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Model and simulation on the efficiencies of microcavity OLEDs

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ABSTRACT

This paper presents simple calculation models of the external quantum efficiency and power efficiency for the microcavity OLEDs. The models take into account the energy spatial distribution of the device and provide a rough estimate of the efficiencies for the planar surface emitting devices, by which the integrating sphere and monochrometer were saved. The external quantum efficiency and luminous current efficiency from the structures of glass/DBR/ITO/NPB/Alq: C545T/Alq/LiF/Al and glass/ITO/NPB/Alq: C545T/Alq/LiF/Al were calculated based on these models and the measured data. Comparing with conventional OLED, the external quantum efficiency and luminous current efficiency of the MOLED were improved 3.1% and 8% at low current density (<10 mA/cm^2, corresponding to the display brightness range), respectively.

1. Introduction

Since Purcell suggested that the spontaneous emission (SE) rate of a radiating system can be altered in a microcavity in 1946 [1], this concept is now well established, owing to the experimental and theoretical development of cavity quantum electrodynamics [2–4]. The microcavity redistributes SE angularly through interference effects, which is extremely useful to improve light extraction from the high refractive index solid state emitter [5]. Planar microcavity structure is a simple physics model and has been intensively investigated. By now planar microcavities have been applied to many kinds of optoelectronic devices working at different wavebands such as resonant cavity light emitting diodes [6]/microcavity organic light emitting diodes [7] (RCLEDs/MOLEDs), vertical cavity surface emitting lasers (VCSELs) [8], planar muffin-tin cavity millimeter-wave electron accelerator [9] and F-P cavity THz emitter [10] to improve their radiative properties.

The external quantum efficiency is a useful parameter in understanding the fundamental physical mechanisms of electro-optical conversion devices. This paper concerns with the external quantum efficiency, which is the product of the number of photons created in the planar microcavity surface emitting devices (internal quantum efficiency) and the number of photons that make it out of the material (light extraction efficiency). For a planar surface emitting device, because of the refractive index discrepancy between the outside medium n_{out} and the emitting layer n_{in}, only a portion of photons whose direction lies in the escape cone can be extracted out of the device. The escape cone is defined as $\Omega=2\pi\{1-\cos[\arcsin(n_{out}/n_{in})]\}$. When introducing a resonant cavity to planar devices, because of interference effects, the directionality of the spontaneous emission emitted inside the semiconductor would be modified into the escape cone [11]; thus the extraction efficiency can be improved. Here we presented simple calculation models of the external quantum efficiency and power efficiency for the microcavity OLEDs. The external quantum efficiency and luminous current efficiency of the MOLED were calculated based on these models; the respective improvements of 3.1% and 8% were achieved compared with those of conventional OLED.

2. Model presentations

For the microcavity OLEDs, different from the lambertian emitters, the luminance (lm/sr/m^2 or cd/m^2) is a function of not only the emitted wavelength but the viewing angle. Assuming $L_v(\theta)$(lm/sr/m^2) is the angular-dependent luminance and θ ($0\le\theta\le\pi/2$, the same below) is the angle to the normal of the device, while $L_v(\theta,\lambda)$(lm/sr/m^2/nm) is the spectral luminance at viewing angle θ, then

$$L_v(\theta)=\int L_v(\theta,\lambda)d\lambda=\xi(\theta)\int P(\theta,\lambda)V(\lambda)d\lambda. \qquad (1)$$

Here λ is the wavelength in nanometers; $P(\theta,\lambda)$ is the relative spectral power distribution of the device at viewing angle θ; $V(\lambda)$ is the normalized photopic spectral response function; $\xi(\theta)$ is a parameter relative to θ.

$$\xi(\theta)=\frac{L_v(\theta)}{\int P(\theta,\lambda)V(\lambda)d\lambda} \qquad (2)$$

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The spectral luminous intensity (lm/sr/nm) at viewing angle θ is

$$I_v(\theta,\lambda) = AL_v(\theta,\lambda)\cos\theta. \tag{3}$$

Here A is the device active area. So the spectral luminous flux (lm/nm) at viewing angle θ can be written by

$$\Phi_v(\theta,\lambda) = I_v(\theta,\lambda)\frac{d\Omega}{d\theta} = \pi AL_v(\theta,\lambda)\sin 2\theta. \tag{4}$$

Here Ω is the solid angle seen from O (see Fig. 1), which equals to the surface area of the spherical cap with $R=1$ and angular radius θ.

The luminous flux (lm) into half space is

$$\Phi_v = \iint \Phi_v(\theta,\lambda)d\theta d\lambda = \pi A\int_0^{\frac{\pi}{2}} L_v(\theta)\sin 2\theta\, d\theta. \tag{6}$$

So, the luminous power efficiency (lm/W) of the surface emitting devices is

$$\eta_{LE} = \frac{\Phi_v}{VI} = \frac{\pi A\int_0^{\frac{\pi}{2}} L_v(\theta)\sin 2\theta\, d\theta}{VI}. \tag{7}$$

Here I and V are driving current and voltage of the device, respectively.

The current efficiency η_{LC} (lm/sr/A) is defined as

$$\eta_{LC} = \frac{L_v(0)A}{I}. \tag{8}$$

Here $L_v(0)$ is the luminance in the normal direction.

The number of monochromatic photons in visible band emitted into $d\Omega$ solid angle at viewing angle θ is

$$N_p(\theta,\lambda) = \frac{\lambda\Phi_v(\theta,\lambda)}{K_m hcV(\lambda)} = \frac{\lambda\pi A\xi(\theta)\sin 2\theta P(\theta,\lambda)}{K_m hc}. \tag{9}$$

Here h is the Plank constant; c is the velocity of the light. K_m is a conversion constant based on the maximum sensitivity of the eye (683lm/W). The total number of photons in visible band emitted into $d\Omega$ solid angle at viewing angle θ is

$$N_p(\theta) = \int N_p(\theta,\lambda)d\lambda = \frac{\pi AL_v(\theta)\sin 2\theta}{K_m hc}\frac{\int\lambda P(\theta,\lambda)d\lambda}{\int P(\theta,\lambda)V(\lambda)d\lambda}. \tag{10}$$

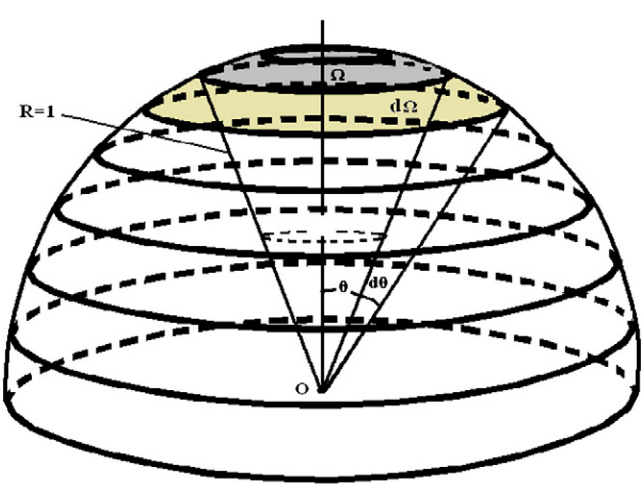

Fig. 1. Schematic to the definition of the solid angle Ω.

Then, the total number of photons in visible band emitted into half-space is

$$N_p = \int_0^{\frac{\pi}{2}} N_p(\theta)d\theta = \frac{\pi A}{hc}\int_0^{\frac{\pi}{2}}\left[L_v(\theta)\sin 2\theta\frac{\int\lambda P(\theta,\lambda)d\lambda}{\int P(\theta,\lambda)V(\lambda)d\lambda}\right]d\theta. \tag{11}$$

So the external quantum efficiency of the microcavity OLEDs can be written as

$$\eta_{ext} = \frac{N_p}{N_e} = \frac{\pi\ e}{K_m hcJ}\int_0^{\frac{\pi}{2}}\left[L_v(\theta)\sin 2\theta\frac{\int\lambda P(\theta,\lambda)d\lambda}{\int P(\theta,\lambda)V(\lambda)d\lambda}\right]d\theta. \tag{12}$$

Here e is the quantity of the electron charge; N_e is the number of injected electrons; J is current density.

3. Experiment

We made a simple microcavity OLED with the structure of glass/DBR/ITO/NPB/Alq: C545T/Alq/LiF (1 nm)/Al. DBR and the Al cathode are the two-parallel reflectors, which are necessary for the F-P microcavity. DBR consists of 4 pairs of TiO_2 (53 nm)/SiO_2 (87 nm) quarter wave layers. The refractive indices of TiO_2 and SiO_2 are 2.41 and 1.46, respectively. For comparison, a conventional OLED was deposited with the structure of glass/ITO/NPB/Alq: C545T/Alq/LiF (1 nm)/Al. The DBR, ITO, organic materials and the cathode Al were deposited as described elsewhere [12].

The EL area of MOLED and conventional OLED were 1×1.3 mm^2 and 1×1.2 mm^2 respectively. The device was mounted on a rotational stage. In order to achieve a higher level of precision the emitted light was collected at 5° increments away from the surface normal. At the same time, we have repeated measures for up to 10 times and got the arithmetical mean.

4. Results and discussions

Fig. 2 shows the normalized intensity spatial distribution of the MOLED and conventional OLED. The cavity device shows stronger angular dependence and large part of the light was concentrated on the cavity axis, which is in the interest of fiber coupling applications. While the conventional OLED shows more homogeneous light spatial distribution, Fig. 3 shows the EL spectra of MOLED and OLED. The full width at half maximum (FWHM) of the MOLED is 12 nm significantly narrowed from that of 54 nm measured from OLED. Fig. 4 shows the brightness as a function of operation current density of MOLED and conventional OLED, respectively. The brightness of 120,000 and 83,000 cd/m^2 for MOLED and conventional OLED operated at around 1230 mA/cm^2 was resulted, respectively. The brightness of MOLED was improved about 44.6% compared with conventional OLED. The simulated external quantum efficiencies from Eq. (12) and the measured data for the MOLED and OLED are shown in Fig. 5. The external quantum efficiency of the MOLED is close to or slightly higher than that of OLED at moderate luminance, which corresponds to the brightness level of screen display. At a current density of 2.4 mA/cm^2, the brightness and external quantum efficiency are 200 cd/m^2, 1.33% for MOLED and 166 cd/m^2, 1.29% for conventional OLED, respectively. The external quantum efficiency of the MOLED was improved about 3.1% compared with conventional OLED. The luminous current efficiency–current density characteristics of the MOLED and OLED are shown in Fig. 6. The luminous current efficiency of 9.5 and 8.8 cd/A was obtained for MOLED and conventional OLED operated at 16 mA/cm^2, respectively. The luminous current efficiency of MOLED was improved about 8% compared with conventional OLED. As shown in Figs. 5 and 6, only a minor improvement in the external quantum efficiency and luminous current efficiency was achieved at

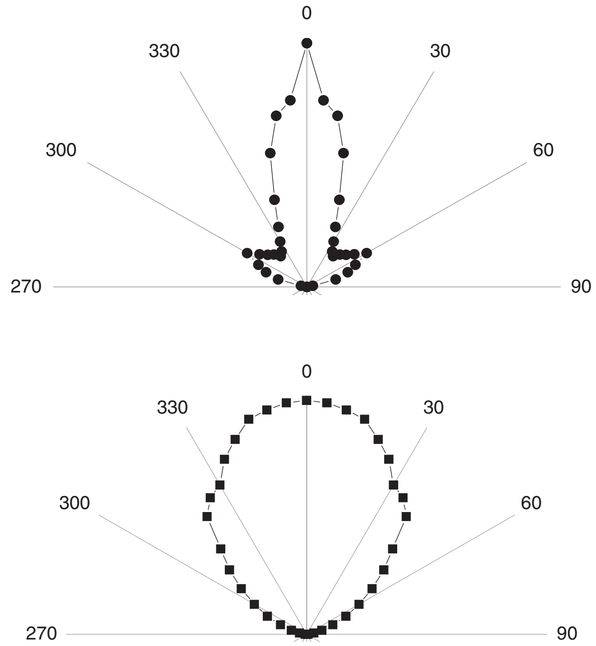

Fig. 2. Normalized intensity spatial distribution of the microcavity (above) and conventional (below) OLEDs.

low current density (<10 mA/cm^2). The possible reasons are: a) due to adding DBR layers, the MOLED has more interfaces than conventional OLED, which results in the larger reflection, absorption, scattering and waveguide losses; b) during the cavity design process, we did not consider the coupling between vacuum electric field and dipole, so the luminance of the cavity device did not reach its maximum.

5. Conclusions

By conclusion, we presented simple calculation models of the external quantum efficiency and power efficiency for the planar surface emitting devices working at different wavelength range. These models can provide a rough estimate of the efficiencies for these devices, by which the integrating sphere and monochrometer were saved. So they are applied to the case when the required accuracy is not high enough. Then, we fabricated two OLEDs with and without cavity and calculated their external quantum efficiency and luminous current efficiency at different current density. At a current density of 2.4 mA/cm^2, the brightness and external quantum efficiency are 200 cd/m^2, 1.33% for MOLED and 166 cd/m^2, 1.29% for conventional OLED, respectively. The luminous current efficiency of MOLED was improved 8% compared with conventional OLED.

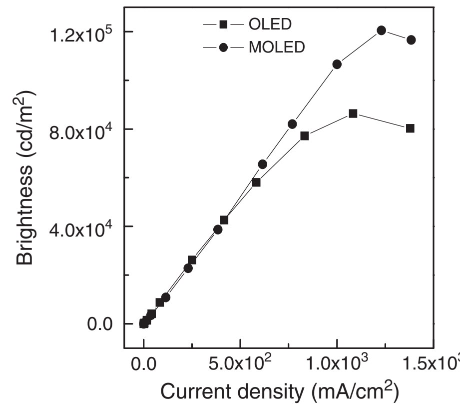

Fig. 4. Brightness–current density characteristics of the microcavity (above) and conventional (below) OLEDs.

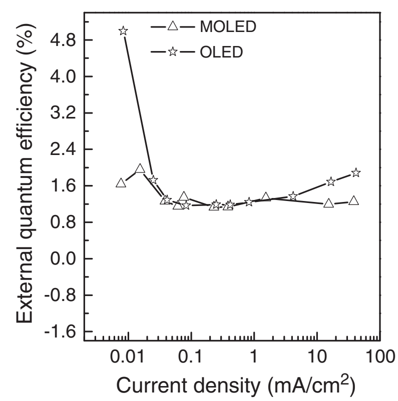

Fig. 5. External quantum efficiency–current density characteristics of the microcavity and conventional OLEDs.

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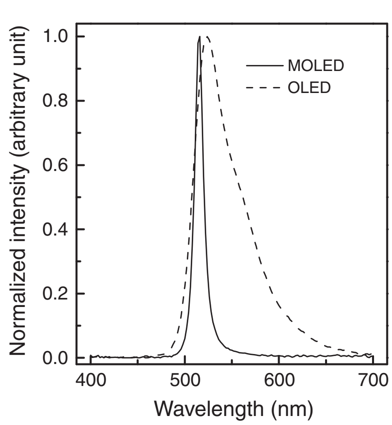

Fig. 3. Normalized EL spectra of the microcavity and conventional OLEDs.

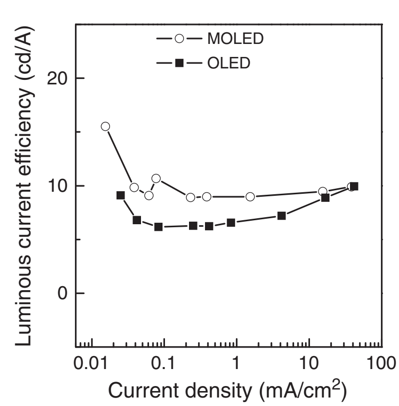

Fig. 6. Luminous current efficiency–current density characteristics of the microcavity and conventional OLEDs.

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