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Effect of Emitter Position on Emission Intensity in an Organic Planar Microcavity *

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We have fabricated a $\lambda/2$-length planar microcavity between two silver mirrors that had the same thickness and consisted of a sandwich structure LiF1/Alq$_3$/LiF2. By altering the relative thickness of the two LiF layers, the adjustment of the position of thin layer Alq$_3$ in the microcavity was achieved and the apparent photoluminescence (PL) intensity change was observed. The maximal emission intensity device, corresponding to the luminescence layer located at antinode, is four times that of the minimal one whose luminescence layer is near a silver mirror that is close to a node. This indicates that the coupling between vacuum electric field and dipole strongly affects the emission intensity in the forward direction of the microcavity plane. Comparing the PL intensity between the microcavity and the non-cavity devices with the same sandwich structure LiF1/Alq$_3$/LiF2 in free space, at the resonance wavelength a maximal enhancement factor of nine is obtained.

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Recently, electroluminescence in combination with a planar microcavity to tailor the broad spectrum of organic materials has triggered a great deal of interest. In this way the narrowed red, green and blue single modes in a microcavity organic light-emitting diode as well as white light one with multimode have been realized and emission intensity enhancement in the forward direction has been observed in almost all cases.[1,2,4,5] A microcavity can not only realize the tunability of the wavelength but also increase the emission intensity at resonance wavelength in the forward direction of the microcavity plane, due to the fact that microcavity can change the mode density within the cavity, thus increasing the spontaneous emission rate at resonance wavelength and suppressing those at off-resonance wavelength. Experiments supporting this have been demonstrated.[1,2,4,5] For an ideal planar microcavity, the radiative rate of the material embedded within it will have a maximum value of three times that of the free space radiative rate at a wavelength close to the microcavity resonance.[6] In the presence of non-radiative decay channels, an increase of the total radiative rate can lead to an enhancement of the light emission efficiency.[7] According to the Femi golden rule, the transition rate of an electric dipole can be written as[8]

$$\frac{1}{\tau} = \frac{4\pi}{\hbar}\rho_{\mathrm{cav}}(\omega)\left\langle \left| \boldsymbol{d}\cdot\varepsilon(r)\right|^2 \right\rangle, \tag{1}$$

where ε(r) is the vacuum electric-field amplitude at the location $\boldsymbol{r}$ of the emitter, $\boldsymbol{d}$ is the electric dipole, and $\rho_{\mathrm{cav}}(\omega)$ is the density of modes at the angular frequency ω of emitters. For a certain dipole in a certain microcavity, from Eq. (1) it can be found the vacuum electric-field amplitude at the position of the dipole in the microcavity is only the factor that determines the spontaneous emission rate. The standing-wave electric field in a cavity is parallel to the cavity plane, so only the dipole parallel to the cavity has the microcavity effects. The electric-field strength is zero at a node and its maximum is at an antinode, and it changes by sinusoidal function from node to antinode. According to this, the different area of a material embedded within a microcavity will contribute a different fraction to the emission at the normal direction of the cavity plane. It can be expected that a dipole located at an antinode within a microcavity will show a maximal emission intensity and that located at an off-antinode position will show less.

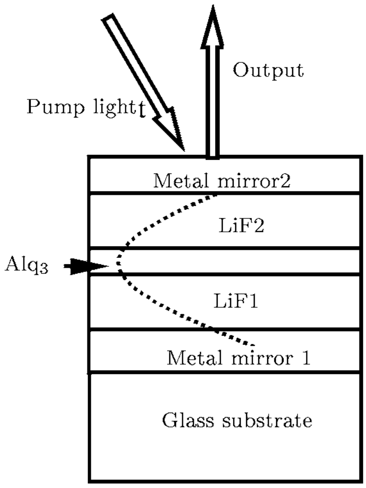

Fig. 1. Schematic diagram of the microcavity device structure. The dashed line indicates the distribution of the electric field.

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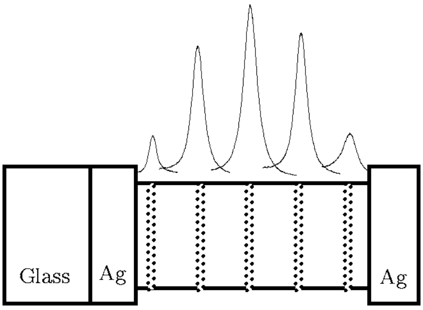

Fig. 2. Emission intensity versus the position of Alq$_3$ in the cavity. The dotted lines denote the position of Alq$_3$. From left to right, the curves show the spectra emitted from devices A, B, C, D and E.

In this work, a $\lambda/2$-length planar microcavity was fabricated. The schematic structure of the microcavity used in the experiment is shown in Fig. 1. The microcavity is defined between two silver mirrors with the same thickness and consists of a sandwich structure LiF1/Alq$_3$/LiF2, where Alq$_3$ is used as the emitter layer with a thickness of about 10nm, and two LiF layers are used as the filler layers. The relative thickness of LiF1 and LiF2 is adjusted to change the position of Alq$_3$ in the cavity and its total thickness remains a constant value to keep the cavity modes consistent with each other for different devices. According to the symmetric structure and the cavity length of the microcavity, it is believable that there is an antinode in the middle and two nodes at the sides of the cavity. By measuring the photoluminescence (PL) spectra, it is shown that the position of the dipole in the microcavity, namely the coupling strength between the vacuum electric field and the dipole, affects strongly the emission in the forward direction. When the Alq$_3$ thin layer is located in the middle of cavity, corresponding to the antinode, its PL intensity shows an enhancement factor of four compared with that positioned near one of the silver films, that is, close to a node. Comparing the PL intensity between the microcavity and non-cavity devices with the same sandwich structure LiF/Alq$_3$/LiF in free space, at the resonance wavelength a maximal enhancement factor of nine is obtained.

The microcavity devices were fabricated first by depositing a 35 nm thick silver film on a cleaned glass substrate, then an LiF1 layer with different thicknesses for five samples (A, 3 nm; B, 30 nm; C, 57 nm; D, 84 nm; E, 111 nm), followed by an $\mathrm{Al_{q3}}$ layer formed simultaneously for all the devices, then again a different LiF2 layer (A, 111 nm; B, 84 nm; C, 57 nm; D, 30 nm; E, 3 nm) and all the devices were finished by another 35 nm silver film deposition. During the fabrication of the microcavity devices, a non-cavity LiF1/Alq$_3$/LiF2 with the same thickness for every corresponding layer as device C but without any silver mirror was also fabricated. All the films were deposited by the vacuum thermal evaporation method at a vacuum degree of 1×10^{-3} Pa with the deposition rates of 2, 1 and 0.1 nm/s for silver, LiF and Alq$_3$, respectively. The thickness and the deposition rates of the films were monitored with a quartz crystal thickness monitor placed near the substrate.

The PL spectra were measured in the forward direction of the device with an HITACH F-4500 fluorescence spectrophotometer. The devices were excited by 325 nm wavelength light from a xenon light. At this wavelength the silver film shows a maximal transmission and Alq$_3$ has a great absorption. The receiving slit was 150 mm away from the device and the emission area is about $5\times5\,\mathrm{mm}^2$.

To determine the resonant mode of the microcavity the transmission spectra of a 35nmAg/LiF/10nmAlq3/LiF/35nmAg model are calculated by using the characteristic matrix method. The refractive indices of LiF and Alq$_3$ are set to be 1.36 and 1.7, respectively. It is shown that when the total thickness of the two LiF layers is 114 nm, the transmission spectra peak near 520 nm, which corresponds to the peak of Alq$_3$ spontaneous emission spectrum. However, the experiment indicates that the cavity mode is at 500 nm. We attributed the 20 nm deviation to the thickness difference between the calculated and experimental values.

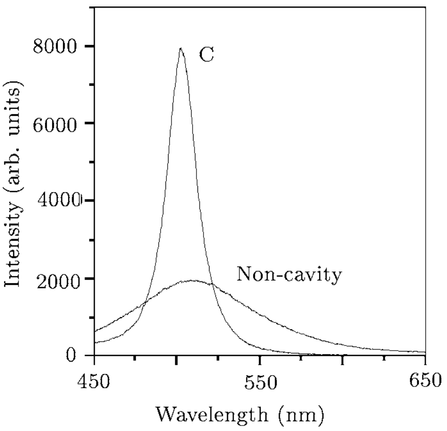

Fig. 3. Relative emission intensity from microcavity device C and non-cavity device.

The PL spectra of five microcavity devices as well as their corresponding structures, namely the position of the Alq$_3$ thin layer, are shown in Fig. 2. All the spectral peak positions are at 500 ± 10 nm, so it is reasonable to compare straightforwardly their magnitude without any modification because the natural spectrum of Alq$_3$ shows almost the same intensity. The excitation light and emissive light from Alq$_3$ will penetrate into the top silver mirror, which is uniform for different microcavity devices, and the LiF2 layer. The transparency of LiF in the wavelength range $110\,\mathrm{nm}-7\,\mu\mathrm{m}$ ensures that the excitation light received by Alq$_3$ is consistent with all the devices and the emission light from Alq$_3$ is not absorbed. Thus we can compare the emission intensity from the different microcavity devices.

From Fig. 2, we can see that when moving the emissive layer in the cavity, the emission intensity in the forward direction takes a symmetric change with the symmetric axis in the middle of the cavity. The maximal emission intensity, corresponding to the luminescence layer located in the middle of the cavity, is four times that of the minimal emission whose luminescence layer is near the top silver mirror. As predicted, the antinode of the $\lambda/2$-length cavity is located in the middle of the cavity, and the electric-field magnitude diminishes gradually by sinusoidal function towards two sides. According to Eq. (1) the spontaneous emission intensity will attenuate when moving the luminescent layer from the middle to any one side of the cavity. The symmetry of the emission intensity in Fig. 2 implies the symmetry of the vacuum electric-field distribution in the cavity.

The PL spectra of microcavity device C and that of non-cavity device glass \LiF2\Alq$_3$\LiF1 are shown in Fig. 3. Comparing the cavity device with the non-cavity device, the apparent emission intensity enhancement with a ratio of 3.5 is observed at the resonance wavelength. Differing from some other cases[1,3−6,9] where the microcavity was defined with full-reflectivity and semi-reflectivity mirrors, and the emission light transmits out of the cavity by the semi-reflectivity mirror, in our experiment the two mirrors have the same thickness, that is, the same reflectivity. Therefore, if the total emission light out of the cavity by the two mirrors is also output by one side, the enhancement ratio would be seven. Allowing for the excitation light loss caused by the top silver mirror, which has an 80% transmission at 325 nm, the corrected enhancement factor reached as high as nine. In this case, the reflectivity R of the silver film at a wavelength of 500 nm is about 75%. The theoretical peak enhancement factor, which is given by $2(1+R)/(1-R)$ for a planar microcavity,[9] is about 14. Thus in this case the experimental data are in very good agreement with the theoretical data.

In summary, we have demonstrated that the position of the dipole in a microcavity, namely the vacuum electric-field magnitude, affects strongly the emission in the forward direction. When the Alq$_3$ thin layer is located in the middle of cavity, corresponding to the position of antinode, its PL intensity shows an enhancement factor of four compared with that positioned near one silver mirror, that is, close to a node. Comparing the PL intensity between microcavity and non-cavity devices with the same sandwich structure LiF/Alq$_3$/LiF in free space, at the resonance wavelength a maximal enhancement factor of nine is obtained.

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