light intensity. This tendency is quite important for the design of full-colour and white-light OLEDs by combined with light emitting layers of different colours. For example, based on the numerical results in Fig. 5, the light intensity and efficiency of full-colour and white-light OLEDs can be optimized and increased by adjusting the location and the sequent layers with different emitting light colours.

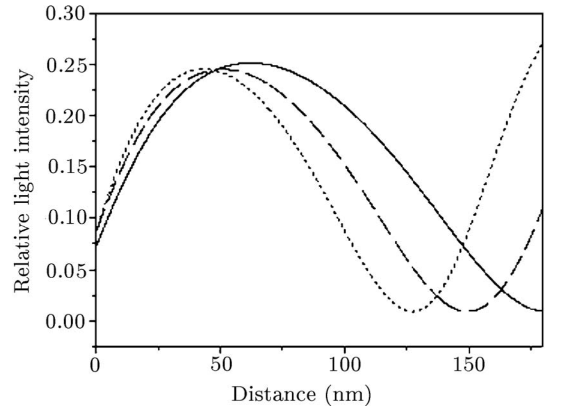

Fig. 5. Relative light intensity versus the distance between the cathode and the light-emitting molecule. The solid, dashed, and dotted lines represent light at wavelengths of 640, 540, 460 nm, respectively. The first peaks of the solid, dashed, and dotted lines are located at 81, 65, and 56 nm, with the Mg cathode.

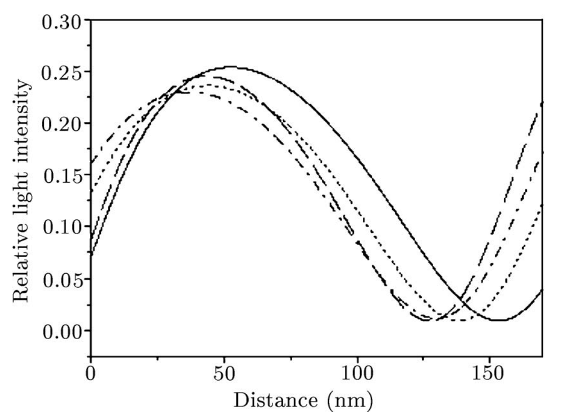

Fig. 6. Relative light intensity versus the distance between the cathode and the light-emitting molecule. The dashed-dotted, dotted, solid, and dashed lines represent the cases with cathodes of Ca, Ag, Mg, and Al, and the first peaks at 46, 54, 56, and 69 nm, respectively, with the central wavelength of 540 nm.

For the case of different metal cathode such as Ca, Ag, Mg, and Al, Fig. 6 shows the relative light intensity as the function of location of emission zone at the wavelength of 540 nm. We can find that the optimal distances of the light-emitting molecule from the different metal cathodes for the maximum of light intensity are quite different because of different reflection phase shift. For the Ca, Ag, Mg, and Al metal cathodes, the optimal locations of emission zone are 46, 54, 56, and 69 nm, respectively. These results are also important for design and optimum of structures of OLEDs.

In conclusion, we have numerically investigated the dependence of light emission intensity on the distance of the emission zone from the metal cathode. It can be concluded that light emission of OLEDs is strongly influenced by interference by the metal cathode. Optical output can be optimized by adjusting the location of emission zone. For the cases of different wavelengths and metal cathodes, the optimized distances of emission zone from metal cathode were investigated and compared numerically, which can be instructive and reference for design of OLEDs for high efficiency.

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