

Design of tunable wavelength microcavity organic electroluminescent diode with liquid crystal

Haixing Chen (陈海星), Jianpu Wang (王建浦), Weidong Shen (沈伟东)
Haifeng Li (李海峰), Xu Liu (刘旭), and Peifu Gu (顾培夫)

State Key Lab of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027

Received February 27, 2003

A novel designed method for tunable wavelength microcavity organic electroluminescent diode (MOLED) based on the birefringence of liquid crystal was presented. By modulated the refractive index of liquid crystal, the device could radiate with different wavelength continuously. The simulated result showed that the tunable range could reach to 60 nm and the full width of half maximum is 5.5 nm. The device could be applied to wavelength converter and tunable light source.

OCIS codes: 230.3990, 230.3670, 230.3720, 250.3680.

Currently, organic thin film electroluminescent diode (OLED) is attracting much attention for its promising application since Tang^[1] reported his two layers organic electroluminescent device in 1987 and then Burroughes^[2] achieved the same electroluminescent device with the polymer material in 1990. However, the emission characteristics of the device based on the organic thin film electroluminescent are shown with a big scattering angle and the broad spectral width, which result in the weak emission light density. In 1992, Yokoyama^[3] referred to modify the emission characteristics by applying the planar microcavity structure on the organic electroluminescent device to narrow the spectral width and enhance the emission light density.

Microcavity organic electroluminescent diode (MOLED) has already utilized as the light source for liquid crystal projector and color display. Some researchers have reported their methods and structures to achieve the tunable wavelength emission MOLED^[4,5]; Becker^[6] had built a tunable microcavity light-pump organic luminescent structure with the liquid crystal as the tunable layer. In this paper, we presented a novel design of MOLED structure based on the modulation of the refractive index of liquid crystal. The numerical simulation showed the feasibility of this kind structure.

The principle of MOLED is mainly employed the effect of Purcell^[7]. Organic electroluminescent devices normally give a weak emission density; one could enhance it remarkably by the introduction of the planar microcavity^[8]. By choosing the liquid crystal as the microcavity material, we designed the novel structure for the tunable wavelength MOLED which could achieve continuously multi-wavelength light emission with the change of modulated voltage (i.e. the change of the refractive index of liquid crystal). The schematic designed structure is shown in Fig. 1.

Firstly, a thin Al film is deposited thermally onto one glass substrate acting as both the cathode and one of the reflected mirrors of microcavity. Then the organic light-emitting material PFB5+9%PBD^[9] is prepared by spin coating. The transparent conducting layer (ITO) acting as the anode and the alignment layer is deposited by e-beam evaporation. Another glass substrate is deposited with alternating TiO₂/SiO₂ quarter-wave layers

as the other reflected mirror, and then the ITO layer and the alignment layer are deposited respectively. Finally, the two prepared glass substrates are assembled with a certain thick spacer, and then vacuum is filled with the liquid crystal. Dc voltage V_1 is applied between the Al layer and the ITO layer as the driver source for the organic light emitting material, while ac voltage V_2 is used to drive the rotation of the liquid crystal molecule.

The spectral calculation of MOLED could be given by^[4]

$$|E(\lambda)|^2 = \frac{(1 - R_d) [1 + R_m + 2\sqrt{R_m} \cos(\frac{4\pi x}{\lambda})]}{1 + R_m R_d - 2\sqrt{R_m R_d} \cos(\frac{4\pi L}{\lambda})} |E_n(\lambda)|^2, \quad (1)$$

where λ is the light-emitting wavelength, x is the effective distance of the emitting layer from the metal mirror, R_m and R_d are the reflectivities of the metal mirror and dielectric mirror, respectively. L is the total optical length of the microcavity device and $E_n(\lambda)$ is an original spectrum for non-microcavity OLED. Taking into account a substantial penetration depth into the dielectric mirror, L can be expressed by

$$L = \frac{\lambda}{2} \left(\frac{n_{\text{eff}}}{\Delta n} \right) + \sum_i n_i d_i + \left| \frac{\Phi_m}{4\pi} \right| \lambda, \quad (2)$$

where n_{eff} and Δn are the effective refractive indices and the index difference between the two layers of the dielectric mirror, n_i and d_i are the refractive indices and the

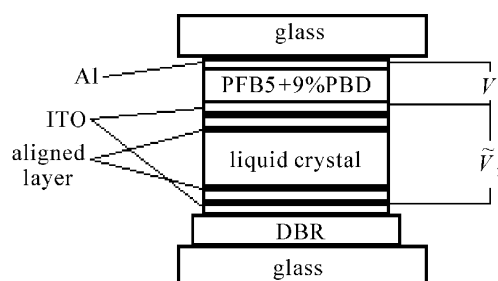


Fig. 1. Schematic diagram of tunable MOLED with liquid crystal spacer.

thickness of the organic layer and the ITO layer, and Φ_m is the phase change at the metal mirror. Normally, the penetration depth into the metal mirror is very small, so the third term in formula could be omitted.

When applied the ac electric field, the orientation of the liquid crystal molecules can be aligned on the direction of electric field and thus the effective refractive index of liquid crystal layer is changed with the rotated angle of molecules. It is well known that the relation on the effective refractive index $n(\theta)$ and the angle between the optical axis and the direction of incident light is given by (as shown in Fig. 2)

$$n(\theta) = \left(\frac{\sin^2 \theta}{n_e^2} + \frac{\cos^2 \theta}{n_o^2} \right)^{-\frac{1}{2}}, \quad (3)$$

where n_o and n_e are the refractive indices of the ordinary light and the extraordinary light, respectively. In the designed structure, $n(\theta)$ would be changed when the modulated ac voltage V_2 altered, thus the total optical thickness of the liquid crystal layer (i.e. $n_{LC}d_{LC}$) would be changed, which affects the light-emitting spectrum. We can get a certain light-emitting region by selecting the appropriate parameter of the microcavity structure.

The simulation of the wavelength-tunable MOLED can be derived from the theory of Fabry-Perot resonator. According the resonate condition of Fabry-Perot cavity

$$2 \sum_i n_i d_i \cos \theta = m\lambda, \quad (4)$$

where $n_i d_i$ is the optical thicknesses of the microcavity components, θ is the light-emitting angle of the device, m is the arbitrary integer and can be taken 3 or 4, which satisfy the microcavity condition. The full width of half maximum (FWHM) of the device could approximately be given by

$$\text{FWHM} = \frac{\lambda}{m\pi} \cdot \frac{1 - \sqrt{R_m R_d}}{(R_m R_d)^{\frac{1}{4}}}. \quad (5)$$

With the change of the refractive index of the liquid crystal, the light-emitting wavelength of the MOLED shifts continuously, the region of tunable wavelength can be given by

$$\Delta\lambda = \frac{2(n_e - n_o)}{mn_e} \left(\frac{1}{2}m\lambda - L_0 \right), \quad (6)$$

where L_0 is the optical thickness of non-tunable component of microcavity, n_o and n_e are the refractive indices

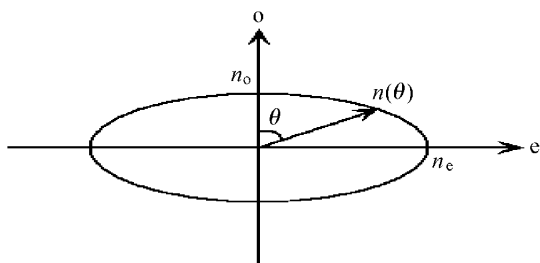


Fig. 2. The refractive index ellipse of liquid crystal.

of the ordinary light and the extraordinary light, respectively.

In our design, the thickness of PFB5+9%PBD layer is 80 nm and its refractive index is 1.75, the thickness of ITO is 50 nm and the refractive index is 2.0, the alignment layers can be obtained by obliquely deposited SiO₂ thin film^[10], its thickness is 20 nm and refractive index is 1.46, so the L_0 is 398.4 nm. The reflectivity of the Al layer in visible light region is 0.9 and the dielectric mirror is 0.92, then the physical thickness of the liquid crystal layer could be obtained when the wavelength λ is ascertained. Here we used a nematic liquid crystal (Merck Ltd. E44), which the difference refractive index between n_o and n_e can reach to 0.27 at 589.3 nm, and then the region ($\Delta\lambda$) of the tunable wavelength can be calculated by Eq. (6).

The numerical calculation is shown in Fig. 3 where the curve of the lower panel is the original spectrum of non-microcavity with the organic material PFB5+9%PBD^[9] and the upper panel shows the simulated result of the design wavelength-tunable MOLED, the dash line shows the light-emitting density of non-microcavity. The maximum point of light-emitting density is near 550 nm as shown in Fig. 3, this is coincident with the maximum position in the lower panel. In practice, one can change the drive voltage V_1 to control the light-emitting density for keeping the equal emission density. The tunable wavelength region of the device can reach to 60 nm and the FWHM is 5.5 nm decided by Eq. (5). It also can be found that there are some weak density transmittance peaks in short-wavelength region, since the low order modes are in existence.

As for MOLED, the emitted light is concentrated in a certain range of angle centered at the axis being normal to the device surface. It can be derived from Eq. (4), in fact, the different angles are corresponding to the different microcavity length, and thus the light-emitting modes are. The simulated calculation is shown as Fig. 4, where the light-emitting wavelength is 550 nm. The emission power is concentrated in a small angle region near

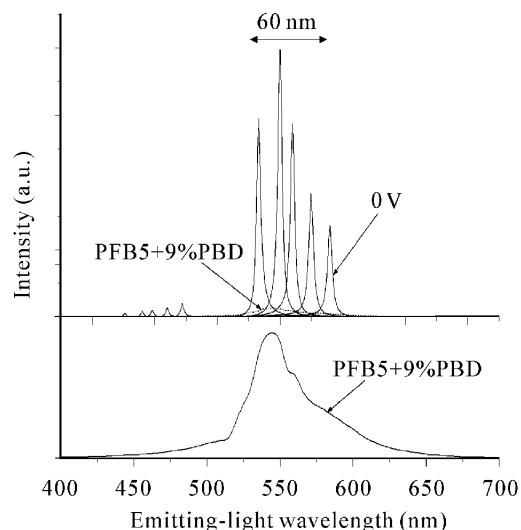


Fig. 3. Upper panel: transmittance of tunable wavelength microcavity OLED with the index change of liquid crystal for the applied ac. Lower panel: the original emitting-light spectrum of OLED of PFB5.

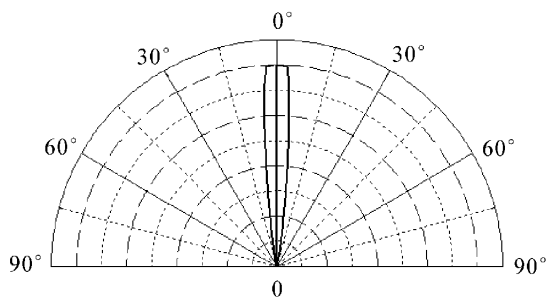


Fig. 4. Spatial distribution of emitting-light at 550 nm.

the axis being normal to the device surface. Similarly, the practical light-emitting density distribution with the observed angle is dependent on the original spectrum of non-cavity.

In conclusion, we designed a novel tunable wavelength MOLED device by employing the birefringence effect of liquid crystalline material. The simulated calculation showed that the wavelength can be shifted up to 60 nm and the FWHM is 5.5 nm, exhibiting a strong directionality in light-emitting space. Tunable-wavelength MOLED possesses many advantages, such as small volume, high emission density, and wavelength tunable and easy large-scale production, which have significantly application to

wavelength converter, tunable light source and color projection in future.

H. Chen's e-mail address is seastarchen@yahoo.com.cn.

References

1. C. W. Tang and S. A. VanSlyke, *Appl. Phys. Lett.* **51**, 913 (1987).
2. J. H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. MacKay, R. H. Friend, P. L. Burn, and A. B. Holmes, *Nature* **347**, 539 (1990).
3. H. Yokoyama, *Science* **256**, 66 (1992).
4. S. Tokito, T. Tsutsui, and Y. Taga, *J. Appl. Phys.* **86**, 2407 (1999).
5. A. Dodabalapur, L. J. Rothberg, R. H. Jordan, T. M. Miller, R. E. Slusher, and Julia, *J. Appl. Phys.* **80**, 6954 (1996).
6. H. Becker and R. H. Friend, *Appl. Phys. Lett.* **72**, 1266 (1998).
7. E. M. Purcell, *Phys. Rev.* **69**, 681 (1946).
8. E. F. Schubert, N. E. J. Hunt, M. Micovic, R. J. Malik, D. L. Sivco, A. Y. Cho, and G. J. Zydzik, *Science* **265**, 943 (1994).
9. J. P. Wang, X. Liu, H. Ye, S. G. Xu, and M. J. Yan, *Proc. SPIE* **4918**, 39 (2002).
10. J. L. Janning, *Appl. Phys. Lett.* **21**, 173 (1972).