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Organic Light-emitting Devices with A Coupled Microcavity

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Abstract: The optical and electroluminescent(EL) properties of organic light emitting devices(OLED) with a coupled microcavity(CMC) structure were investigated. CMC is a kind of complicated microcavity. The modeled optical and luminescent properties of the CMC is simplified by treating the passive cavity as a bottom mirror, and consistent with the measured results. The EL spectral radiance of the CMC in the normal direction was enhanced by a factor of 3.6 at peak of 502 nm, 5.6 at peak of 550 nm, and 0.5 at the whole spectrum region comparing with the normal OLED driving at the same current density. The highest current efficiency and luminance of 7.0 cd/A and 22 660 cd/m^2 for the CMC were obtained in the normal direction, comparing with those of 4.2 cd/A and 13 600 cd/m^2 for the non-cavity OLED.

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1 Introduction

Recently, microcavity organic light-emitting dides(OLED) has attracted much attention plane microcavity are formed by a Fabry-Perot cavity with an active medium embedded between two mirrors[1-3]. The emission properties of a semiconductor material, such as spectrum distribution and spatial distribution of emission, can be tailored in microcavities with dimensions comparable to an optical wavelength. By using one-dimensional microcavity structures, many applications have been reported, such as microcavity light-emitting diodes, vertical-cavity surface emitting lasers and microcavity OLEDs[4-7]. Microcavity in an OLED device can reduce the emission bandwidth, improve the color purity, and increase luminance output efficiency as compared with normal OLED's[6-7].

Coupled microcavity(CMC) is a structure consists of two planar FP microcavities that are surrounded by external mirrors and coupled by a central mirror. Lately, CMCs made of inorganic semiconductors have been grown and investigated to show very different emission characteristics compared with a single microcavity[8-10], which presents many potential applications, for instance highly selective wavelength filters, bistable devices, a range of optical and electro-optic switches, laser oscillators. Recently, a vertical double-coupled organic microcavity has been reported on its reflectance and the photoluminescence(PL) characteristics[11]. We consider that studies on the electroluminescent(EL) properties may support efforts to better understand organic CMCs. Since the CMC structure can significantly suppress the transverse electric(TE) leaky modes and it is beneficial to the structure design of organic electrically pumped lasers[9-10]. In this paper, we report the EL properties of CMC OLED. We introduce a simple way to simulate the optical properties

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of CMC structure. The results show that the forward current efficiency and luminance of a CMC OLED can be enhanced substantially, which implies a potential application for communication.

2 Experiments

In a CMC structure, two unattached microcavities are border upon each other. In this research, one cavity is a passive cavity that has no emitting material. The other is an active cavity that has two organic layers. The first organic layer is a hole transport layer made by 4-4′-bis [N-(1-naphthyl)-N-phenyl-amino] biphenyl(NPB) materials. Another is an emitting layer made by ris-8-hydroxyquinoline aluminum(Alq_3) materials. The two samples with the following structures were fabricated.

CMC: Glass/ [HL] ^{2}H2L [HL] ^{2}/ITO (65 nm)/NPB(74 nm)/Alq_3(63 nm)/LiF(1 nm)/Al (100 nm).

OLED: Glass/ITO(65 nm)/NPB(74 nm)/Alq_3(63 nm)/LiF(1 nm)/Al(100 nm).

For CMC sample, the passive cavity has a structure of [HL] ^{2}H2L [HL] ^{2} with transparent conducting indium-tin oxide(ITO) layer. Here H is the material of Ta_2O_5 with a high refractive index of 2.05, and L is the material of SiO_2 with a low refractive index of 1.46. The notation [HL] ^{3} implies a quarter-wavelength of high-index material, H, followed by a quarter-wavelength of low-index material, L, 3 times. Ta_2O_5, SiO_2 and ITO thin film were made by electron-beam evaporation on a BK7 glass substrate in an oxygen atmosphere at a pressure of about 2.0×10^{-2} Pa. The deposition rates of Ta_2O_5, SiO_2 and ITO were 0.2, 0.4, 0.1 nm/s, respectively. Organic materials and Al mirror were deposited by thermal evaporation in high vacuum of 5×10^{-4} Pa. The deposition rates of the organic thin layers were about 0.3 nm/s. The cathode was composed of 1 nm LiF capped with 100 nm Al. To make comparison, the reference noncavity OLED was fabricated on an ITO-coated glass substrate in the same conditions. Typical active areas were 2 mm × 2 mm. The thickness of organic films were monitored by a crystal oscillator during deposition. The real thickness was measured with an Atom Force Microscope. EL spectra, luminance yield, and CIE color coordinates of the devices were measured by a Photo Research PR-705 spectrophotometer driven with a Keithley 2400 source meter. The detections were through the glass side. The reflectance spectrum was measured with an AvaSpec spectrometer. All data are taken under ambient conditions.

3 Results and Discussion

In order to simplify the device analysis, the whole passive cavity was treated as a bottom mirror, thus the CMC becomes a simple cavity with organic layers confined between a bottom dielectric mirror and a top metal Al mirror. The reflectance characteristics of the CMC as a function of wavelength were measured(line) and simulated(dash) based on a transfer matrix method [12]. The measured reflectance spectra and the calculated reflectance phase shift of bottom mirror and Al mirror were shown in Fig. 1. It shows that metal Al mirror has an average reflectance of about 89%, and a linearly varied phase shift at an average value of 2.8. Resulting from a single cavity(or a filter) structure, the bottom mirror exhibits a reflectance dip(cavity mode) at the Bragg wavelength of 520 nm within the region of stop band from 460 to 610 nm, and a phase-folding characteristic in phase shift. As shown in Fig. 1, a splitting in the cavity modes is observed within the stop band due to the optical coupling between passive cavity and active cavity. The measured two resonance peaks are 500 nm and 548 nm, which are very close to the calculated results, *i. e.* 498 nm and 550 nm.

Fig. 2 shows EL spectra of the CMC and the OLED in the normal detection driven at the same current density of 40 mA/cm^2. The calculated EL spectrum of the CMC(Dot line) is also plotted for comparison. The OLED has a wide-band EL spectrum centered at 524 nm with a full width at half maximum(FWHM) of 104 nm. An effect of spectral narrowing and an enhancement of the emission intensity of the CMC are clearly observed. The EL intensity of the CMC is enhanced at the two resonance wavelengths at 502 nm and 550 nm with a same

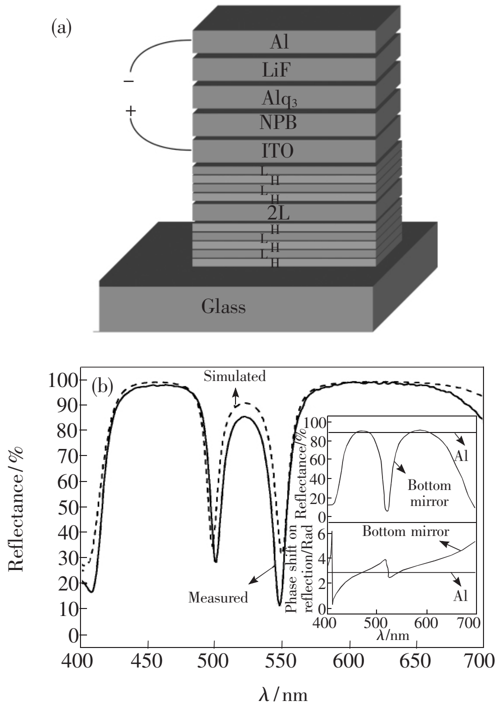

Fig. 1 (a) Structure of the CMC, (b) Measured and simulated reflectance spectra of the CMC. The inset shows the measured reflectance spectra of bottom mirror and Al mirror, and the calculated phase shift of bottom mirror and Al mirror on reflection.

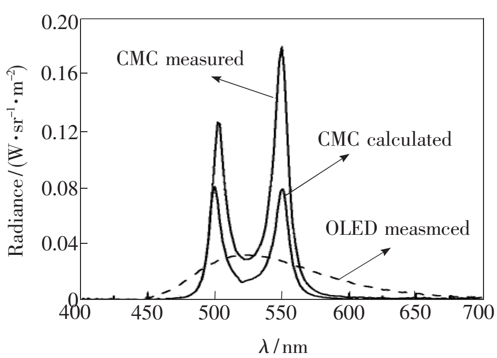

Fig. 2 EL spectra of the CMC and the reference OLED in the normal detection driven at 40 mA/cm^2, Dot line shows the calculated EL spectrum of the CMC.

FWHM of 12 nm, and is suppressed in the other region. The peak intensity at 502 nm was 3.6 times stronger than that of OLED, and 5.6 times at 550 nm. Furthermore, the whole spectral radiance of the CMC is 5.48 W/(sr · m^2), which had an enhancement factor of 0.5 comparing with that of OLED.

Fig. 3(a) and Fig. 3(b) present the dependence of current efficiency and luminance on current density of the OLED(dash) and CMC(line) at the viewing angle of 0° and 30°. For the OLED device, the maximum luminance in the normal direction was 13 600 cd/m^2 obtained at 600 mA/cm^2, and the maximum efficiency is 4.2 cd/A obtained at 100 mA/cm^2. While for the CMC the maximum luminance and efficiency are 22 660 cd/m^2 at 500 mA/cm^2, and the 7.0 cd/A at 100 mA/cm^2, respectively. At the typical luminance of 100 cd/m^2, the current efficiency, voltage and current density are 2.84 cd/A, 5.5 V and 4 mA/cm^2 for the noncavity OLED, and 5.3 cd/A, 5.4 V and 2 mA/cm^2 for the CMC, respectively. At the viewing angle of 30°, the dependence of current efficiency and luminance on current density of the OLED(dash) and the CMC(line) was compared under current density of 100 mA/cm^2. Although the CMC still exhibits better EL properties than the OLED, the difference in luminance and efficiency between them becomes decrescent, which implies the emission intensities from CMC decrease very fast with the viewing angle.

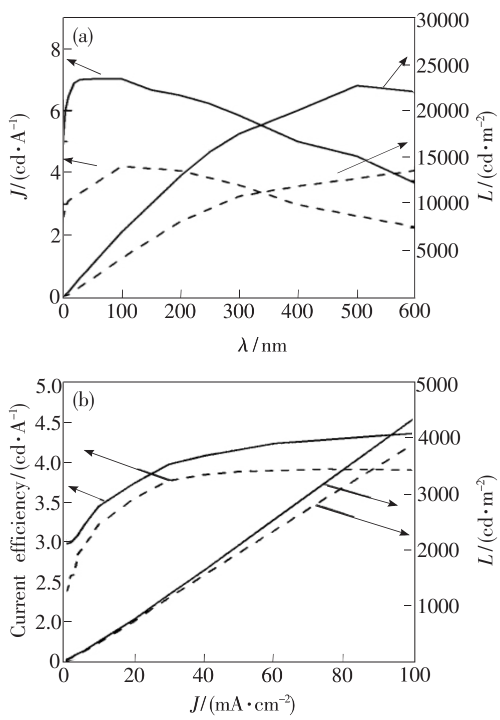

Fig. 3 Luminance-current density-current efficiency characteristics of the CMC and the OLED at the viewing angle of 0°(a) and 30°(b)

Fig. 4(a) and Fig. 4(b) show the measured EL spectra of the CMC and the OLED as a function of viewing angle off the surface normal. With the increasing angular displacement 0° to 70° from the normal, the OLED has almost the same EL spectra, accompanied by a luminance decreasing from 901 cd/m^2 to 472 cd/m^2, and the current efficiency declining from 4.5 cd/A to 2.36 cd/A. The 1931 Commission Internationale de l'Eclairage (CIE) color coordinate of the OLED as shown in Fig. 4(c) is(0.32, 0.54), unchanged with viewing angle. While for CMC, the luminance decreases much fast from 1 349 cd/m^2 to 224 cd/m^2, and the current efficiency is declined from 6.7 cd/A to 1.1 cd/A. At the same time, the EL spectra as well as the CIE color coordinates shift a lot due to the changing of cavity length. The EL peaks at 502 nm and 550 nm at the viewing angle of 0° are blue shifted to 470 nm

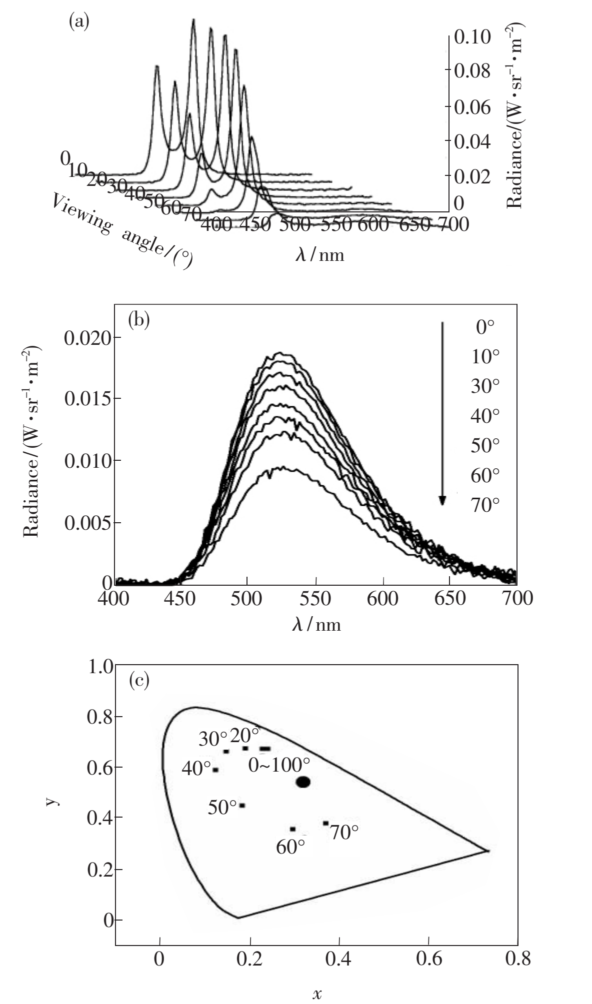

Fig. 4　EL spectra of the CMC(a), the OLED(b), and the 1931 color coordinates of the CMC and OLED(c) as a function of viewing angle under the current density of 20 mA/cm^2.

and 512 nm at the viewing angle of 40°, respectively. The resonance peak at 470 nm fades away gradually at the viewing angle of 50° ~ 70°, accompanied by appearing a new resonance peak around 600 nm. Therefore, a near-white-light emission is achieved at the view angle of 60° with a CIE coordinates of(0.30, 0.35).

The angular dependent luminance and current efficiency of both OLED and CMC were measured and shown in Fig. 5. It shows that under the same driving current density, luminance and current efficiency of the CMC are enhanced within the viewing angles of 33°, but is suppressed at large viewing angles. Therefore the emission of the CMC is concentrated in a sharp cone around the sample normal. It implies that compared with a noncavity OLED, CMC offers some advantages, such as enhanced luminance and current efficiency, improved spectral purity and directionality, which can provide efficient light-coupled into optical fibers. It should be noted that the reflectance of the bottom mirror is about 90%. Compared with the top mirror, it is too high for the light outputing from CMC. In the further work, an improved current efficiency can be expected for an optimized CMC structure.

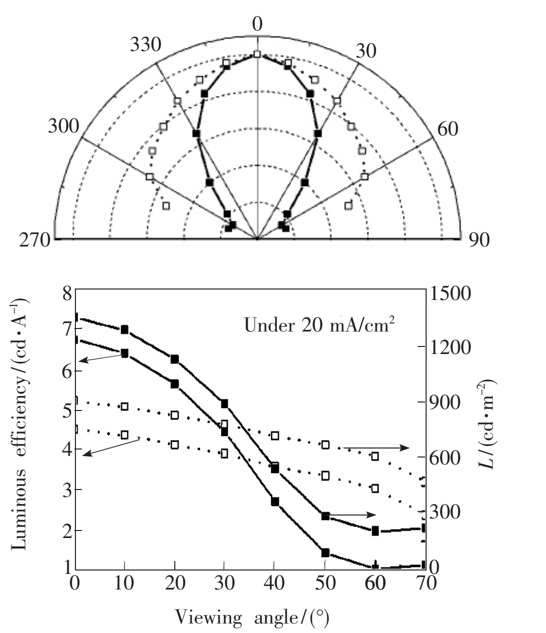

Fig. 5　Angular distribution of luminance and current efficiency for the OLED(dot + hollow square) and CMC(line + square) driven at 20 mA/cm^2.

4 Conclusion

In summary, optical and EL properties of a CMC OLED has been investigated. It was observed that CMC structure strongly modifies the EL properties of OLED. Optical coupling between passive cavity and active cavity yields a splitting in the cavity modes with the appearance of two resonance peaks of 502 nm and 550 nm within the stop band. The maximum current efficiency and luminance in the normal direction are 7.0 cd/A and 22 660 cd/m^2 for the CMC, and 4.2 cd/A and 13 600 cd/m^2 for the noncavity OLED.

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耦合微腔结构的有机电致发光器件

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摘要: 研究了耦合微腔结构的有机发光器件的光学和电致发光性能。通过将被动腔作为底部反射镜的方法,简化了耦合微腔的光学和发光性能的模拟,所得到的结果与实验符合得较好。在相同电流密度下与同样结构的普通OLED相比,耦合腔OLED的光谱强度在502 nm处增强了3.6倍,在550 nm处增强了5.6倍,光谱积分强度增加了0.5倍。普通OLED的最大电流效率和亮度是4.2 cd/A和13 600 cd/m^2。而耦合腔OLED

则为 7.0 cd/A 和 22 660 cd/m^2。这种结构的器件出射光更集中于腔轴方向，有利于设计开发较高效率的有机激光器件。

关　键　词： 有机电致发光器件; 耦合微腔; 电致发光

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